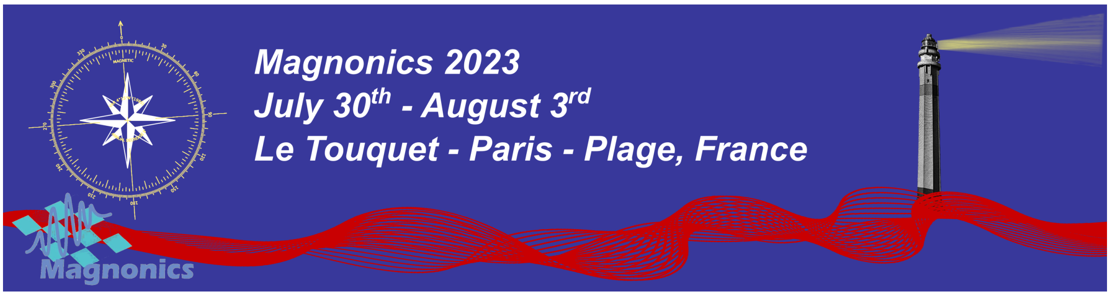

Magnonics 2023 Workshop

July 30th - August 3rd

Le Touquet - Paris - Plage, France

Magnonics

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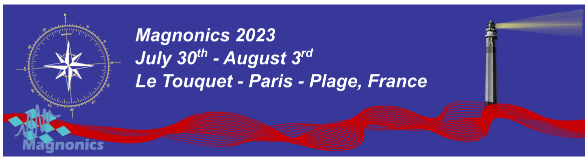

© Illustration par Robert Boullier pour la SNCF (1905).

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- Olena Gomonay (JGU Mainz)
- Dirk Grundler (EPF Lausanne)
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- YoshiChika Otani (U. of Tokyo)
- Philipp Pirro (T.U. Kaiserslautern)
- Caroline Ross (MIT)
- Katrin Schultheiß (HZDR Dresden)
- Tatiana Rappoport (U. Rio de Janeiro)
- Silvia Tacchi (IOM Perugia)

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Welcome Address

On behalf of the organizing committee, it is our great pleasure to welcome you to Magnonics 2023, the 8th edition of this workshop dedicated to the fundamentals and applications of magnons. This year's conference will be held in the beautiful coastal town of Le Touquet - Paris - Plage, from Sunday, July 30th to Thursday, August 3rd, 2023.

We look forward to welcoming you as a participant, as leading experts, researchers and innovators from around the world to exchange knowledge, share insights and explore the latest advances in the field of Magnonics. The conference promises to be a stimulating and enriching experience, providing a platform for fruitful discussions and forging collaborations.

The conference program has been carefully crafted by the Scientific Committee to cover a wide range of topics encompassing various aspects of Magnonics and its recent novel research directions, ensuring a comprehensive exploration of the field. Some of the key areas of focus include

- Magnetization dynamics and damping (linear, nonlinear, propagating spin-waves driven by spin torque, spin orbit torque, spin currents, gradients, VCMA, and others).
- Magnonics in/of spin textures, of anti-ferromagnets, of 2D materials.
- Magnonic crystals, materials and heterostructures.
- Magnonic devices, including microwave and terahertz devices.
- Hybrid magnonic, including quantum, optical, phonon, and plasmon.
- Magnonics for logic and computing applications.
- Novel techniques for spin wave generation, detection, and control, including new microscopy and spectroscopy techniques.

To this end, we have selected a diverse line-up of speakers who will present their latest research, and hopefully stimulate discussions to identify fruitful future directions. In addition, we have allocated ample time for poster sessions to allow a large number of attendees to showcase their work and receive valuable feedback from the community.

To symbolize our commitment to illuminate future research directions in the field of Magnonics, we have chosen the lighthouse of La Canche as the guiding symbol for this 2023 edition. Lighthouses, with their towering structures perched on coastal landscapes, have served as beacons of light, guiding ships safely through treacherous waters and signaling the way to new horizons. Metaphorically, they represent the pursuit of knowledge and the quest for discovery. They also serve as a reminder that we are on a journey together, exploring uncharted territory and pushing the boundaries of magnonic research.

In addition to intellectual stimulation, we hope you will take time to enjoy the picturesque setting of Le Touquet - Paris - Plage. The coastal charm combined with the vibrant atmosphere offers a unique blend of relaxation and cultural exploration. As a special highlight, we have organized a social event at Nausicaá the largest aquarium in Europe (www.nausicaa.fr/en). This will be followed by a social dinner within the ocean conservatory, where we will be surrounded by beautiful and exotic fish and other animals of the ocean. We hope that these networking opportunities will foster interaction among participants and create a memorable experience for all involved.

To ensure your successful attendance, please review the attached conference program, which includes details of your presentation schedule, poster session, and other relevant information. Should you have any specific needs or questions, please do not hesitate to contact our organizing committee. We are here to assist you in any way we can.

Once again, we would like to express our sincere appreciation for your participation in Magnonics 2023. Your expertise and contributions will undoubtedly enrich the conference, and we look forward to meeting you in person. Together, let us explore new frontiers in Magnonics and forge lasting connections within this vibrant community.

Ursula Ebels, Madjid Anane, Grégoire de Loubens, Matthieu Bailleul, and Olivier Klein

History

Le Touquet-Paris-Plage, often referred to simply as Le Touquet, is a coastal town in northern France with a rich history and has been associated with several prominent figures.

Early development: Le Touquet-Paris-Plage was originally a small fishing village on the Opal Coast. In the late 19th century, it caught the attention of two entrepreneurs, Alphonse Daloz and Hippolyte de Villemessant. They envisioned transforming the area into an elegant seaside resort to attract wealthy tourists. With the help of the famous architect Louis Quételart, they developed a master plan for the town.

Le Touquet was officially founded in 1882, when the first casino and luxury hotel, the Hotel des Anglais, were built. The town grew rapidly and became popular with Europe's elite, being a preferred destination for leisure and relaxation. The SNCF poster on the front page is a reminder of this noble heritage, summed up by the reference to "Arcachon du Nord".

Le Touquet continued to flourish at the beginning of the 20th century. It attracted wealthy visitors, including artists, writers and celebrities (amongst others Edouard Leveque, who gave the name to the Opal coast because of its specific light). The town's infrastructure expanded with the construction of golf courses, tennis courts, equestrian facilities and a racetrack. Le Touquet's history as a prestigious resort town has contributed to its reputation and cultural significance. Today, it continues to attract visitors seeking its beautiful beaches, charming architecture and rich heritage.

On a more anecdotal note with national resonance, Emmanuel Macron, the current President of France, has a personal connection to Le Touquet. He has spent several family vacations in the town since his childhood. Macron's parents owned a vacation home in Le Touquet and he has fond memories of the place.

Some of you may also want to visit the La Canche lighthouse, which provides a fitting backdrop for the Magnonics 2023 conference. Built in 1949, the La Canche Lighthouse has stood the test of time and proudly stands as a testament to the region's maritime heritage.

Access

You may find below some practical information to reach the resort.

By plane

The nearest international airports to Le Touquet-Paris-Plage are:

- London Heathrow Airport. From Heathrow, you have a few options. You can take a direct flight from Heathrow to Lille Airport (Lille-Lesquin) in France, which is the closest major airport to Le Touquet. From Lille, you can proceed to Le Touquet by train or taxi. Alternatively, you can take a train or taxi from Heathrow to London St Pancras International station and then take the Eurostar train to Lille, followed by a train or taxi to Le Touquet.

- Lille Airport (Aéroport de Lille-Lesquin) - Located approximately 130 kilometers (81 miles) northeast of Le Touquet, Lille Airport offers both domestic and international flights. It serves various destinations in Europe and beyond.

- Brussels Airport (Brussels-Zaventem Airport) - Situated around 180 kilometers (112 miles) northeast of Le Touquet, Brussels Airport is the main international airport in Belgium. It offers a wide range of domestic and international flights to numerous destinations worldwide.

- Paris Charles de Gaulle Airport (Aéroport Paris-Charles de Gaulle) - Although it is not as close as the previous two airports, Paris Charles de Gaulle Airport is a major international hub with numerous flight connections. It is located approximately 250 kilometers (155 miles) south of Le Touquet and is accessible via various transportation options (see below).

While these airports are the nearest international options, it's worth noting that Le Touquet also has its own small airport, Le Touquet-Côte d'Opale Airport (Aéroport Le Touquet-Côte d'Opale). However, this airport primarily handles general aviation and private flights rather than commercial international flights.

By train

To reach Le Touquet-Paris-Plage from Paris by train, you can follow these steps:

Start by making your way to Gare du Nord station in Paris, which has regular train services to Le Touquet-Paris-Plage. Once you're at the train station, locate the ticket counters or self-service ticket machines. If you prefer, you can also book your tickets online in advance through the official website of the French national railway company, SNCF (www.sncf.com) or through other reliable ticketing platforms.

Purchase a ticket to Etaples-Le Touquet station, which is the closest train station to Le Touquet-Paris-Plage. Trains from Paris to Etaples-Le Touquet are usually direct, but it's always a good idea to check the train schedule for any connections or changes.

Board the train bound for Etaples-Le Touquet and enjoy the approximately 2.5-hour journey from Paris. The trains are comfortable and offer amenities like restrooms and sometimes food and beverage services.

Once you arrive at Etaples-Le Touquet station, you'll need to take a short onward journey to reach Le Touquet-Paris-Plage itself. You can either take a taxi or use public transportation options like buses or local shuttles to reach your final destination.

It's always advisable to check the train schedules and ticket availability in advance to ensure a smooth journey. The SNCF website or mobile app will provide up-to-date information regarding train times, ticket prices, and any possible changes.

Shuttle service

The workshop will run a shuttle service on Sunday and Thursday between Le Grand Hotel du Touquet and the Etaples train station. Departures of the bus from Etaples to the Grand Hotel will be synchronized with train schedule from Paris with estimated departure time at 16:00, 16:45, 17:50, and 20:15.

Please note that alternative transportation options, such as taxis, may be scarce. For those who prefer walking, it is approximately a 5 km journey. Additionally, participants can contact the Hotel or send an email to the organizers to arrange for pick-up from the train station.

Regular bus

There is bus service available to reach Le Grand Hotel du Touquet from Etaples train station. The bus network serving the Le Touquet-Paris-Plage area is operated by a company called "Les Mouettes" (Compagnie des Autobus des Mers).

From Etaples train station, you can take Bus Line 510 to reach Le Touquet-Paris-Plage. This bus line connects Etaples to Le Touquet and operates on a regular schedule. The bus stop closest to Le Grand Hotel du Touquet is usually "Le Touquet - Place de l'Hermitage" or "Le Touquet - Aéroport." You can check the exact bus stops and schedules on the Les Mouettes website or by contacting their customer service.

It's worth noting that bus schedules may vary depending on the day of the week and the time of year, so it's advisable to check the latest schedules to plan your journey accordingly.

Taxi

Enclosed is a list of Taxis that operate in Le Touquet

- CRETON : 06 09 38 45 75
- JONATHAN : 06 80 70 98 62
- BENJAMIN : 06 08 01 57 09
- DRIVE ME : 06 07 60 01 74
- SEB TAXI : 06 61 70 86 25
- ALEXIS : 06 80 06 10 32
- OPALE : 06 07 10 13 57

Useful information

Tourism Office

Office de tourisme du Touquet-Paris-Plage en Côte d'Opale
Jardin des Arts Avenue du Verger
62520 Le Touquet-Paris-Plage office-tourisme@letouquet.com
Tél: +33 3 21 06 72 00

Hotel Information

We have arranged it so that all of the scientific and social events will be in one place.

ADDRESS OF THE GRAND HOTEL:

4 Bd de la Canche,
62520 Le Touquet-Paris-Plage, France
Tél: ++33 (0)3 21 06 88 88
`https://legrandhotel-letouquet.com/`

- Breakfast: The breakfast service at the Grand Hotel will be available from 6:30 to 10:30.
- Lunch and Dinner: Details regarding lunch and dinner arrangements will be provided closer to the conference date.
- Cocktails: Information about the cocktails timing and location will be announced during the conference.
- Conference Room and Posters: The specific location of the conference room and poster presentations will be indicated at the venue.
- Swimming Pool and Spa: The Grand Hotel offers free access for participants to its swimming pool and spa facilities. Special treatments can be booked at your own costs.
- Other Attractions: Participants can also take advantage of other amenities such as mini-tennis and video games at the Grand Hotel.
- Bar: please note that the bar service at the Grand Hotel is not included in the conference package. Any drinks consumed at the bar will be at your own expense and will be paid for directly at the bar (no charging to the room is possible).

Social Events

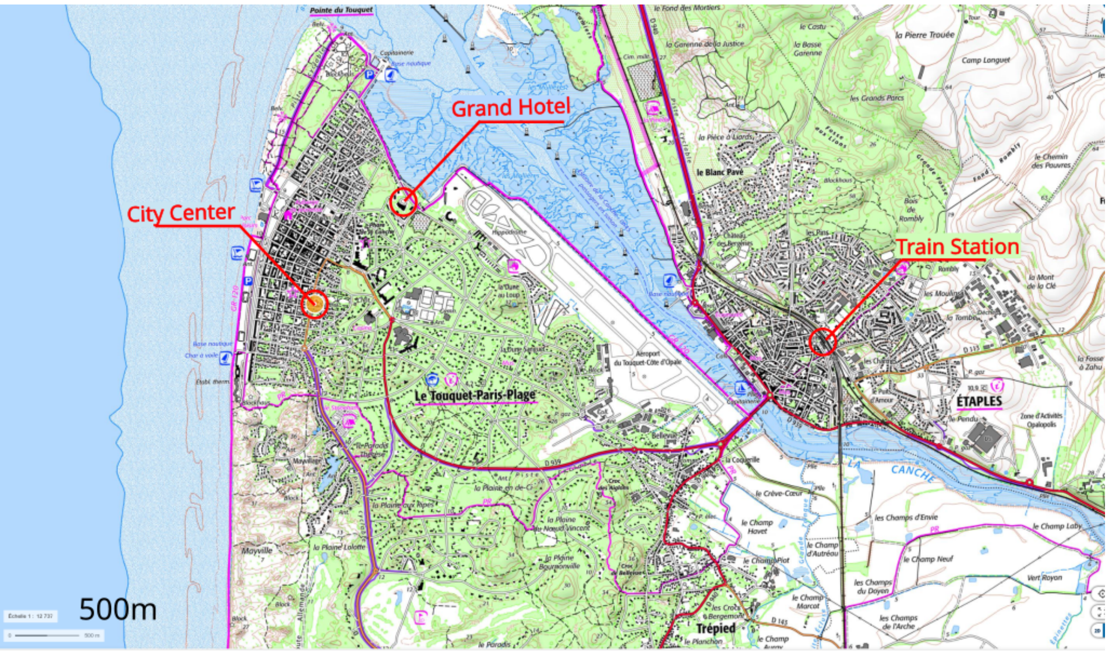
The social event will take place at Nausicaá, a renowned aquarium in Boulogne-sur-Mer. Further details, including the departure time of the shuttle bus and the approximate return time to the hotel, will be communicated closer to the event date.

- Tuesday Afternoon:
  Participants will have some free time on Tuesday afternoon before departing for Nausicaá. You can choose to explore Le Touquet downtown or relax at the beach during this time.
- Le Touquet Downtown:
  To explore Le Touquet downtown, you can visit the website of the Tourism Office [https://en.letouquet.com/]. There, you will find information about various attractions, restaurants, and activities available in the area.
- Getting to Le Touquet Downtown from Grand Hotel:
  Le Touquet downtown can be reached from the Grand Hotel with a pleasant 20-minute walk. You can also use Google Maps for directions.

Miscellaneous

- Swimming: While swimming near the estuary close to the hotel, please be cautious of dangerous currents and quicksands. Follow the signs for your safety. If you prefer to swim under supervision, the downtown Le Touquet beach is further away but offers a nice walk and supervised swimming.
- Walking: If you enjoy walking, we recommend exploring the Park of the Estuary of la Canche, which is located just 500 m away from the hotel. From there, you can follow the beach southwards to reach downtown Le Touquet, enjoying a beautiful walk.
- Sunset Viewing: For a stunning sunset experience, we recommend observing it from the estuary area.
- Drinks and Dining: In addition to the bar at the Grand Hotel, Le Touquet offers a variety of restaurants and bars to suit different tastes. Restaurant La Base Nord, situated on the estuary, offers a beautiful setting, while bar L'IMPASSE downtown is one of the many bars that are popular during the summer.
- Hippodrome: If you're interested in showjumping, the hippodrome is located very close to the hotel and might be worth to visit for.

Map of Le Touquet



Program

Timetable of Magnonics 2023

	Sunday, July 30th	Monday, July 31st	Tuesday, Aug. 1st	Wednesday, Aug. 2nd	Thursday, Aug. 3rd
08:00 - 09:00		08:00 Breakfast nan	08:00 Breakfast nan	08:00 Breakfast nan	08:00 Breakfast nan
09:00 - 10:00		09:00 Silvia Viola Kusminskiy I01 09:30 Moojune Song C01 09:45 Samer Kurdi C02	09:00 Xiaoqin Elaine Li I06 09:30 Ruben Leenders C09 09:45 Viktoriia Radovskaia 10	09:00 Isabella Boventer I10 09:30 Hiroki Matsumoto C12 09:45 Jilei Chen C13	09:00 Igor Barsukov I15 09:30 H. Kurebayashi C20 09:45 Dennis K. de Wal C21
10:00 - 11:00		10:00 Alexander A. Serga C03 10:15 Georg Schmidt I02 10:45 Coffee break nan	10:00 Igor Ngouagnia C11 10:15 Helmut Schultheiss I07 10:45 Coffee break nan	10:00 Yannik Kunz C14 10:15 Mehrdad Elyasi I11 10:45 Coffee break nan	10:00 Shreyas S. Joglekar C22 10:15 Hugo Merbouche I16 10:45 Coffee break nan
11:00 - 12:00		11:15 Christian Back I03 11:45 Aya El Kanj C04	11:15 Maciej Krawczyk I08 11:45 Gianluca Gubbiotti I09	11:15 Joo-Von Kim I12 11:45 Hannah Bradley C15	11:15 Oleksandr Dobrovolskiy I17 11:45 Sanchar Sharma C23
12:00 - 13:00		12:00 Chris Koerner C05 12:15 Caroline Ross C06 12:30 Lunch nan	12:15 NSF nan 12:30 Lunch nan	12:00 K.G.Fripp C16 12:15 Artem Litvinenko C17 12:30 Lunch nan	12:00 Richard Schlitz C24 12:15 Denis R. Candido C25 12:30 Lunch
13:00 - 14:00					
14:00 - 15:00		14:30 Toeno van der Sar I04	14:30 Social Event	14:30 Vincent Vlaminck I13	14:00 Departure nan
15:00 - 16:00		15:00 Nirel Bernstein C07 15:15 Ondřej Wojewoda C08 15:30 Daniela Petti I05		15:00 Qi Wang C18 15:15 Stephanie Lake C19 15:30 Tomosato Hioki I14	
16:00 - 17:00	16:45 Thibaut Devolder T01	16:00 Coffee break nan 16:30 Poster 1		16:00 Coffee break nan 16:30 Poster 2	
17:00 - 18:00	17:30 Kei Yamamoto T02				
18:00 - 19:00	18:15 Philipp Pirro T03	P1	nan	P2	
19:00 - 20:00	19:00 Dinner nan	19:00 Dinner nan	19:00 Social Dinner nan	19:00 Dinner nan	

SUNDAY, JULY 30TH

16:45 - 17:30 *T01 : Tutorial.*

Spin Waves: Electrical Methods for the Study of Their Dynamics.

Thibaut Devolder
Université Paris-Saclay, CNRS, Centre De Nanosciences Et De Nanotechnologies, 91120, Palaiseau, France

17:30 - 18:15 *T02 : Tutorial.*

Suhl Instability in Spintronics.

Kei Yamamoto
Advanced Science Research Center, Japan Atomic Energy Agency, Japan

18:15 - 19:00 *T03 : Tutorial.*

Computing with Coherent Magnons.

Philipp Pirro
RPTU Kaiserslautern-Landau, Kaiserslautern, Germany

19:00 - 20:00 *Dinner*

MONDAY, JULY 31ST

08:00 - 09:00 *Breakfast*

Session: Hybrid magnonics (photon, phonon, plasmon, quantum) (part 1)

09:00 - 09:30 *I01 : Invited Talk.*

Cavity Magnomechanics: Fundamentals and Applications.

Silvia Viola Kusminskiy
Institute for Theoretical Solid State Physics, RWTH Aachen University, Germany

09:30 - 09:45 *C01 : Contributed Talk.*

Time-Domain Coherent Manipulation of Remotely Coupled Magnonic Resonators.

Moojune Song
Materials Science Division, Argonne National Laboratory, USA

09:45 - 10:00 *C02 : Contributed Talk.*

Filtering and Imaging of Frequency-Degenerate Spin Waves Using Nanopositioning of a Single-Spin Sensor.

Samer Kurdi
Department of Quantum Nanoscience, Kavli Institute of Nanoscience, TU Delft, The Netherlands

10:00 - 10:15 *C03 : Contributed Talk.*

Bose-Einstein Condensation of Parametrically Pumped Magnon Gas to the Uniform Precession State.

Alexander A. Serga
Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Kaiserslautern, Germany

10:15 - 10:45 *I02 : Invited Talk.*

Strong Coupling of Microwaves and Magnons in YIG Microstructures.

Georg Schmidt
Institut Für Physik, Martin-Luther-Universität Halle-Wittenberg, 06099 Halle, Germany

10:45 - 11:15 *Coffee break*

Session: Magnetization dynamics and damping (part 1)

11:15 - 11:45 *I03 : Invited Talk.*

Dynamic Detection of Current-Induced Spin-Orbit Magnetic Fields.

Christian Back
School of Natural Sciences, Department of Physics, Technical University of Munich, Germany

11:45 - 12:00 *C04 : Contributed Talk.*

Antiferromagnetic Magnon Spintronic Based on Non-Reciprocal and Non-Degenerated Ultra-Fast Spin-Waves in the Canted Antiferromagnet α-Fe_2O_3 .

Aya El Kanj

Unité Mixte De Physique, CNRS, Thales, Université Paris-Saclay, 91767 Palaiseau, France

12:00 - 12:15 *C05 : Contributed Talk.*

Frequency Multiplication by Collective Nanoscale Spin-Wave Dynamics.

Chris Koerner

Physics Institute, Martin Luther University Halle-Wittenberg, Germany

12:15 - 12:30 *C06 : Contributed Talk.*

Interactions between Magnons and Domain Walls in Garnet Racetracks.

Caroline Ross

MIT, DMSE 6-113, 77 Massachusetts Ave. Cambridge, MA 02139, USA

12:30 - 14:30 *Lunch*

Session: Novel techniques of excitation and detection (part 1)

14:30 - 15:00 *I04 : Invited Talk.*

Coherent Manipulation of Spins in Diamond via Spin-Wave Mixing.

Toeno Van Der Sar

Department of Quantum Nanoscience, Kavli Institute of Nanoscience, Delft University of Technology, The Netherlands

15:00 - 15:15 *C07 : Contributed Talk.*

Spin Torque Driven Skyrmion Resonance Technique in Magnetic Bulk Crystals.

Nirel Bernstein

Department of Applied Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

15:15 - 15:30 *C08 : Contributed Talk.*

Phase-Resolved Optical Characterization of Nanoscale Spin Waves.

Ondřej Wojewoda

CEITEC BUT, Brno University of Technology, Purkyňova 123, Brno, 612 00, Czech Republic

15:30 - 16:00 *I05 : Invited Talk.*

Three-Dimensional Nanoscale Imaging of Propagating Spin Waves in a Synthetic Antiferromagnet.

Daniela Petti

Physics Department, Politecnico Di Milano, Italy

16:00 - 16:30 *Coffee break*

16:30 - 19:00 *Poster 1*

19:00 - 20:00 *Dinner*

TUESDAY, AUGUST 1ST

08:00 - 09:00 *Breakfast*

Session: Novel techniques of excitation and detection (part 2)

09:00 - 09:30 *I06 : Invited Talk.*

Long-Lived Zone-Boundary Magnons in an Antiferromagnetic Insulator.

Xiaoqin Elaine Li
Physics Department, University of Texas at Austin, U.S.A.

09:30 - 09:45 *C09 : Contributed Talk.*

Ultrafast Nonlinear Conversion of Magnons in an Antiferromagnet.

R. A. Leenders
Department of Physics, Lancaster University, Bailrigg, Lancaster, United Kingdom

09:45 - 10:00 *C10 : Contributed Talk.*

Light-Driven Control of Spin-Wave Damping in an Antiferromagnet.

Viktoriia Radovskaia
Radboud University, Nijmegen, The Netherlands

10:00 - 10:15 *C11 : Contributed Talk.*

Auto-Oscillation Instability and Pattern Generation in FMR-Driven BiYIG Nanodisks.

Igor Ngouagnia Yemeli
SPEC, CEA, CNRS, Université Paris-Saclay, France

10:15 - 10:45 *I07 : Invited Talk.*

Non-Linear Spin-Wave Excitation of Spin Defects in SiC.

H. Schultheiss
Helmholtz-Zentrum Dresden–Rossendorf, Institute of Ion Beam Physics and Materials Research, Germany

10:45 - 11:15 *Coffee break*

Session: Magnonics in 2D / texture / AFM (part 1)

11:15 - 11:45 *I08 : Invited Talk.*

Naturally Formed Magnonic Crystals: Ferromagnetic Film with Magnetization Stripe Domains.

Maciej Krawczyk

Institute of Spintronics and Quantum Information, Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

11:45 - 12:15 *I09 : Invited Talk.*

Spin-Wave Edge and Cavity Modes in a Moiré Magnonic Crystal.

Gianluca Gubbiotti

Istituto Officina Dei Materiali Del Consiglio Nazionale Delle Ricerche (IOM-CNR), Perugia, Italy.

12:15 - 12:30 *NSF*

12:30 - 14:30 *Lunch*

14:30 - 19:00 *Social Event*

16:00 - 16:30 *Coffee break*

19:00 - 20:00 *Social Dinner*

WEDNESDAY, AUGUST 2ND

08:00 - 09:00 *Breakfast*

Session: Hybrid magnonics (photon, phonon, plasmon, quantum) (part 2)

09:00 - 09:30 *I10 : Invited Talk.*

Towards Magnonic Logic with Oxide Heterostructures-Controlling Spin Wave Propagation in Magnonic Waveguides via Magnetoelectric Coupling.

Isabella Boventer

Unité Mixte De Physique, CNRS/Thales, Université Paris-Saclay, 91767 Palaiseau, France.

09:30 - 09:45 *C12 : Contributed Talk.*

Cavity Magnomechanics in a Synthetic Antiferromagnet with Surface Acoustic Waves.

Hiroki Matsumoto

Department of Physics, The University of Tokyo, Japan

09:45 - 10:00 *C13 : Contributed Talk.*

Hybridized Propagation of Spin Waves and Surface Acoustic Waves in a Multiferroic-Ferromagnetic Heterostructure.

Jilei Chen

Nan

10:00 - 10:15 *C14 : Contributed Talk.*

Magnetooptical Investigation of Nonreciprocal Phonon-Magnon Interaction.

Yannik Kunz

Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, 67663 Kaiserslautern, Germany

10:15 - 10:45 *I11 : Invited Talk.*

Many-Body Magnonic Open Quantum Systems.

Mehrdad Elyasi

Advanced Institute for Materials Research, Tohoku University, Sendai, Japan

10:45 - 11:15 *Coffee break*

Session: Magnonic logic and computing, other applications (part 1)

11:15 - 11:45 *I12 : Invited Talk.*

Aspects of Unconventional Computing with Nonlinear Magnonics.

Joo-Von Kim

Centre De Nanosciences Et De Nanotechnologies, CNRS, Université Paris-Saclay, 91120 Palaiseau, France

11:45 - 12:00 *C15 : Contributed Talk.*

Antiferromagnetic Artificial Neuron Modeling of Biological Neural Networks.

Hannah Bradley

Department of Physics, Oakland University, USA

12:00 - 12:15 *C16 : Contributed Talk.*

Nonlinear Chiral Magnonic Resonators: Towards Magnonic Neurons.

K.G.Fripp

Faculty of Environment, Science and Economy, University of Exeter, United Kingdom

12:15 - 12:30 *C17 : Contributed Talk.*

A Spinwave-Based Ising Machine.

Artem Litvinenko

Department of Physics, University of Gothenburg, Sweden

12:30 - 14:30 *Lunch*

Session: Magnonics devices (µwave and THz) (part 1)

14:30 - 15:00 *I13 : Invited Talk.*

Non-Reciprocal Spin Wave Beams in Out-Of-Plane Magnetized Films from Circular Antennas.

Vincent Vlaminck

IMT Atlantique, Microwave Dpt., CS 83818, 29238 Brest, France

15:00 - 15:15 *C18 : Contributed Talk.*

Inverse Design in Magnonics.

Qi Wang

School of Physics, Huazhong University of Science and Technology, Wuhan, China

15:15 - 15:30 *C19 : Contributed Talk.*

Exploring Nonlinear Magnon Dynamics via Amplification of Spin Waves Propagating through Mirrored Spin-Wave Concentrators.

Stephanie Lake

Institut Für Physik, Martin-Luther-Universität Halle-Wittenberg, Germany

15:30 - 16:00 *I14 : Invited Talk.*

Magnon State Tomography and Magnon Noise Control by Nonlinearity.

Tomosato Hioki

Advanced Institute for Materials Research, Tohoku University, Japan,

16:00 - 16:30 *Coffee break*

16:30 - 19:00 *Poster 2*

19:00 - 20:00 *Dinner*

THURSDAY, AUGUST 3RD

08:00 - 09:00 *Breakfast*

Session: Magnetization dynamics and damping (part 2)

09:00 - 09:30 *I15 : Invited Talk.*

Observation of Antiferromagnetic Magnons in a Nanodevice in ST-AFMR Experiments.

Igor Barsukov
Physics and Astronomy, University of California, Riverside, CA, USA

09:30 - 09:45 *C20 : Contributed Talk.*

Creation of Nonlinear Magnon Polaritons.

Hidekazu Kurebayashi
London Centre for Nanotechnology, University College London, London WC1H 0AH, UK

09:45 - 10:00 *C21 : Contributed Talk.*

All-Electrical and Spin Seebeck Effect Driven Magnon Transport in Quasi-Two-Dimensional Antiferromagnetic Materials $CrPS_4$ and $MnPS_3$..

Dennis K. De Wal
Zernike Institute for Advanced Materials, University of Groningen, the Netherlands

10:00 - 10:15 *C22 : Contributed Talk.*

Spin Wave Assisted Switching of Permalloy Nanomagnets on Yttrium Iron Garnet.

Shreyas S. Joglekar
Institute of Materials, École Polytechnique Fédérale De Lausanne (EPFL), Switzerland

10:15 - 10:45 *I16 : Invited Talk.*

True Amplification of Spin Waves in Magnonic Nano-Waveguides.

Hugo Merbouche
Institute for Applied Physics, University of Muenster, Germany

10:45 - 11:15 *Coffee break*

Session: Hybrid magnonics (photon, phonon, plasmon, quantum) (part 3)

11:15 - 11:45 *I17 : Invited Talk.*

Nonreciprocal Magnonics upon Ferromagnet/Superconductor Heterostructures.

Oleksandr Dobrovolskiy
University of Vienna, Faculty of Physics, Nanomagnetism and Magnonics, Austria

11:45 - 12:00 *C23 : Contributed Talk.*

Arbitrary Quantum State Generation of Magnons.

Sanchar Sharma
Theoretical Solid State Physics, RWTH Aachen, Germany

12:00 - 12:15 *C24 : Contributed Talk.*

Magnetization Dynamics Affected by Phonon Pumping.

Richard Schlitz
Department of Materials, ETH Zürich, 8093 Zürich, Switzerland

12:15 - 12:30 *C25 : Contributed Talk.*

Magnon-Mediated Entanglement of Solid-State Spin Qubits.

Denis R. Candido
Department of Physics and Astronomy, University of Iowa, USA

12:30 - 15:00 *Lunch / Departure*

Poster Session 1 (Monday 16:30 - 19:00)

Name	Code	Title
R.E. Arias	PA36	Scattering of Magnetostatic Surface Modes of Ferromagnetic Films by Geometric Defects
B. Assouline	PA05	Amplification of Electron-Mediated Spin Currents by Stimulated Spin Pumping
Z. Boyu	PA19	All-Optical Helicity-Independent Switching State Diagram in Gd-Fe-Co Alloys
R. Ciola	PA22	Spin Dynamics of Skyrmion Lattices in a Chiral Magnet Resolved by Micro-Focused ...
E. Clot	PA31	Development of a NV-Center Microscope for Spin-Wave Spectroscopy
P. Connick	PA46	PT Symmetry Breaking and Topological Features in Dissipatively Coupled Spin Dynamics
A. De	PA41	Spin Dynamics with Inertia in Ultrathin Permalloy Films
R. Dreyer	PA10	Imaging and Phase-Locking of Non-Linear Spin-Wave Phenomena
S. Eimer	PA06	Domain Wall Motion and DMI on Perpendicular Magnetic Anisotropy Based Spintronics ...
V. Errani	PA45	Negative Energy Modes in Antiferromagnets for Amplification and Analogue Gravity
A. Finco	PA18	Probing the Internal Texture of Skyrmions through Spin Waves with a Quantum Sensor
Z. Guo	PA14	Manipulating Exchange Bias with a Single Femtosecond Laser Pulse
P.M. Gunnink	PA16	Zero-Frequency Chiral Magnonic Edge States Protected by Non-Equilibrium Topology
Y. Henry	PA25	On the Nature of the Ferromagnetic Resonance Excitations in Cobalt Stripe Domain ...
T. Ito	PA11	Non-Local Spin Transport Measurement in Ferrimagnetic GdCo Thin Films
V. Iurchuk	PA08	Tailoring Crosstalk between Localized 1D Spin-Wave Nanochannels Using Focused Ion ...
V. Iurchuk	PA07	Strain-Tunable Gyrotropic Dynamics in Individual Magnetic Vortices
M. Jafari	PA35	Static and Dynamic Magnetic Properties of Two-Dimensional Van Der Waals Materials: ...
K. Kotus	PA20	Selective Resonant Triggering of the Skyrmion by Higher-Order Spin-Wave Modess
L. Körber	PA13	Spin Waves in Curved Magnetic Shells: Numerical Techniques and Recent Advances
A. Lentfert	PA21	Coherent Magnetization Dynamics in Strongly Quenched Systems
K.L. Lenz	PA32	Growth of Perpendicular Magnetic Anisotropy in Gallium-substituted Yttrium Iron ...
R. Lopes Seeger	PA38	Spin Wave Properties of CoFeB Grown on Piezoelectric Substrates
M. Massouras	PA27	Noncommutativity of Parametric Spin Wave Excitations in YIG Disks
A. Mucchietto	PA12	Magnonic Grating Coupler Effect, Magnon-Induced Nanostripe Reversal, Magnon ...
K. Nikolaev	PA09	Propagation of Spin Waves in Intersecting Yttrium Iron Garnet Nanowaveguides
B.K. Nikolic	PA04	Spin and Charge Pumping in the Presence of Spin-Orbit Coupling in THz Spintronics ...
G. Olivetti	PA33	Inversion of the Polarity of Angular Velocity inside a Precessing Magnet
S. Pile	PA23	The Asymmetry Quantification of Spin-Wave Dynamics in Single and Double Confined ...
G. Pradhan	PA34	Spin-Wave Dynamics in Curved Magnets
S. Salama	PA42	Micromagnetic Simulations of Magnon Nonlinear Interactions in a YIG Disk Magnetic Vortex
K. Schultheiss	PA24	Modification of Three-Magnon Splitting by In-Plane Magnetic Fields
M.R. Schweizer	PA44	Confinement of Bose–Einstein Magnon Condensates in Adjustable Complex ...
G. Soares	PA40	Damping in Garnet Microdisks Coupled to Microwave Antennas
K. Sobucki	PA17	Three Magnon Processes in Spin-Wave Scattering on Localised Modes for Controllable ...
T. Srivastava	PA39	Resonant Dynamics of Three-Dimensional Skyrmionic Textures in Thin Film Multilayers
D. Stoeffler	PA30	Micromagnetic Study of Parallel Pumping of Spinwaves into CoFeB/By Bilayer with ...
L. Sánchez-Tejerina	PA37	Spin Waves in Ferrimagnets at and around the Angular Magnetization Compensation ...
L. Temdie	PA02	Wave Vector Dependence of the Relaxation Time for Exchange Spin Waves
T. Valet	PA26	Modal Analysis of Axially Symmetric Magnetic Textures
V.I. Vasyuchka	PA43	Efficient Spin-Wave Transmission in YIG/Pt-Interfaced Structures
V. Vlaminck	PA01	Antenna Design for Spin Wave Caustic Beams
A. Voronov	PA28	Spin-Wave Transport in Two-Dimensional Partially-Compensated Ga:YIG Structures
D. Wagle	PA03	Caustic Spin Wave Beams in an Extended Thin Film Excited by a Nanoconstriction
H. Wang	PA29	Long-Distance Coherent Propagation of High-Velocity Antiferromagnetic Spin Waves
S. Yoshii	PA15	Significant Suppression of Magnon Damping in Ultrathin Co Films by Modulating ...

Poster Session 2 (Wednesday 16:30 - 19:00)

Name	Code	Title
Á. ádám Papp	PB31	Machine-Learned Gradient Patterns in YIG via Focused-Ion-Beam Irradiation
F.G. Aliev	PB11	Dynamics and Reversible Control of the Vortex Bloch Point Domain Wall in Short ...
M. Ardisson	PB35	Modelling a 3-Port Network in Cavity Magnonics for Nonreciprocal RF Devices
N. Beaulieu	PB51	Low Damping of Submicronic Thin Films of YIG Grown by RF Sputtering
M. Bechberger	PB10	Excitation of Propagating Spin Waves in Ga:YIG Thin Films
D. Breitbach	PB12	Bistability Based Magnon Computing
J. Carter-Gartside	PB01	Magnonic Spectral Symmetry-Breaking in a Trilayered Artificial Spin-Vortex Ice
P. Che	PB44	Brillouin Light Scattering Characterization of Voltage-Controlled Magnonic Crystals ...
L. Christienne	PB48	Acoustic Driven Ferromagnetic Resonance in Iron Thin Film: Impact of Spin Wave ...
A.V. Chumak	PB22	Influence of Paramagnetic GGG Substrates on YIG Films at Millikelvin Temperatures
G. Csaba	PB49	Coupled Parametric Excitations in Neighboring Nanomagnets
T. Devolder	PB04	Electrical Evidence and Modeling of the Unidirectionnality of the Energy Flow Carried ...
C. Dubs	PB02	Toward Larger-Area Magnonic Platform Materials: 3-Inch, Nanometer-Thin YIG Films
R. Erdélyi	PB07	Numerical Investigations of the Linearity of Magnonic Devices for RF Signal Processing
A.M. Friedel	PB34	Magnetisation Dynamics of Epitaxial $Co_2MnSi/X/Co_2MnAl$ Heusler Bilayers with ...
P. Graczyk	PB43	Optimizing Acoustic Wave - Spin Wave Resonant Coupling in the Magnetoelastic Systems
J. Greil	PB21	Nanoscale YIG Gratings for Interference-Based Spin-Wave Devices in Thin YIG Layers
J. Greil	PB13	YIG Gratings for Interference-Based Spin-Wave Devices
G. Gubbiotti	PB27	Magnonic Band Structures of CoFeB and CoFeB/Ta/NiFe Meander-Shaped Films
H. Guo	PB08	Control of Bulk and Surface Magnon Modes in 3D Ferromagnetic Nanonetworks by ...
T. Gustafson	PB47	Multi-Port Sample Carrier System for All-Electrical Characterisation of Thin-Film ...
A. Hakam	PB37	Leveraging Spin-Torque Oscillator's Phase Dynamics for Unconventional Computing
A. Hamadeh	PB30	Hybrid Magnonic-Oscillator System: towards the Development of Hybrid Artificial ...
X. Han	PB18	Magnon Junction Effect in $Y_3Fe_5O_12/CoO/Y_3Fe_5O_12$ Insulating Heterostructures
D. Hayashi	PB19	Observation of Dispersion Relation for Hybridized Magnons in Synthetic Antiferromagnets
C. Heins	PB39	Spin-Wave Quantization and Nonlinear Scattering in Non-Reciprocal Materials
M. Ibarra Gomez	PB41	A Numerical Study of Spin Torque Nano-Oscillators Based Ising Machines
B. Jungfleisch	PB03	Nonlinear Multi-Magnon Scattering in Ensembles of Nanomagnets
A. Khitun	PB05	Traveling Salesman Problem Solution Using Magnonic Combinatorial Device
A. Kolli	PB38	Nonlinear Interactions between Spin-Wave Modes in YIG Microdisks
A. Koujok	PB29	Dynamical Diversity of Magnetization Dynamics in Interacting Systems through Tunable ...
K. Kuenstle	PB36	Magneto-Optical Investigation of Magnetoacoustic Waves in Yttrium Iron Garnet / Zinc ...
W. Legrand	PB23	Understanding the Magnetic Properties of Ultrathin BiYIG Grown by Sputtering
J. Leiberton	PB26	Topological Magnons for Hybrid Magnonic Systems
V. Levati	PB45	Magnetic Nanopatterning of YIG Films via Direct Laser Writing for Magnonics
S. Lord	PB24	Characterising Noncollinear Exchange Coupled Trilayers of Epitaxial ...
S. Mae	PB06	Magnon Suppression Flowing $Y_3Fe_5O_12$ via Inductive Effect
L. Martins	PB40	A Non-Volatile Binary Synapse Based on a Vortex Nano-Oscillator
J. Maskill	PB15	Modulated Spin-Wave System for Neuromorphic Machine Learning
H. Merbouche	PB32	Degenerate and Non-Degenerate Parametric Excitation in YIG Nanostructures
A. Mukhopadhyay	PB20	Binary Encoding of Spin-Wave Active Ring Oscillator Modes
T.O. Puel	PB16	Enhancement of Microwave to Optical Spin-Based Quantum Transduction via a Magnon ...
E. Rongione	PB33	Emission of Coherent THz Magnons in an Antiferromagnetic Insulator Triggered by ...
F. Ryburn	PB25	Nonreciprocal Magnetoacoustic Excitation of Magnons in Yttrium Iron Garnet
S. Tacchi	PB09	Spin-Wave Dynamics in Co_2 MnSi Heusler Magnonic Crystals
C. Trevillian	PB50	Universal Set of Magnon-Mediated Quantum Gates
F. Vilsmeier	PB28	Spatial Control of Hybridization Induced Spin Wave Transmission Stop Band
T. Vogel	PB42	The Influence of the Field Direction on the Symmetries of Angle Dependent FMR Studies ...
Y. Wang	PB17	Electric Field Gated Magnon Transistor
S. Wintz	PB46	Direct Observation of Propagating Spin Waves with Large Non-Reciprocity
J. Zou	PB14	Domain Wall Qubits on Magnetic Racetracks

Orals

Tutorial. T01
Sunday
16:45

Spin Waves: Electrical Methods for the Study of Their Dynamics

Thibaut Devolder[1,*]

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Spin-waves (SW), or their quantized counterparts (magnons) are waves formed by the collective spin excitations in a magnetic body. In standard magnetic thin films and devices, the relevant spin-waves have typically frequencies in the 1-50 GHz range and usable wavelengths from 10 nm to 10 µm. As spin-waves determine to a large extent the rate at which one can manipulate the magnetization, they are of central importance in various applications of spin electronics, e.g. solid state magnetic memories, microwave magnetic oscillators and magnetization-based rf devices.

In this tutorial, I will start with a survey of electrical methods for the study of spin-wave dynamics from their thermal population level up to the onset of the non-linear regime. I will focus on the electrical generation, electrical detection, and propagation of spin-waves with three attentions: (i) the impact of the spin wave dispersion relation, (ii) the impact of the helicity mismatch between spin waves and electromagnetic radiation, and (iii) the importance of the multimode character of spin wave conduits.

Tutorial. T02
Sunday
17:30

Suhl Instability in Spintronics

Kei Yamamoto[1,*]

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Suhl instability refers to a class of parametric instabilities of ferromagnetic spin waves [1]. Among them, the parametric pumping, which arises from the direct non-linear coupling between a pair of magnons and a spatially uniform external microwave field, has been frequently used in spintronics to drive a large number of magnons out of equilibrium [2]. Another variant of the instability, the first-order Suhl instability originating from three-magnon splitting, requires an even smaller input power to trigger, but has not attracted as much attention yet. In this work, we demonstrate that the first-order Suhl instability can lead to some interesting behaviours beyond a mere increase of linewidth. After reviewing the established theoretical model for Suhl instability, we discuss two specific situations which have recently been realised in experiments [3]. Firstly, when the Kittel mode is strongly coupled to a microwave cavity, the instability is shown to close the anti-crossing gap in the spectrum (Figure 1) Secondly, a free decay from the instability-driven stationary state is shown to exhibit dynamics of a hybrid mode between the Kittel mode and the unstable magnon pair. We give simple analytical formulae that provide clear physical pictures for these uniquely non-linear phenomena.

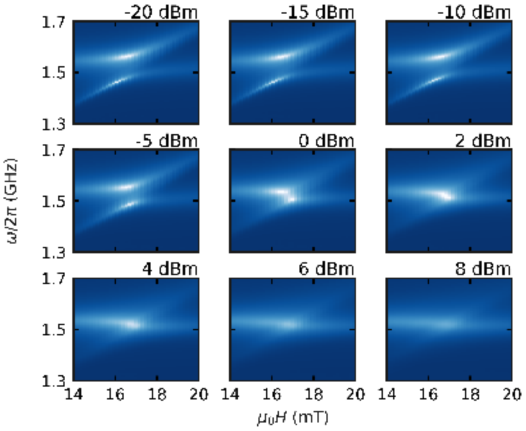

Figure 1: Closing of magnon-polariton anti-crossing gap by the onset of Suhl instability.

REFERENCES

[1]H. Suhl, “The theory of ferromagnetic resonance at high signal powers”, Journal of Physics and Chemistry of Solids **1**, 209–227 (1957).

[2]T. Brächer, P. Pirro, and B. Hillebrands, “Parallel pumping for magnon spintronics: amplification and manipulation of magnon spin currents on the micron-scale”, Physics Reports **699**, 1–34 (2017).

[3]O. Lee, K. Yamamoto, M. Umeda, et al., “Nonlinear magnon polaritons”, Physical Review Letters **130**, 046703 (2023).

Tutorial. T03
Sunday
18:15

Tutorial: Computing with Coherent Magnons

Philipp Pirro[1,*]

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In this tutorial presentation, I will introduce the basic concepts for logic devices [1, 2] based on coherent spin waves [3] and how information can be carried in the spin-wave amplitude or phase. Starting from linear wave superposition concepts like spin-wave majority gates, and XNOR gates inspired by Boolean logic, I will discuss the realization of nanoscaled magnonic circuits on chip including the challenge of energy efficient signal excitation, restoration, use of frequency multiplexing and device cascadability. I will show how nonlinear magnonic devices, which use the dependence of the magnonic properties on the magnon intensity, can be used to construct all-magnonic circuits which can significantly reduce the need for energy hungry conversion to the electronic domain. Based on this type of nonlinear circuits, I will discuss how magnonics could be used to realize unconventional logic concepts which are not based on Boolean logic gates, but on soft computing concepts like neuromorphic or stochastic computing.

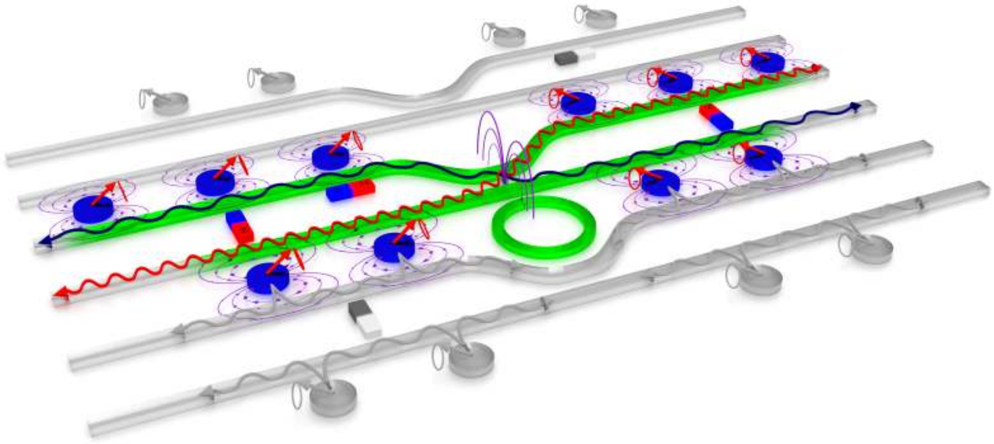

Figure 1: Schematic representation of a hybrid magnonic network for neuromorphic computing which connects different magnon sources (spintronic auto-oscillators, in blue) via nanoscopic magnonic waveguides (green). Elements like magnonic ring resonators allow to enhance nonlinearity and select frequencies tune while reconfiguration is achieved using permanent magnets .

REFERENCES

[1] A. Mahmoud, F. Ciubotaru, F. Vanderveken, et al., “Introduction to spin wave computing”, Journal of Applied Physics **128**, 161101 (2020).
[2] A. V. Chumak, P. Kabos, M. Wu, et al., “Advances in magnetics roadmap on spin-wave computing”, IEEE Trans. Magn. **58**, 1–72 (2022).
[3] P. Pirro, V. Vasyuchka, A. A. Serga, and B. Hillebrands, “Advances in coherent magnonics”, Nat. Rev. Mater. **6**, 1114–1135 (2021).

Invited. I01
Monday
09:00

Cavity Magnomechanics: Fundamentals and Applications

Silvia Viola Kusminskiy[1,2,*]

[1]Institute for Theoretical Solid State Physics, RWTH Aachen University, Germany
[2]Max Planck Institute for the Science of Light, Germany

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Cavity magnonic systems are ideally suited to explore the range of possibilities opened by tailoring the interactions between photons, phonons, and magnons. On the one hand, the radiation pressure-like coupling between magnons and phonons in magnets can modify the phonon frequency (magnomechanical spring effect) and decay rate (magnomechanical decay) via dynamical backaction. The full array of backaction effects have been recently demonstrated by coupling the uniform magnon mode of a magnetic sphere (the Kittel mode) to a microwave cavity [1]. Moreover, the ability to evade backaction effects has been recently demonstrated [2, 3], which is a requisite for applications such as magnomechanical based thermometry [4]. On the other hand, a magnomechanical system can be tailored to exploit a different regime, where a phonon and a magnon mode hybridize forming a magnon-phonon polariton. This regime can be useful e.g. for transduction of information [5], by harnessing the tunability of the system and the characteristics of both collective excitations of the magnetic material [6]. In this talk I will go over the underlying principles of cavity magnomechanics and discuss possible applications ranging from quantum thermometry to wavelength conversion.

REFERENCES

[1]C. A. Potts, E. Varga, V. A. S. V. Bittencourt, S. V. Kusminskiy, and J. P. Davis, “Dynamical Backaction Magnomechanics”, Phys. Rev. X **11**, 031053 (2021).

[2]C. A. Potts, Y. Huang, V. A. S. V. Bittencourt, S. V. Kusminskiy, and J. P. Davis, “Dynamical Backaction Evading Magnomechanics”, `10.48550/arXiv.2211.13766` (2023).

[3]V. A. S. V. Bittencourt, C. A. Potts, Y. Huang, J. P. Davis, and S. V. Kusminskiy, “Magnomechanical backaction corrections due to coupling to higher order Walker modes and Kerr nonlinearities”, `10.48550/arXiv.2301.11920` (2023).

[4]C. Potts, V. Bittencourt, S. V. Kusminskiy, and J. Davis, “Magnon-Phonon Quantum Correlation Thermometry”, Phys. Rev. Applied **13**, 064001 (2020).

[5]F. Engelhardt, V. Bittencourt, H. Huebl, O. Klein, and S. V. Kusminskiy, “Optimal Broadband Frequency Conversion via a Magnetomechanical Transducer”, Phys. Rev. Appl. **18**, 044059 (2022).

[6]M. Müller, J. Weber, F. Engelhardt, et al., “Chiral phonons and phononic birefringence in ferromagnetic metal - bulk acoustic resonator hybrids”, `10.48550/arXiv.2303.08429` (2023).

Magnonics 2023
July 30th - August 3rd
Le Touquet - Paris - Plage, France
Magnonics

Invited. I02
Monday
10:15

Strong Coupling of Microwaves and Magnons in YIG Microstructures

Georg Schmidt[1,2*], **Philip Geyer**[1], **Tharnier O. Puel**[3], **Michael E. Flatté**[3,4]

[1,2]Institut Für Physik, Martin-Luther-Universität Halle-Wittenberg, 06099 Halle, Germany
[2]Interdisziplinäres Zentrum Für Materialwissenschaften, Martin-Luther-Universität Halle-Wittenberg, 06099 Halle, Germany
[3]Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52245, USA
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Recently, strong coupling between magnon modes and other elementary excitations has attracted more and more interest. Magnon modes in an yttrium iron garnet (YIG) sphere of several hundred micrometer diameter were successfully coupled to the microwave modes of a large microwave cavity[1]. Also coupling of magnons in YIG to phonons[2] or to optical photons[3] has already been shown. All these experiments have in common that rather macroscopic pieces of YIG were used. This is unfavorable if the effect is to be integrated for device purposes, both in terms of size and technology. On the other hand coupling between magnetic microstructures and superconducting resonators has been reported making use of ferromagnetic metals that can easily be patterned[4, 5]. Nevertheless, the lifetime of spin waves in ferromagnetic metals is rather small and although strong coupling could be demonstrated, it would be desirable to use microscopic YIG resonators instead. We have realized coupling between microwave photons in superconducting lumped element resonators and magnons in Permalloy and YIG nanostructures, respectively. With the metallic ferromagnet, we realize an unusual coupling behavior because of the strong shape anisotropy in an elongated structure. With YIG, we are able to reach the strong coupling regime. This is possible because of an optimized lumped element resonator that concentrates the magnetic field in the magnetic microstructure.

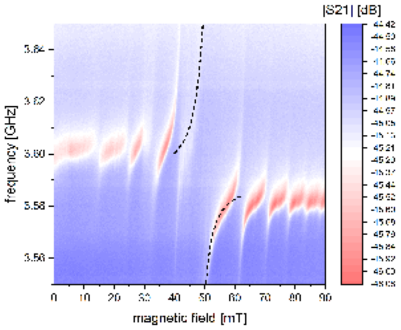

Figure 1: Anticrossings of several magnon modes in a YIG microstructure with the microwave mode in a superconducting microwave resonator.

REFERENCES

[1] Y. Tabuchi, S. Ishino, T. Ishikawa, et al., “Hybridizing ferromagnetic magnons and microwave photons in the quantum limit”, Phys. Rev. Lett. **113**, 083603 (2014).

[2] X. Zhang, C.-L. Zou, L. Jiang, and H. X. Tang, “Cavity magnomechanics”, Science Advances **2**, e1501286 (2016).

[3] A. Osada, R. Hisatomi, A. Noguchi, et al., “Cavity optomagnonics with spin-orbit coupled photons”, Phys. Rev. Lett. **116**, 223601 (2016).

[4] Y. Li, T. Polakovic, Y.-L. Wang, et al., “Strong coupling between magnons and microwave photons in on-chip ferromagnet-superconductor thin-film devices”, Phys. Rev. Lett. **123**, 107701 (2019).

[5] J. T. Hou and L. Liu, “Strong coupling between microwave photons and nanomagnet magnons”, Phys. Rev. Lett. **123**, 107702 (2019).

Dynamic Detection of Current-Induced Spin-Orbit Magnetic Fields

Christian Back[1,2,*], **L. Chen**[1], **Robert Islinger**[2], **J. Stigloher**[2], **M.M. Decker**[1], **M. Kronseder**[2], **D. Schuh**[2], **D. Bougeard**[2], **D. Weiss**[2]
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[2]Physics Department, University of Regensburg, Germany

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Current-induced spin-orbit torques (SOTs) in hybrid magnetic structures such as ferromagnetic/non-magnetic metal heterostructures open up far-reaching possibilities for the development of spintronic devices to store, process and transmit information in a simple architecture. It has been shown that by the use of SOTs the magnetization of the FM layer in such structures can efficiently be switched and the switching dynamics can be followed using sophisticated time resolved experiments. It is a key task to i) search for efficient SOT devices and to ii) quantify both the magnitude and symmetry of the current-induced spin-orbit magnetic fields (SOFs). We have used a non-invasive method based on time-resolved magneto-optical Kerr microscopy to determine the SOFs based on magnetization dynamics [1]. As a prototypical sample structure we use the well-understood Fe/GaAs(001) hybrid. Sending a microwave current into a narrow Fe/GaAs (001) strip generates both an Oersted field and SOFs due to the reduced symmetry at the Fe/GaAs interface The combination of these fields excites spin standing waves (SSWs) due to lateral confinement in the narrow FM strip. Due to their different symmetries, the SOFs and the Oersted field predominantly excite distinctly different mode patterns. Therefore, it is possible to determine the size of the SOFs by analyzing the shape of the SSW patterns. This method, which is conceptually different from previous approaches based on line shape analysis, is phase independent and self-calibrating. It can be used to measure current-induced SOFs in other material systems, in particular also in highly resistive hybrid structures.

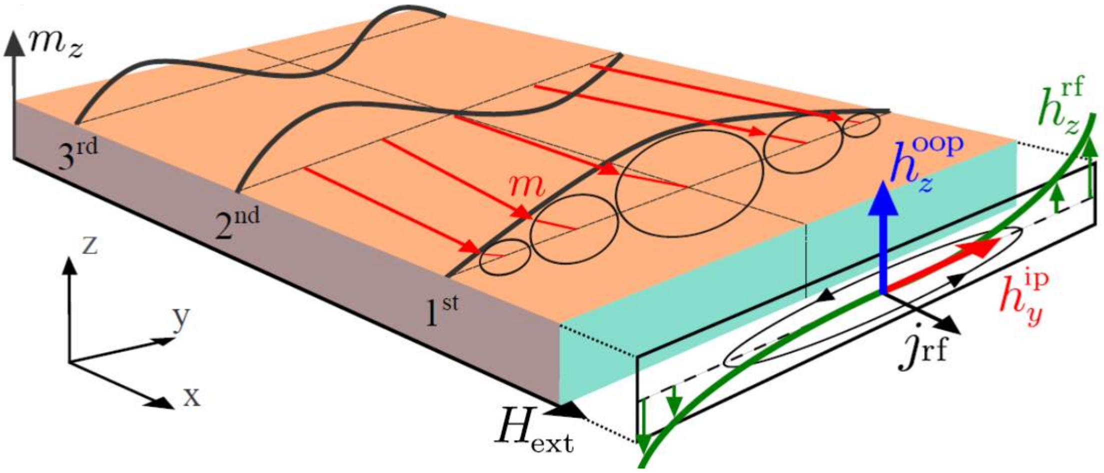

Figure 1: Sketch of the experiment. Standing spin wave patterns (first, second and third modes) are excited by the combined action of Oersted (indicated in green) and spin orbit fields (indicated in blue and red).

REFERENCES

[1] L. C. et al., “Dynamic detection of current-induced spin-orbit magnetic fields”, Phys. Rev. B **104**, 014425 (2021).

Invited. I04
Monday
14:30

Coherent Manipulation of Spins in Diamond via Spin-Wave Mixing

Toeno Van Der Sar[1,*]

[1]Department of Quantum Nanoscience, Kavli Institute of Nanoscience, Delft University of
Technology, The Netherlands
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Magnetic imaging based on nitrogen-vacancy (NV) spins in diamond enables probing condensed matter systems with nanoscale resolution [1]. In this talk I will introduce NV magnetometry as a tool for imaging spin waves – the wave-like spin excitations of magnetic materials. Using the NV sensitivity to microwave magnetic fields, we can map coherent spin waves [2] and incoherent magnon gases [3] and provide insight into their interaction and damping [4]. By using a single NV in a scanning diamond tip we gain access to spin-wave scattering at the nanoscale [5]. I will highlight how we can use spin-wave mixing to generate frequency combs that enable high-fidelity, coherent control of the NV spins even when the applied microwave drive fields are far detuned from the NV spin resonance frequency [6] (Figure. 1). These results form a basis for developing NV magnetometry into a tool for characterizing spin-wave devices and expand the control and sensing capabilities of NV spins.

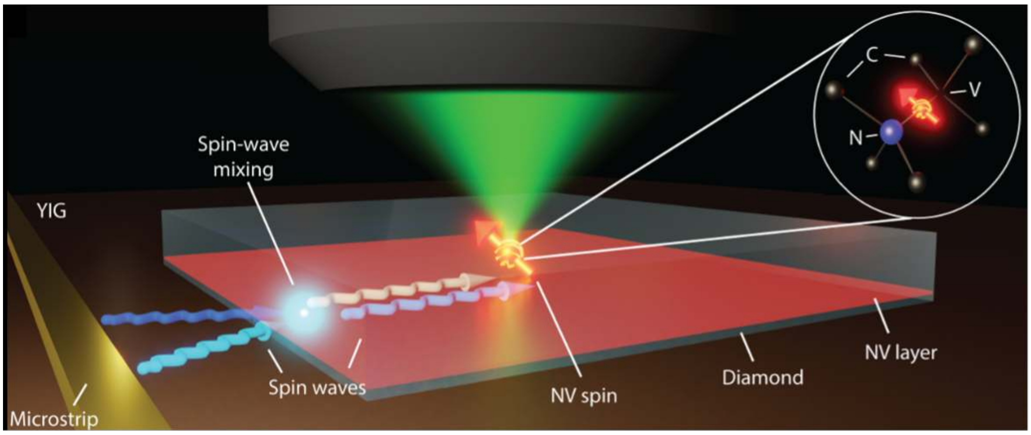

Figure 1: Using spin-wave mixing and frequency combs for coherent control of spins in diamond.

REFERENCES

[1] F. Casola, T. V. D. Sar, and A. Yacoby, "Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond", Nature Reviews Materials **3**, `10.1038/natrevmats.2017.88` (2018).

[2] I. Bertelli, J. Carmiggelt, T. Yu, et al., "Magnetic resonance imaging of spin-wave transport and interference in a magnetic insulator", Science Advances **6**, `10.1126/sciadv.abd3556` (2020).

[3] B. G. Simon, S. Kurdi, H. La, et al., "Directional excitation of a high-density magnon gas using coherently driven spin waves", Nano Letters **21**, 8213–8219 (2021).

[4] I. Bertelli, B. G. Simon, T. Yu, et al., "Imaging spin-wave damping underneath metals using electron spins in diamond", Advanced Quantum Technologies **4**, 2100094 (2021).

[5] B. G. Simon, S. Kurdi, J. J. Carmiggelt, et al., "Filtering and imaging of frequency-degenerate spin waves using nanopositioning of a single-spin sensor", Nano Letters **22**, 9198–9204 (2022).

[6] J. J. Carmiggelt, I. Bertelli, R. W. Mulder, et al., "Broadband microwave detection using electron spins in a hybrid diamond-magnet sensor chip", Nature Communications **14**, 490 (2023).

Invited. I05
Monday
15:30

Three-Dimensional Nanoscale Imaging of Propagating Spin Waves in a Synthetic Antiferromagnet

Daniela Petti[1,*], Davide Girardi[1], Simone Finizio[2], Guglielmo Rubini[1], Sina Mayr[2], Claire Donnelly[3], Federico Maspero[1], Simone Cuccurullo[1], Valerio Levati[1], Jörg Raabe[2], Edoardo Albisetti[1]
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Spin waves are considered promising candidates for the next generation energy efficient devices for both analog and digital computing and signal processing. Despite the growing interest in harnessing the third dimension also in magnonics [1], the experimental visualization of propagating spin waves in three dimensions has been elusive, due to the harsh requirement of combining nanoscale spatial resolution in 3D, and time resolution across the GHz frequency range. In this framework, recently, the Time-Resolved Soft X-Ray Laminography (TR-SoXL) technique has been developed at the PolLux beamline of the Swiss Light Source. The TR-SoXL is a synchrotron-based technique that allows to obtain the three-dimensional time-resolved reconstructions of the magnetization dynamics [2] of thin samples, with nanoscale resolution. To obtain the 3D resolution, the sample stage presents an additional rotation state, whose axis is tilted respect to the incoming x-rays. The different projections obtained at the different Laminography rotation angles are analyzed with an iterative reconstruction algorithm, which allows to recover the components of the magnetization. Here, first we reconstructed the three-dimensional static magnetization configuration of a NiFe 40/Ru 0.9/CoFeB 50 (nm) synthetic antiferromagnet (SAF) microstructure. Then, we demonstrate the time-resolved three-dimensional imaging of spin waves emitted by nanoscale spin textures (see Figure. 1), i.e. vortices and domain walls [3] stabilized at 0 field within the microstructure. We map the trajectory of the dynamic magnetization in the three-dimensional space, and the properties of the spin-wave modes throughout the film volume. We experimentally demonstrate the existence of complex three-dimensional interference patterns, generated by non-uniform spin-wave amplitude profiles, and analyze them via micromagnetic simulations. This work opens the way to the direct visualization, study and control of nanoscale propagating spin waves in three-dimensions, and of their interactions in thin films and nanostructures. This in turn allows the design of novel functionalities in next generation magnonic devices.

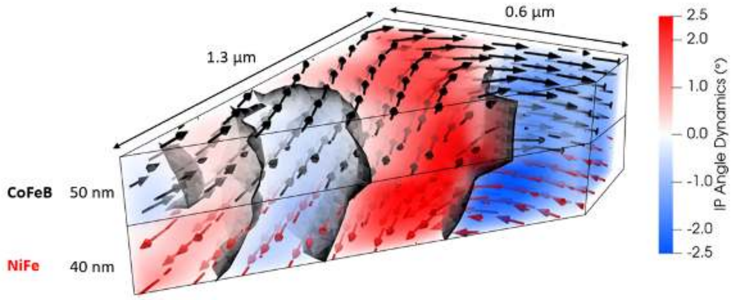

Figure 1: 3D reconstruction of propagating spin waves emitted by a domain wall. The blue/red color-code refers to the in-plane projection of the angle of precession of the spins. The black contours highlight the spin-wave wavefronts.

REFERENCES

[1] G. Gubbiotti, ed., *Three-dimensional magnonics* (Jenny Stanford Publishing, July 2019).

[2] C. Donnelly, A. Hierro-Rodríguez, C. Abert, K. Witte, L. Skoric, D. Sanz-Hernández, S. Finizio, F. Meng, S. McVitie, J. Raabe, D. Suess, R. Cowburn, and A. Fernández-Pacheco, “Complex free-space magnetic field textures induced by three-dimensional magnetic nanostructures”, Nature Nanotechnology **17**, 136–142 (2021).

[3] E. Albisetti, S. Tacchi, R. Silvani, G. Scaramuzzi, S. Finizio, S. Wintz, C. Rinaldi, M. Cantoni, J. Raabe, G. Carlotti, R. Bertacco, E. Riedo, and D. Petti, “Optically inspired nanomagnonics with nonreciprocal spin waves in synthetic antiferromagnets”, Advanced Materials **32**, 1906439 (2020).

Invited. I06
Tuesday
09:00

Long-Lived Zone-Boundary Magnons in an Antiferromagnetic Insulator

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Magnons in antiferromagnetic (AFM) insulators, exhibit desirable features such as fast dynamics in the THz range and minimal frequency shifts in the presence of fluctuating external fields. However, large damping associated with THz magnons in AFMs, especially for exchange magnons with short wavelengths, presents a serious challenge for magnonic applications. Topological magnons may offer a novel approach to overcome outstanding challenges associated with THz magnonics.

We investigate magnons in CoTiO$_3$ (CTO), a material with confirmed topological magnon bands [1, 2]. Multiple magnon peaks are identified using temperature- and magnetic-field dependent Raman scattering experiments. While light scattering experiments typically probe Brillouin-zone center magnons, two-magnon scattering resonances are commonly observed in AFMs. In the case of CTO, the saddle points at the high symmetry M points (Fig. 1) on the Brillouin zone boundary lead to an exceptionally large density of states, thus, dominating two-magnon scattering processes. Most intriguingly, these exchange magnons with nanometer wavelengths exhibit a significantly sharper linewidth (limited by instrument resolution) than the Γ point magnon at the zone center. We discuss the reasons why CTO hosts long-lived zone-boundary magnons.

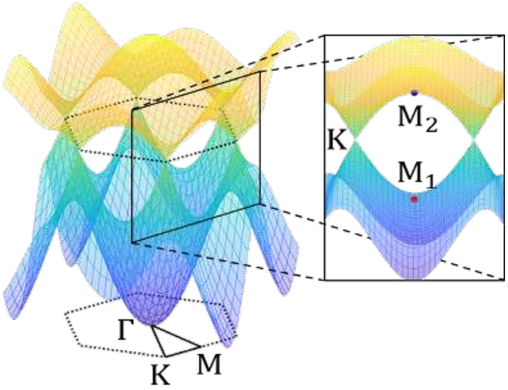

Figure 1: Illustration of magnon dispersion in CTO

REFERENCES

[1] B. Yuan, I. Khait, G.-J. Shu, F. Chou, M. Stone, J. Clancy, A. Paramekanti, and Y.-J. Kim, “Dirac magnons in a honeycomb lattice quantum xy magnet cotio 3”, Physical Review X **10**, 011062 (2020).

[2] M. Elliot, P. A. McClarty, D. Prabhakaran, R. Johnson, H. Walker, P. Manuel, and R. Coldea, “Order-by-disorder from bond-dependent exchange and intensity signature of nodal quasiparticles in a honeycomb cobaltate”, Nature Communications **12**, 3936 (2021).

Invited. I07
Tuesday
10:15

Non-Linear Spin-Wave Excitation of Spin Defects in SiC

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Hybrid magnon-quantum spin systems have been gathering scientific interest in the last years due to their increased coupling strength [1, 2], scalability down to the nanoscale regime [3–5], and their potential as energy efficient quantum buses [4, 6]. While magnon-mediated control of quantum spins has been demonstrated with NV-centers in diamond [2, 3, 6], it has remained elusive on the silicon carbide (SiC) platform mainly due to the absence of a resonance overlap between the magnetic system and the spin-defect center.

Here, we circumvent this challenge by harnessing nonlinear magnon scattering processes taking place in a magnetic vortex to access spin-wave eigenmodes that overlap with the intrinsic resonance of silicon-vacancy (VSi) defect centers in 4H-SiC [7]. The eigenmodes created by the scattering process generate dynamic dipolar fields that in turn drive dipolar transitions in the VSi spin-defect in SiC. This interaction scheme also allows us to decouple the antenna excitation from the spin-wave excitation of the spin defect, enabling pure spin-wave driven excitation of the VSi defect centers in SiC. The resonant interaction between the spin-wave eigenmodes and the VSi spins can be tuned by changing the external field as well as the microwave power being delivered by the lithographically patterned coplanar waveguide which drives the nonlinear dynamics in the magnetic vortex. Our results offer a route to develop hybrid magnon-quantum spin systems that benefit from the electrical and optical properties of SiC for future quantum computing applications.

This work was supported in part by the German Research Foundation under Grants SCHU 2922/4-1 and AS 310/9-1.

REFERENCES

[1] C. Mühlherr, V. O. Shkolnikov, and G. Burkard, “Magnetic resonance in defect spins mediated by spin waves”, Phys. Rev. B **99**, 195413 (2019).

[2] P. Andrich, C. F. de las Casas, X. Liu, H. L. Bretscher, J. R. Berman, F. J. Heremans, P. F. Nealey, and D. D. Awschalom, “Long-range spin wave mediated control of defect qubits in nanodiamonds”, en, npj Quantum Information **3**, 28 (2017).

[3] X. Wang, Y. Xiao, C. Liu, E. Lee-Wong, N. J. McLaughlin, H. Wang, M. Wu, H. Wang, E. E. Fullerton, and C. R. Du, “Electrical control of coherent spin rotation of a single-spin qubit”, en, npj Quantum Information **6**, 78 (2020).

[4] L. Trifunovic, F. L. Pedrocchi, and D. Loss, “Long-Distance Entanglement of Spin Qubits via Ferromagnet”, en, Physical Review X **3**, 041023 (2013).

[5] M. Bejarano, F. J. T. Goncalves, M. Hollenbach, T. Hache, T. Hula, Y. Berencén, J. Fassbender, M. Helm, G. V. Astakhov, and H. Schultheiss, “Mapping the Stray Fields of a Micromagnet Using Spin Centers in SiC”, IEEE Magnetics Letters **12**, Conference Name: IEEE Magnetics Letters, 1–5 (2021).

[6] D. Kikuchi, D. Prananto, K. Hayashi, A. Laraoui, N. Mizuochi, M. Hatano, E. Saitoh, Y. Kim, C. A. Meriles, and T. An, “Long-distance excitation of nitrogen-vacancy centers in diamond via surface spin waves”, Applied Physics Express **10**, 103004 (2017).

[7] K. Schultheiss, R. Verba, F. Wehrmann, K. Wagner, L. Körber, T. Hula, T. Hache, A. Kákay, A. A. Awad, V. Tiberkevich, A. N. Slavin, J. Fassbender, and H. Schultheiss, “Excitation of Whispering Gallery Magnons in a Magnetic Vortex”, Physical Review Letters **122**, 097202 (2019).

Invited. I08
Tuesday
11:15

Naturally Formed Magnonic Crystals: Ferromagnetic Film with Magnetization Stripe Domains

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The formation of regular patterns is an intriguing process that can be realized by spontaneous translational symmetry breaking initiated by linear eigen-wave dynamics in homogeneous systems with a change of control parameter. Such a process has been observed in hydrodynamic systems, such as thermal convection, diffusion in two-component systems, non-linear optics, chemical reactions, as well as in biological systems [1]. Similarly, in a uniformly magnetized thin ferromagnetic layer, as a result of reducing the magnetic field magnitude, regular magnetization stripe domains may appear [2]. From the opposite side, the regular magnetization pattern may create a periodic potential for the formation of the spin-wave band structure. Moreover, the properties become even more intriguing when non-reciprocal interactions are taken into account.

We show that spin waves trigger the formation of the stripe domain structure with decreasing magnetic field in thin films with perpendicular magnetic anisotropy with or without Dzialoshynskii-Moryia interactions [3]. Interestingly, the pattern can flow in one direction in the nonreciprocal case. It is shown that periodic stripe domains in a thin ferromagnetic film allow forming of spin-wave spectra with magnonic bands and bandgaps [4, 5]. We also realized spontaneous translational symmetry breaking by strong homogeneous microwave pumping of a micron-sized permalloy stripe with the resulting transition directly imaged by scanning transmission x-ray microscopy [6]. We found that beyond the formation of discrete translational symmetry in space, the pattern oscillates in time, indicating the generation of the magnonic crystals with modulation in space and time. The periodicity of the magnetization enables the formation of a magnonic band structure, resulting in the generation of ultra-short spin waves with a wavelength of up to 100 nm from the second Brillouin zone. Thanks to the conducted studies, we show that a ferromagnetic thin film with periodic stripe domains can be considered a naturally formed magnonic crystal in a homogeneous ferromagnetic thin film, useful for the control and propagation of spin waves.

The research leading to these results has received funding from the Polish National Science Centre projects UMO-2018/30/Q/ST3/00416 and UMO-2020/37/B/ST3/03936.

REFERENCES

[1] M. C. Cross and P. C. Hohenberg, “Pattern formation outside of equilibrium”, Rev. Mod. Phys. **65**, 851–1112 (1993).

[2] M. Grassi, M. Geilen, K. A. Oukaci, et al., “Higgs and Goldstone spin-wave modes in striped magnetic texture”, Phys. Rev. B **105**, 094444 (2022).

[3] J. Kisielewski, P. Gruszecki, M. Krawczyk, V. Zablotskii, and A. Maziewski, “Between waves and patterns: spin wave freezing in films with dzyaloshinskii-moriya interaction”, Phys. Rev. B (2023).

[4] C. Banerjee, P. Gruszecki, J. W. Klos, et al., “Magnonic band structure in a Co/Pd stripe domain system investigated by Brillouin light scattering and micromagnetic simulations”, Phys. Rev. B **96**, 024421 (2017).

[5] K. Szulc, S. Tacchi, A. Hierro-Rodriguez, et al., “Reconfigurable magnonic crystals based on imprinted magnetization textures in hard and soft dipolar-coupled bilayers”, ACS Nano **16**, 14168–14177 (2022).

[6] N. Träger, P. Gruszecki, F. Lisiecki, et al., “Real-space observation of magnon interaction with driven space-time crystals”, Phys. Rev. Lett. **126**, 057201 (2021).

Spin-Wave Edge and Cavity Modes in a Moiré Magnonic Crystal

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Moiré superlattices consisting of twisted layers of van der Waals materials [1] exhibit extraordinary electronic behaviours such as superconductivity and correlated topological states. The concept of moiré physics was recently applied in photonics to reconstruct photonic band structures providing novel functionalities such as magic-angle lasers. To date, moiré physics in magnonic systems has only been studied from a theoretical point of view [2]. In this work, we fabricated nanostructured moiré magnonic crystals based on low-damping yttrium iron garnet thin films. We report the experimental observation of the spin-wave moiré edge and cavity modes using Brillouin light scattering spectro-microscopy in a nanostructured magnetic moiré lattice consisting of two twisted triangle antidot lattices based on an yttrium iron garnet thin film. Spin-wave moiré edge modes are detected at an optimal twist angle and with a selective excitation frequency. At a given twist angle, the magnetic field acts as an additional degree of freedom for tuning the chiral behavior of the magnon edge modes. Micromagnetic simulations indicate that the edge modes emerge within the original magnonic band gap and at the intersection between a mini- flatband and a propagation magnon branch. [3]

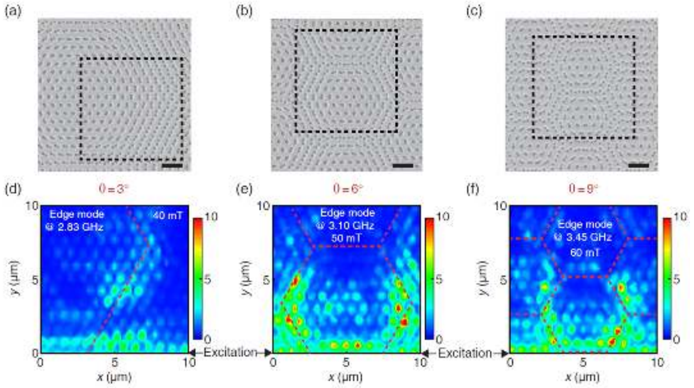

Figure 1: Spin-wave edge mode profiles at different twist angles. a-c, SEM images of moiré magnonic crystals with twist angles of 3°, 6°, and 9°, respectively. d-f, Spatial-resolved BLS measurement at a twist angle of 3°, 6°, and 9°, respectively.

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REFERENCES

[1] Y. Cao and et al, “Unconventional superconductivity in magic-angle graphene superlattices”, Nature **556**, 43–50 (2018).
[2] Y.-H. Li and et al, “Moiré magnons in twisted bilayer magnets with collinear order”, Phys. Rev. B **102**, 094404 (2020).
[3] H. Wang and et al, “Observation of spin-wave moiré edge and cavity modes in twisted magnetic lattices”, submitted.

Invited. I10
Wednesday
09:00

Towards Magnonic Logic with Oxide Heterostructures-Controlling Spin Wave Propagation in Magnonic Waveguides via Magnetoelectric Coupling

Isabella Boventer[1,*], **Ping Che**[1], **Sali Salama**[2], **Jean-Paul Adam**[2], **Amr Abdelsamie**[1], **Aymeric Vecchiola**[1], **Vincent Garcia**[1], **Stéphane Fusil**[1], **Karim Bouzehouane**[1], **Romain Lebrun**[1], **Agnès Barthélémy**[1], **Manuel Bibes**[1], **Paolo Bortolotti**[1], **Abdelmadjid Anane**[1]
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Magnonics uses magnons, the quanta of spin waves as the central information carriers. Lately, it is receiving considerable attention as it promises miniaturized low-power-consuming information technologies thanks to the absence of moving charges and the nanoscale wavelength of spin waves at giga-hertz frequencies. However, voltage controlled magnonic devices are required for eased operation and integration with existing technologies. Additionally, to realize fully spin-wave based computing, the further development of low-power, compact, integrated and reconfigurable magnonic devices are necessary, such as magnonic crystals [1–3] and logics [4] beyond current state of the art such as magnonic half-adders [5] or transistors [6]. Magnetoelectric coupling offers the possibility to control the spin degree of freedom via charge degree freedom in oxide interfaces. By using thin-film multiferroic bismuth ferrite BiFeO3 (BFO)- lanthanum strontium manganite La2/3Sr1/3MnO3 (LSMO) heterostructures, we first employ the presence of the magnetoelectric coupling in this structure to realize voltage-controlled, reconfigurable magnonic crystals [2]. The opening of a magnonic bandgap shows the impact of periodically imprinted ferroelectric domains in the BFO layer on the spin wave propagation in the LSMO layer. However, towards spin wave computing using multiferroics, a magnonic crystal represents only one important building block towards full magnon-based computing. Thus, we continue to explore this material platform by realizing reprogrammable magnonic waveguides which we define by imprinting ferroelectric domains in the multiferroic BFO layer. Further, we study the origin of the observed control of ferroelectric domain states on the spin wave's properties such as local exchange bias [2, 7]. We observe the emergence of a frequency difference between the LSMO layers modulated by the differently written ferroelectric domains considering both the possible in-plane and the out-of-plane-polarization directions in BFO. This frequency difference allows us to directly select the specific waveguide channel depending on the choice of frequency. In turn, this can serve for generating basic logic operations in the LSMO layer using well-defined ferroelectric polarization patterns in the BFO layer . The imprinted ferroelectric domains can be reconfigured repeatedly without losing their quality and are long-lived. Our results open a new path for the function of magnonics-based logic devices by CMOS compatible voltage control. In general, by bridging between the scientific fields of functional oxides and magnonics, we propose new perspectives for the development of beyond CMOS based technologies [8].

REFERENCES

[1] A. V. Chumak, A. A. Serga, and B. Hillebrands, "Magnonic crystals for data processing", Journal of Physics D: Applied Physics **50**, 244001 (2017).
[2] H. Merbouche, I. Boventer, V. Haspot, et al., "Voltage-Controlled Reconfigurable Magnonic Crystal at the Submicrometer Scale", en, ACS Nano **15**, 9775–9781 (2021).
[3] H. Merbouche, M. Collet, M. Evelt, et al., "Frequency Filtering with a Magnonic Crystal Based on Nanometer-Thick Yttrium Iron Garnet Films", en, ACS Applied Nano Materials **4**, 121–128 (2021).
[4] A. V. Chumak, P. Kabos, M. Wu, et al., "Advances in Magnetics Roadmap on Spin-Wave Computing", IEEE Transactions on Magnetics **58**, 1–72 (2022).
[5] Q. Wang, M. Kewenig, M. Schneider, et al., "A magnonic directional coupler for integrated magnonic half-adders", en, Nature Electronics **3**, 765–774 (2020).
[6] A. V. Chumak, A. A. Serga, and B. Hillebrands, "Magnon transistor for all-magnon data processing", en, Nature Communications **5**, 4700 (2014).
[7] Q. Xu, Y. Sheng, X. Xue, et al., "Exchange bias in BiFeO$_3$/La$_{0.67}$Sr$_{0.33}$MnO$_3$ bilayers", Japanese Journal of Applied Physics **53**, 08NM01 (2014).
[8] P. Che, S. Salama, J. P. Adam, et al., "In preparation", (2023).

Invited. I11
Wednesday
10:15

Many-Body Magnonic Open Quantum Systems

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Magnons have recently emerged as strong candidates for quantum information. The crystalline anisotropy, as well as the dipolar and exchange interactions lead to nonlinear magnon-magnon interactions of third order and higher in a magnetic material. Decades ago, such interactions were shown to be responsible for several types of (Suhl) instabilities, as well as for channels of dissipation. More recently, experiments demonstrated a magnon condensation at the bottom of a dipolar-exchange dispersion as a result of four magnon interactions. As the research focus on spin waves has shifted towards the coherence and the possibilities in quantum information and computation, the context of nonlinearity has gained even more attention. We explain some recent theoretical and experimental demonstrations that have opened new avenues in implementing magnon nonlinearities for quantum information or stochastic computing paradigms.

Nonlinearities are necessary for generation of quantum states. Magnonic many-body open quantum systems have been predicted to be resource for quantum information by providing steady state quantum entanglement [1]. Magnon nonlinearities have been shown to be responsible for probabilistic bit operation useful for emulating quantum computation [2]. The many-body magnon interactions can also be used to design quantum memories. In addition, magnon nonlinearities have opened new avenues in other well-established quantum information platforms for e.g. coherent control of NV spins in hybrid magnet-diamond systems [3]. Jointly with the recently demonstrated non-local three-magnon coupling [4] and nonlinear control of magnon polaritons [5], these pave the way for quantum applications of nonequilibrium open many-body magnonic systems.

REFERENCES

[1]M. Elyasi, Y. M. Blanter, and G. E. W. Bauer, “Resources of nonlinear cavity magnonics for quantum information”, Phys. Rev. B **101**, 054402 (2020).

[2]M. Elyasi, E. Saitoh, and G. E. W. Bauer, “Stochasticity of the magnon parametron”, Phys. Rev. B **105**, 054403 (2022).

[3]J. J. Carmiggelt, I. Bertelli, R. W. Mulder, A. Teepe, M. Elyasi, B. G. Simon, G. E. W. Bauer, Y. M. Blanter, and T. van der Sar, “Broadband microwave detection using electron spins in a hybrid diamond-magnet sensor chip”, Nat. Commun. **14**, 490 (2023).

[4]L. Sheng, M. Elyasi, J. Chen, W. He, Y. Wang, H. Wang, H. Feng, Y. Zhang, I. Medlej, S. Liu, W. Jiang, X. Han, D. Yu, J.-P. Ansermet, G. E. W. Bauer, and H. Yu, “Nonlocal detection of interlayer three-magnon coupling”, Phys. Rev. Lett. **130**, 046701 (2023).

[5]O. Lee, K. Yamamoto, M. Umeda, C. W. Zollitsch, M. Elyasi, T. Kikkawa, E. Saitoh, G. E. W. Bauer, and H. Kurebayashi, “Nonlinear magnon polaritons”, Phys. Rev. Lett. **130**, 046703 (2023).

Invited. I12
Wednesday
11:15

Aspects of Unconventional Computing with Nonlinear Magnonics

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A key challenge in nanomagnetism at present is to devise efficient, low-power devices for applications in information processing. One approach involves neuro-inspired paradigms such as artificial neural networks which are superior for cognitive tasks like pattern recognition with noisy data. For example, recent work on nonlinear spin wave interferences shows how a feedforward-like neural work can be implemented using programmable magnetic obstacles, which has been used to demonstrate vowel recognition [1]. Nevertheless, realizing recurrent neural networks using arrays of nanodevices with a large connectivity remains a difficult task.

In this talk, we will discuss how nonlinear spin wave interactions in magnetic nanostructures can provide a compelling alternative to real-space paradigms. By mapping the network into reciprocal space, i.e., the space spanned by the spin wave eigenmodes, we can exploit the inherent connectivity between a large number of modes when nonlinear interactions are present. We will focus on results obtained using a mode-projection method developed for micromagnetics simulations, which show how input signals, encoded in parametrically-excited spin wave modes in YIG disks, for example, can propagate within the spin wave network in reciprocal space. This propagation is shown to depend strong on transient mode populations and history, which reflects the recurrent nature of the network. We will also discuss how this approach could be applied to other systems, such as three-magnon scattering in vortex-state disks [2], for applications like pattern recognition using reservoir computing.

This work was supported by the Horizon2020 Research Framework Programme of the European Commission under contract no. 899646 (k-NET).

REFERENCES

[1] Á. Papp, W. Porod, and G. Csaba, “Nanoscale neural network using non-linear spin-wave interference”, Nature Communications **12**, 6422 (2021).

[2] L. Körber, C. Heins, T. Hula, J.-V. Kim, H. Schultheiss, J. Fassbender, and K. Schultheiss, “Pattern recognition with a magnon-scattering reservoir”, arXiv:2211.02328 [cond-mat.mes-hall].

Invited. I13
Wednesday
14:30

Non-Reciprocal Spin Wave Beams in Out-Of-Plane Magnetized Films from Circular Antennas

Vincent Vlaminck[1,*], **Loic Temdie**[1,2], **Vincent Castel**[1,2], **Benjamin Jungfleisch**[3], **Hicham Majjad**[4], **Romain Bernard**[4], **Yves Henry**[4], **Daniel Stoeffler**[4], **Matthieu Bailleul**[4]
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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 stir spin wave beams, suggesting prominent performance in particular tasks such as image processing and speech recognition.

Along these ideas, we demonstrated that the beamforming of spin waves in a ferromagnetic thin films follows directly the near-field interference pattern of the excitation geometry [3, 4]. In this communication, we investigate the interference of magnetostatic forward volume waves excited by a quarter circular antenna, which acts as a spin wave concentrator amplifying the magnetization dynamic at its focal point (see Fig.1). We first measure via spin wave spectroscopy the radius and frequency dependence of the amplification ratio in the vicinity of the focal point, and obtain good agreement with the corresponding near-field diffraction [4] and micromagnetic simulations in the linear regime. Secondly, we observe a distortion of the diffraction pattern around the focal point above a certain input power that nevertheless remains below the non-linear threshold of the antenna. This distortion is likely due to a non-linear dynamics at the focal due to the concentration effect. Thirdly, despite the isotropic dispersion relation for these spin wave modes, we observe an asymmetry in the diffraction pattern, which is reversed upon switching the bias field polarity. We attribute this unexpected non-reciprocal effect results to the curvilinear excitation geometry combined with the gyrotropic nature of the spin wave response. We anticipate that these findings open up new perspectives for the exploration of non-reciprocal magnonic devices.

This work was supported by the French ANR project ”MagFunc” and the Département du Finistère through the project “SOSMAG”.

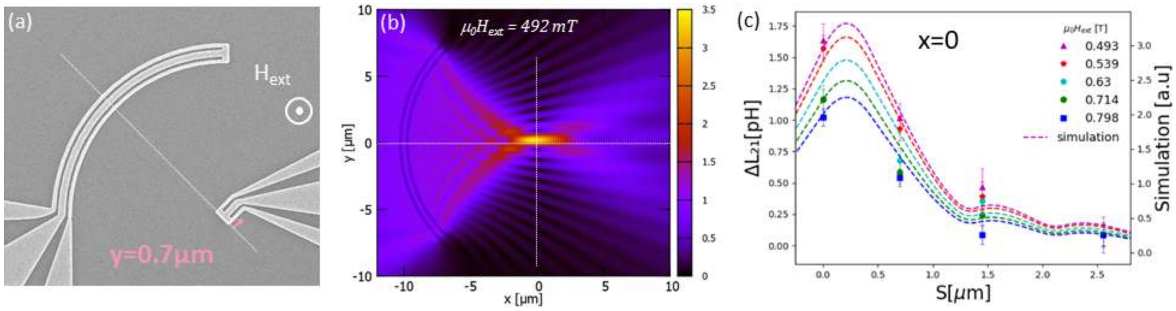

Figure 1: (a) SEM image of a spin wave concentrator. (b) Near-field diffraction simulation at μ_0H$_{ext}$=+492mT showing an up-shift of the spin wave beam. (c) Discrete mapping of the spin wave ampliude across the focal point.

REFERENCES

[1] Á. Papp, W. Porod, Á. I. Csurgay, and G. Csaba, “Nanoscale spectrum analyzer based on spin-wave interference”, Scientific Reports **7**, `10.1038/s41598-017-09485-7` (2017).

[2] Á. Papp, W. Porod, and G. Csaba, “Nanoscale neural network using non-linear spin-wave interference”, Nature Communications **12**, `10.1038/s41467-021-26711-z` (2021).

[3] N. Loayza, M. B. Jungfleisch, A. Hoffmann, M. Bailleul, and V. Vlaminck, “Fresnel diffraction of spin waves”, Physical Review B **98**, `10.1103/physrevb.98.144430` (2018).

[4] V. Vlaminck, L. Temdie, V. Castel, et al., “Spin wave diffraction model for perpendicularly magnetized films”, Journal of Applied Physics **133**, 053903 (2023).

Invited. I14
Wednesday
15:30

Magnon State Tomography and Magnon Noise Control by Nonlinearity

Tomosato Hioki[1,2,*]

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State tomography is one of the essential tools in quantum science to analyze the quantum and classical nature of arbitrary elementary excitations. Elementary excitations in magnetic materials include magnons (spin waves), and magnon dynamics and scattering processes determine various magnetic properties. Recently, magnon states characterized by unconventional fluctuations, such as squeezed states, mixed states, and entanglement between magnons, have been theoretically predicted and are being actively studied with a view to their application to quantum and nonclassical computation using magnetic materials. On the other hand, the state tomography for magnetization dynamics has yet to be developed, and there has been a limitation in investigating the magnon state.

In this talk, we propose and demonstrate a control of magnon noise by using intrinsic nonlinearity of magnons. The magnon state tomography enables us to obtain the Wigner functions, probability distribution functions that represents the fluctuation distribution of magnetization dynamics. Using an AC spin pump and a homodyne detection method, we experimentally realized the observation of magnon fluctuations and the reconstruction of the Wigner function[1]. I will introduce the experimental results of observing mixed magnon states, anisotropic magnon noise generated by parametric process, and temporal evolution of magnon coherence using magnetization state tomography. The demonstration was performed by measuring stochastic magnetization dynamics in a thin magnetic disk. In a thin magnetic disk, the magnetization dynamics can be excited parametrically, characterized by two discretized phases, 0 and π [2, 3]. With thermal fluctuation, the precession motion with the initial phase of either the 0 or π-phase is excited randomly, leading to the formation of a mixed state of magnons above the oscillation threshold. On the other hand, when the excitation power is less than the oscillation threshold, we have anisotropic change of the magnon noise in its quadrature space, where we can define different temperature to two components of the quadrature. Owing to the direct acquisition of the probability distribution of magnons, the magnon state tomography will allow us to explore a new group of states in terms of magnon fluctuations.

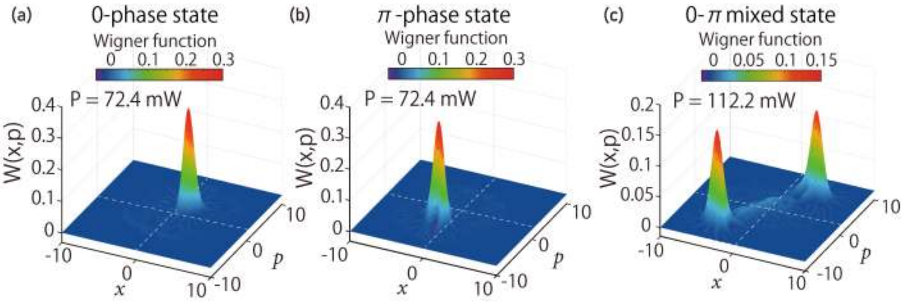

Figure 1: Experimentally obtained Wigner function of parametrically excited magnon dynamics, (a) 0-phase state, (b) π-phase state, (c) 0-π mixed state

REFERENCES

[1]T. Hioki, H. Shimizu, T. Makiuchi, and E. Saitoh, “State tomography for magnetization dynamics”, Phys. Rev. B **104**, L100419 (2021).
[2]T. Makiuchi, T. Hioki, Y. Shimazu, et al., “Parametron on magnetic dot: stable and stochastic operation”, Applied Physics Letters **118**, 022402 (2021).
[3]T. Hioki and E. Saitoh, “Stochastic dynamics of a metal magnon parametron”, Journal of Applied Physics **132**, 203901 (2022).

Invited. I15
Thursday
09:00

Observation of Antiferromagnetic Magnons in a Nanodevice in ST-AFMR Experiments

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Antiferromagnets (AFMs) are promising candidates for next-generation spintronic technologies. They harbour a variety of functionalizable features (*e.g.* topological spin textures and magneto-electric phenomena) and are sought after because of their high speed of operation, robustness against external field perturbation, and susceptibility to spin-torques [1].

Understanding and reliably utilizing interaction between an AFM spin system and spin currents is an important milestone to achieve for the development of antiferromagnetic spintronics. Spin currents pumped from an AFM driven coherently at sub-THz frequencies were measured using inverse spin Hall effect [2]. In turn, the action of a spin current on the AFM spin system was investigated in a series of switching experiments in multi-terminal devices [3] and has to be distinguished from concomitant, mostly thermal effects.

Spin-torque manipulation of a spin system requires large spin current densities and thus, typically, small device dimensions. Development of antiferromagnetic spin-torque applications hinges upon reliable excitation and detection of coherent spin dynamics in a single AFM nanodevice. This necessitates an electrical, magneto-resistive technique [4] – a spin-torque antiferromagnetic resonance (ST-AFMR) experiment.

Here, we demonstrate spin-torque antiferromagnetic resonance measurements in a device of Pt on an insulating antiferromagnetic crystal that is patterned into a nanowire. With magnetic field applied along AFM's easy axis, we achieve electrical detection of antiferromagnetic magnons below and observe Goldstone excitations above the spin-flop field. Using angle-dependent measurements, we discuss the mechanisms of excitation and detection of magnons and draw conclusions for AFM-based magnonic and spin-torque applications [5, 6].

This work was supported by the National Science Foundation through Grant No. ECCS-1810541.

REFERENCES

[1]V. Baltz, A. Manchon, M. Tsoi, et al., “Antiferromagnetic spintronics”, Rev. Mod. Phys. **90**, 015005 (2018).
[2]J. Li, C. B. Wilson, R. Cheng, et al., “Spin current from sub-terahertz-generated antiferromagnetic magnons”, Nature **578**, 70–74 (2020).
[3]H. Meer, F. Schreiber, C. Schmitt, et al., “Direct imaging of current-induced antiferromagnetic switching revealing a pure thermomagnetoelastic switching mechanism in nio”, Nano Lett. **21**, 114–119 (2021).
[4]Ø. Johansen, H. Skarsvåg, and A. Brataas, “Spin-transfer antiferromagnetic resonance”, Phys. Rev. B **97** (2018).
[5]R. Rodriguez, S. Regmi, H. Zhang, et al., “Robust spin injection via thermal magnon pumping in antiferromagnet/ferromagnet hybrid systems”, Phys. Rev. Research **4**, 033139 (2022).
[6]A. Etesamirad, R. Rodriguez, J. Bocanegra, et al., “Controlling magnon interaction by a nanoscale switch”, ACS Appl. Mater. Interfaces **13**, 20288–20295 (2021).

True Amplification of Spin Waves in Magnonic Nano-Waveguides

Hugo Merbouche[1,*], **B. Divinskiy**[1], **D. Gouéré**[2], **A. El Kanj**[2], **R. Lebrun**[2], **V. Cros**[2], **P. Bortolotti**[2], **A. Anane**[2], **S.O. Demokritov**[1], **V.E. Demidov**[1]
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Magnonic nano-devices exploit magnons - quanta of spin waves (SW) - to transmit and process information within a single integrated platform that has the potential to outperform traditional semiconductor-based electronics for low power applications. The main missing cornerstone of this information nanotechnology is an efficient scheme for the direct amplification of propagating spin waves. The recent discovery of spin-orbit torque provided an elegant mechanism for propagation losses compensation. While partial compensation of the spin-wave damping has allowed for spin-wave signal modulation [1], true amplification – the exponential increase in the spin-wave intensity during propagation – has so far remained elusive. In this work we evidence the operating conditions to achieve true amplification using clocked nanoseconds-long spin-orbit torque pulses in sub-micrometer wide magnonic waveguides (Fig.1 a), where the effective magnetization has been engineered [2, 3] to be close to zero to suppress the detrimental magnon-magnon scattering [4]. As a result, we achieve an exponential increase in the intensity of spin waves as they propagate away from the antenna (see Fig.1 b), up to 500% after several micrometers. Using micro-Brillouin Light Scattering, we unambiguously identify the physical phenomena that prevented amplification in previous experimental studies and show how these detrimental effects can be overcome in practice.

These findings open new avenues for the field of nano-magnonics by demonstrating a simple and energy-efficient approach for the on-chip amplification of propagating spin waves, which can be used in most of nanoscale magnonic devices.

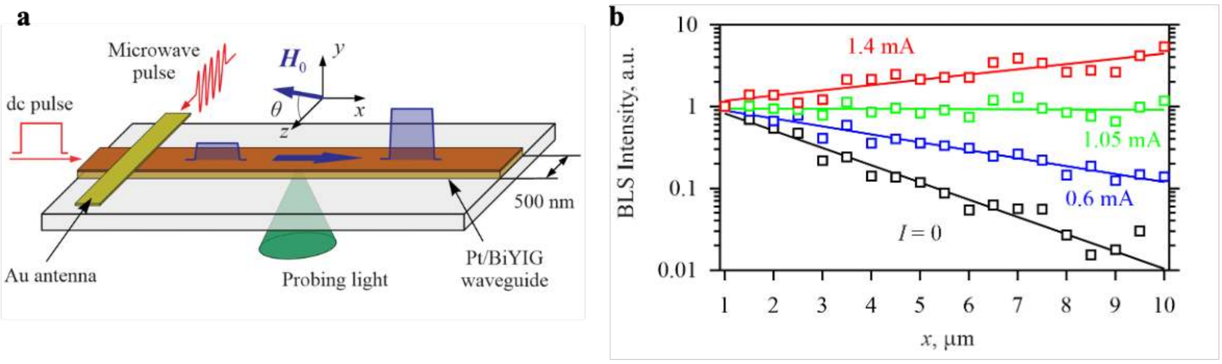

Figure 1: (a) Schematics of the experiment. Spin-wave pulses are excited by an Au antenna and propagate in a BiYIG(20 nm)/Pt(6 nm) waveguide. In-plane dc current flowing in the Pt layer exerts an anti-damping torque on the magnetization. (b) Spatial dependence of the SW pulse intensity measured at different dc currents, as labeled. Symbols show the experimental data. Solid straight lines show the exponential fit. The data are obtained at $f = 5.025\ GHz$ and $H_0 = 1.8\ kOe$ applied at $\theta = 30^\circ$.

REFERENCES

[1] M. Evelt et al., “High-efficiency control of spin-wave propagation in ultra-thin yttrium iron garnet by the spin-orbit torque”, en, Applied Physics Letters **108**, 172406 (2016).

[2] L. Soumah et al., “Ultra-low damping insulating magnetic thin films get perpendicular”, en, Nature Communications **9**, 3355 (2018).

[3] D. Gouéré et al., “Temperature-independent ferromagnetic resonance shift in Bi-doped YIG garnets through magnetic anisotropy tuning”, en, Physical Review Materials **6**, 114402 (2022).

[4] B. Divinskiy et al., “Controlled nonlinear magnetic damping in spin-Hall nano-devices”, en, Nature Communications **10**, 5211 (2019).

Invited. I17
Thursday
11:15

Nonreciprocal Magnonics upon Ferromagnet/Superconductor Heterostructures

Oleksandr Dobrovolskiy[1,*], **Krzysztof Szulc**[2], **Yuliia Kharlan**[2], **Jan Klima**[3], **Tomas Lednicky**[3], **Sebastian Lamb-Camarena**[1], **Clemens Schmid**[1], **Andrii Chumak**[1], **Michal Urbánek**[3], **Jarosław Kłos**[2]
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One of the primary advantages offered by spin waves for operations on data is a rich palette of nonreciprocal phenomena, implying that spin-wave propagation in opposite directions has different properties. The current great interest in quantum magnonics [1] stimulates the exploration of spin waves at cryogenic conditions and in environments of superconducting circuits [2]. In this regard, the combination of magnonic materials with superconductors allows one to use structures with vanishingly small electrical resistance for spin-wave control [3]. In such heterostructures, nonreciprocal spin-wave generation and scattering in ferromagnet (F) can be induced by Meissner screening currents and nonreciprocal motion of the Abrikosov vortex lattice in superconductor (S) [4].

In this talk, a selection of nonreciprocal phenomena in S/F heterostructures will be discussed. In the Meissner state of S [Fig. 1(a)], the bending of stray field lines induces an asymmetric dispersion for the Damon-Eshbach geometry [Fig. 1(b)] and allows for spin-wave propagation in the adjacent F in one direction only. In the Shubnikov phase, the propagation of backward-volume spin waves is nonreciprocal because of the Doppler shifts of the bandgaps in the magnon frequency spectra, which in turn results from the Bragg scattering of spin waves on the moving vortex lattice [Fig. 1(c)]. For the forward-volume geometry, nonreciprocity stems from the unidirectional excitation of spin waves by fast-moving vortices via a Cherenkov-type mechanism [5]. Thus, nonreciprocity can be realized for both Meissner and Shubnikov states of S and for all three spin-wave geometries of F.

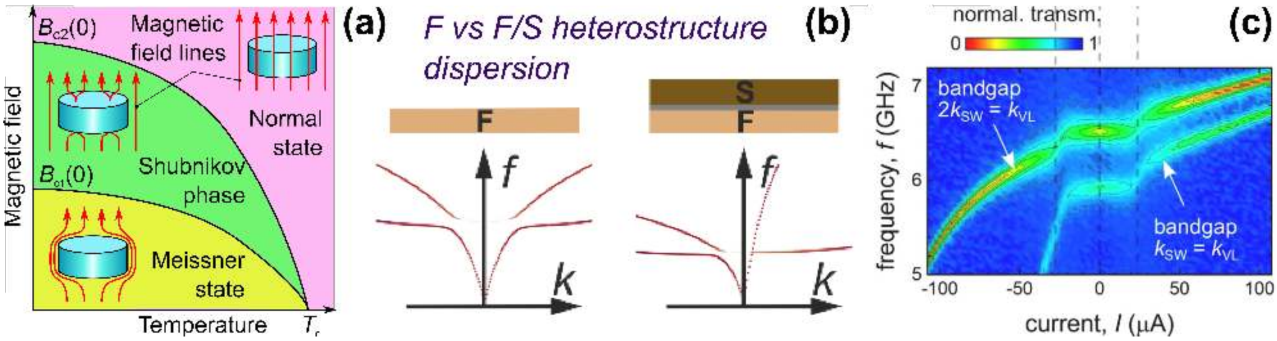

Figure 1: (a) Phase diagram of a superconductor. (b) Spin-wave dispersion for a ferromagnet versus an F/S structure in the Damon-Eshbach geometry. (c) Doppler shifts of the magnon bandgaps for an F/S structure under current polarity reversal.

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REFERENCES

[1] D. Lachance-Quirion, S. P. Wolski, Y. Tabuchi, et al., “Entanglement-based single-shot detection of a single magnon with a superconducting qubit”, Science **367**, 425 (2020).

[2] Y. Li, W. Zhang, V. Tyberkevych, et al., “Hybrid magnonics: physics, circuits, and applications for coherent information processing”, J. Appl. Phys. **128**, 130902 (2020).

[3] O. V. Dobrovolskiy, R. Sachser, and T. Brächer *et al.*, “Magnon-fluxon interaction in a ferromagnet/superconductor heterostructure”, Nat. Phys. **15**, 477 (2019).

[4] O. V. Dobrovolskiy and A. V. Chumak, “Nonreciprocal magnon fluxonics upon ferromagnet/superconductor hybrids”, J. Magn. Magnet. Mater. **543**, 168633 (2022).

[5] O. V. Dobrovolskiy, Q. Wang, D. Y. Vodolazov, et al., “Cherenkov radiation of spin waves by ultra-fast moving magnetic flux quanta”, arXiv:2103.10156 (2021).

Contributed. C01
Monday
09:30

Time-Domain Coherent Manipulation of Remotely Coupled Magnonic Resonators

Moojune Song[1,2,*], **Tomas Polakovic**[3], **Thomas W. Cecil**[4], **John E. Pearson**[1], **Ralu Divan**[5], **Wolfgang Pfaff**[6], **Wai-Kwong Kwok**[1], **Ulrich Welp**[1], **Axel Hoffmann**[7], **Kab-Jin Kim**[2], **Valentine Novosad**[1], **Yi Li**[1]
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Hybrid systems have shown great potential as platforms for efficient quantum information processing interfaces [1]. One such system that has garnered particular attention is the magnon-based hybrid system that couples magnons with superconducting microwave resonators [2]. These systems are of interest due to their potential connectivity with superconducting quantum circuits and their strong coupling with large cooperativity. In this study, we introduce a new method for measuring and manipulating the real-time dynamics of a superconducting microwave circuit-mediated hybrid magnonic system. Our device includes two Yttrium Iron Garnet (YIG) spheres positioned 12 mm apart on a Si substrate, which are coupled through a superconducting NbN microwave resonator circuit. The magnon modes of each sphere can be individually excited and detected using two vertical antennae located next to each YIG sphere. Through the magnon-photon coupling between the microwave resonator and the YIG spheres, the magnon modes of the two remote YIG spheres are strongly coupled, showing a clear avoided crossing of magnon bands from the VNA measurement [3], with a coupling strength of approximately 28 MHz at a frequency of around 5.4 GHz. Using a microwave pulse with a duration of 4 ns, we excited one sphere and observed the induced voltage at the other antenna with a real-time oscilloscope, observing coherent energy exchange between the two coupled magnonic resonators with a period corresponding to the coupling strength (35 ns $\approx$ [28 MHz]$^{-1}$). Moreover, we successfully manipulated the state of the coupled dynamics through interference-type interactions using two consecutive microwave pulses. These findings offer novel insights into the coherent dynamics of strongly-coupled hybrid systems in the time domain and suggest potential avenues for further exploration in quantum-compatible coherent information processing.

REFERENCES

[1]G. Kurizki, P. Bertet, Y. Kubo, et al., “Quantum technologies with hybrid systems”, Proceedings of the National Academy of Sciences **112**, 3866–3873 (2015).
[2]Y. Li, T. Polakovic, Y.-L. Wang, et al., “Strong coupling between magnons and microwave photons in on-chip ferromagnet-superconductor thin-film devices”, Physical Review Letters **123**, 107701 (2019).
[3]Y. Li, V. G. Yefremenko, M. Lisovenko, et al., “Coherent coupling of two remote magnonic resonators mediated by superconducting circuits”, Physical Review Letters **128**, 047701 (2022).

Filtering and Imaging of Frequency-Degenerate Spin Waves Using Nanopositioning of a Single-Spin Sensor

Samer Kurdi[1,*], **Brecht G. Simon**[1], **Joris J. Carmiggelt**[1], **Michael Borst**[1], **Allard J. Katan**[1], **T. Van Der Sar**[1]
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Magnetometry based on nitrogen-vacancy (NV) spins in diamond has recently emerged as a powerful tool for probing spin waves [1], the elementary excitations of coupled spins in magnetically ordered materials. In this talk I will focus on how we utilize scanning NV magnetometry – in which we use a NV sensor spin that is shallowly embedded in the tip of a diamond scanning probe to image spin waves in a thin film insulator (Figure. 1).

A key challenge for nanoscale scanning-NV imaging of spin waves is the magnetic noise generated by the thermally excited spin-wave background. This noise increases dramatically as the NV-spin approaches the sample to within nanometer distance [2, 3], quenching the NV photoluminescence and inducing a fast decay of the NV Rabi oscillations. However, by fine-tuning the balance between the amplitude of the driven spin-wave mode and the non-linearly excited spin-wave noise, we could overcome the challenge of NV photoluminescence quenching which hinders spin-wave imaging. I will show that accurately controlling the NV-film distance on the sub-micron/nm scale allows for selective imaging of short or long wavelength spin waves that are frequency degenerate [4].

These results reveal the power of scanning NV-magnetometry as a tool for spin-wave probing. Whilst showcasing that nanoscale control over the NV-sample distance enables wavenumber-selective imaging of magnetization oscillations and open up new avenues for imaging other coherent spin-wave modes.

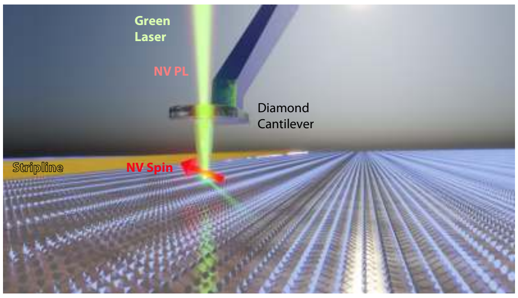

Figure 1: A diamond cantilever, with a nitrogen vacancy centre implanted ∼20 nm below the tip surface, is mounted in a scanning-probe geometry and is used for detecting the stray field of spin waves that are excited by a gold stripline. The nitrogen vacancy spin is initialized using a green laser and read out via spin-dependent photoluminescence (PL).

REFERENCES

[1] I. Bertelli, J. J. Carmiggelt, T. Yu, et al., "Magnetic resonance imaging of spin-wave transport and interference in a magnetic insulator", Science Advances **6**, eabd3556 (2020).
[2] B. G. Simon*, S. Kurdi*, H. La, et al., "Directional excitation of a high-density magnon gas using coherently driven spin waves", Nano Letters **21**, 8231–8219 (2021).
[3] B. A. McCullian, A. M. Thabt, B. A. Gray, et al., "Broadband multi-magnon relaxometry using a quantum spin sensor for high frequency ferromagnetic dynamics sensing", Nature Communications **11**, 5229 (2020).
[4] B. G. Simon*, S. Kurdi*, J. J. Carmiggelt, et al., "Filtering and imaging of frequency-degenerate spin waves using nanopositioning of a single-spin sensor", Nano Letters **22**, 9198–9204 (2022).

Contributed. C03
Monday
10:00

Bose-Einstein Condensation of Parametrically Pumped Magnon Gas to the Uniform Precession State

Alexander A. Serga[1,*], **Timo B. Noack**[1], **Andra Pirktina**[1], **Vitaliy I. Vasyuchka**[1],
Victor S. L'vov[2], **Gennadii A. Melkov**[3], **Mathias Weiler**[1], **Burkard Hillebrands**[1]
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Coherent magnon states, such as Bose–Einstein condensates (BECs), which spontaneously form in an overpopulated magnon gas even at room temperature, have considerable potential for wave-based computing and information processing at microwave frequencies [1].

Such a condensate is commonly created in the low-damping yttrium iron garnet (YIG) films by parametric pumping of magnons with a microwave electromagnetic field. In this process, microwave photons split into magnon pairs with half the pumping frequency f_p and opposite wavevectors. These magnons thermalize to the lower part of the frequency spectrum, and if the pumping power exceeds a certain threshold, a BEC is formed there. In in-plane magnetized films, magnons condense at two frequency-degenerated minima with opposite wavevectors along the magnetization direction. Since the wavelength of such magnon condensate is only a few microns, its observation is quite challenging and is usually performed using Brillouin light scattering spectroscopy.

Here, I present the discovery of a long-wavelength type of magnon BEC in perpendicularly magnetized YIG films. Under such magnetization conditions, the magnon spectrum has only one energy minimum at zero wavenumber. This state corresponds to the Kittel mode and represents a homogeneous precession of the magnetic moment of the sample at the ferromagnetic resonance frequency. The precession signal is easily detected by a conventional microstrip antenna, and its time evolution and spectral characteristics can be measured with high accuracy.

In our experiment, the parametric magnons are generated about 800 MHz above the spectral minimum at 3090 MHz and are broadly distributed around half the pumping frequency during the pumping action (see Figure 1). After the parametric pumping is terminated the spectrally-narrow BEC state with a linewidth of about 1 MHz is formed in the freely evolving magnon gas.

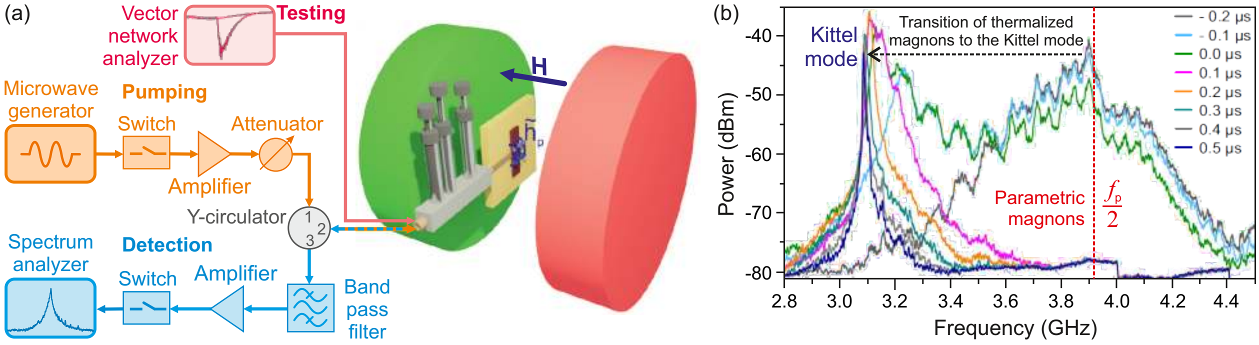

Figure 1: Magnon condensation into the Kittel mode. a) Experimental setup. b) Transition of the pumping-perturbed magnon spectrum to its equilibrium distribution and formation of magnon condensate after the pumping is stopped at time zero.

This research was funded by the European Research Council within the Advanced Grant No. 694709 "Super-Magnonics" and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center–TRR 173/2–268565370 "Spin+X" (project B04).

REFERENCES

[1] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, "Advances in coherent magnonics", Nature Reviews Materials **6**, 1114–1135 (2021).

Antiferromagnetic Magnon Spintronic Based on Non-Reciprocal and Non-Degenerated Ultra-Fast Spin-Waves in the Canted Antiferromagnet α-Fe$_2$O$_3$

Aya El Kanj[1,*], **O. Gomonay**[2], **I. Boventer**[1], **P. Bortolotti1**[1], **V. Cros**[1], **A. Anane**[1], **R. Lebrun**[1]

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Coherent antiferromagnetic spin-waves [1] offer exciting properties allowing for faster and less power-hungry electronics. However, their electrical detection has so far been elusive, making it difficult to investigate their propagating behavior and their integration in magnonic devices. Here we report on the electrical detection of spin-waves in the dipole-exchange regime of a canted antiferromagnet [2] (α-Fe$_2$O$_3$) in the presence of bulk Dzyaloshinskii-Moriya interaction using both inductive (gold, see sketch) and spintronic (platinum, not shown) transducers. Despite the vanishing net moment (3 emu/cm^3), we demonstrate the presence of ultra-fast and non-degenerated spin-waves for wave vectors k parallel or perpendicular to the antiferromagnetic order [3] (see **Figure 1 (b-c)**). In addition, by using time of flight spectroscopy[4], we evidence the presence of reciprocal (bulk) modes and non-reciprocal (surface) magnon modes traveling up to 30 and 10 km/s, respectively. Ultimately, we achieve efficient electrical detection of propagating non-reciprocal antiferromagnetic spin-wave using non-local inverse spin-Hall effects[5]. Our results highlight the rich physics of antiferromagnetic spin-waves, which holds a lot of opportunities for high-frequency magnonics.

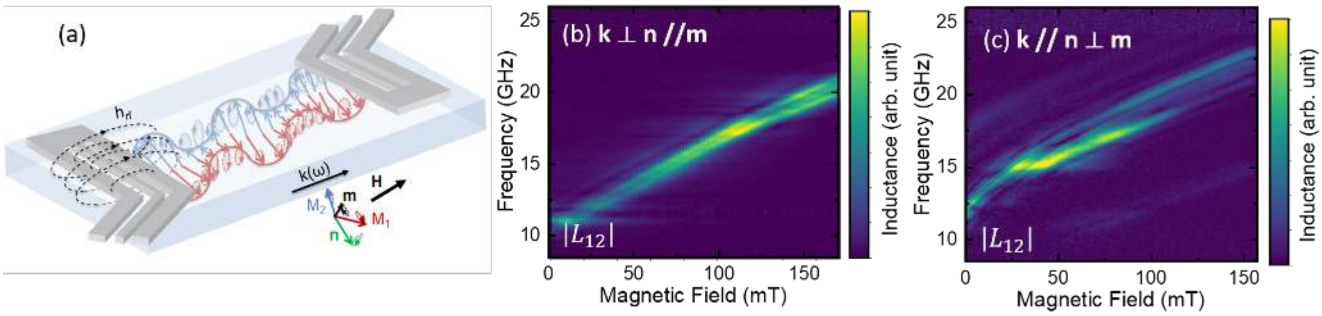

Figure 1: (a) Schematic of the set-up, (b-c) Spin wave transmission measurement showing the transmitted amplitude $|L_{12}|$ at k ≈ 0.6 rad/μm for k ⊥ n (// m) for panel (a) and k // n (⊥ m) for panel (b).

REFERENCES

[1] R. E. Camley, “Long-wavelength surface spin waves on antiferromagnets”, Physical Review Letters **45**, 283–286 (1980).
[2] R. Lebrun, A. Ross, O. Gomonay, et al., “Long-distance spin-transport across the morin phase transition up to room temperature in ultra-low damping single crystals of the antiferromagnet α-fe2o3”, Nature Communications **11**, 6332 (2020).
[3] A. E. Kanj, O. Gomonay, I. Boventer, et al., “Evidence of non-degenerated, non-reciprocal and ultra-fast spin-waves in the canted antiferromagnet α-fe2o3”,
[4] T. Devolder, G. Talmelli, S. M. Ngom, et al., “Measuring the dispersion relations of spin wave bands using time-of-flight spectroscopy”, Physical Review B **103**, 214431 (2021).
[5] A. V. Chumak, A. A. Serga, M. B. Jungfleisch, et al., “Direct detection of magnon spin transport by the inverse spin hall effect”, Applied Physics Letters **100**, 082405 (2012).

Contributed. C05
Monday
12:00

Frequency Multiplication by Collective Nanoscale Spin-Wave Dynamics

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Frequency conversion is a process where an input frequency is converted into higher output frequencies. This functionality is vital for all sorts of electronic devices. A promising alternative to conventional electronics are devices based on the propagation and interaction of spin waves. Utilizing spin waves as a carrier of information instead of the electron's charge promises less energy dissipation and could enable more energy efficient devices. In ferromagnetic materials the characteristic frequency of these excitations is in the gigahertz (GHz) range. This makes the approach competitive with modern electronics for applications like spin wave based computing. However, the interface of magnonic devices with conventional electronics is challenging and often inefficient. Thus, it is preferable to transfer all important functionalities including frequency conversion to the magnonic system.

Here, we locally probe the magnetic excitations in a soft magnetic material, NiFe, by optical methods. We use diamond NV-centers as probes sensitive for rf magnetic fields and reveal the generation of a six octave spanning frequency comb inside the magnetic material upon MHz rf excitation [1]. We employ Super Nyquist Sampling MOKE microscopy [2] to image the generated spin waves and show that the frequency comb emerges coherently. Our micromagnetic models demonstrate that MHz-range excitation causes self-synchronized switching effects in the sample on the micrometer scale which lead to phase-locked spin-wave emission in the GHz range. The discovered frequency multiplication process opens exciting perspectives for spintronic applications, such as all-magnetic mixers or on-chip GHz sources.

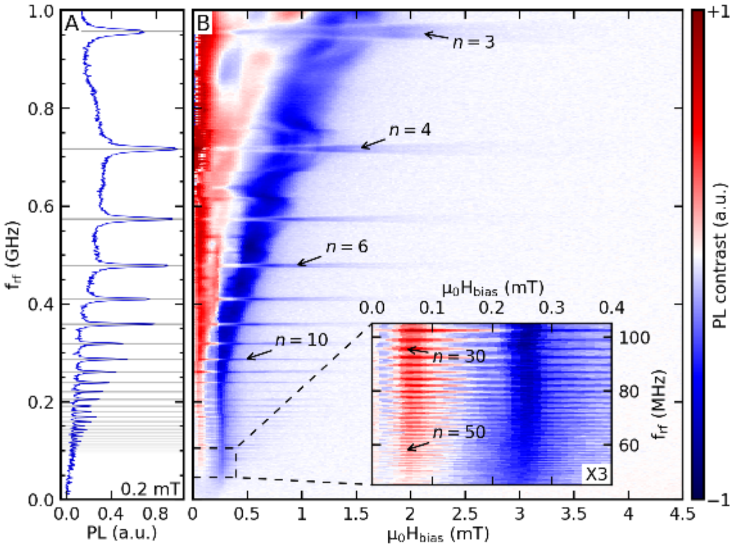

Figure 1: Frequency comb in NiFe (sharp lines) measured by NV-center microscopy. Excitation frequency (y-axis) and static bias field (x-axis) are varied. The NV-centers are sensitive to a fixed frequency of 2.8 GHz, thus the spacing of the comb lines is inversely proportional to the harmonics mode number. Up to the 50th harmonic of the driving frequency are detected.

REFERENCES

[1]C. Koerner, R. Dreyer, M. Wagener, et al., “Frequency multiplication by collective nanoscale spin-wave dynamics”, Science **375**, 1165–1169 (2022).

[2]R. Dreyer, N. Liebing, E. R. J. Edwards, A. Müller, and G. Woltersdorf, “Spin-wave localization and guiding by magnon band structure engineering in yttrium iron garnet”, Phys. Rev. Mater. **5**, 064411 (2021).

Contributed. C06
Monday
12:15

Interactions between Magnons and Domain Walls in Garnet Racetracks

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Advancing the development of spin-wave devices requires high-quality low-damping magnetic materials where magnon spin currents can propagate efficiently and interact effectively with local magnetic textures. We show here how magnons interact with domain walls in in a thin film channel of bismuth yttrium iron garnet (BiYIG, with damping on the order of 10^{-4}) using an antenna excited with a r.f. signal. We found that a magnon spin current can drive DW motion in the channel by means of magnon spin-transfer torque. The DW can be reliably moved over 20 µm distances at zero applied magnetic field by a pulse as short as 1 ns. For pulses below 100 ns the behavior is consistent with an energy requirement of order 4 pJ to depin and translate the domain wall. For linger pulses the behavior suggests a stochastic depinning process. The required energy for driving DW motion is orders of magnitude smaller than those reported for metallic systems. These results facilitate low-switching-energy magnonic devices and circuits where magnetic domains can be efficiently reconfigured by magnon spin currents flowing within magnetic channels.

Magnonics 2023
July 30th - August 3rd
Le Touquet - Paris - Plage, France

Contributed. C07
Monday
15:00

Spin Torque Driven Skyrmion Resonance Technique in Magnetic Bulk Crystals

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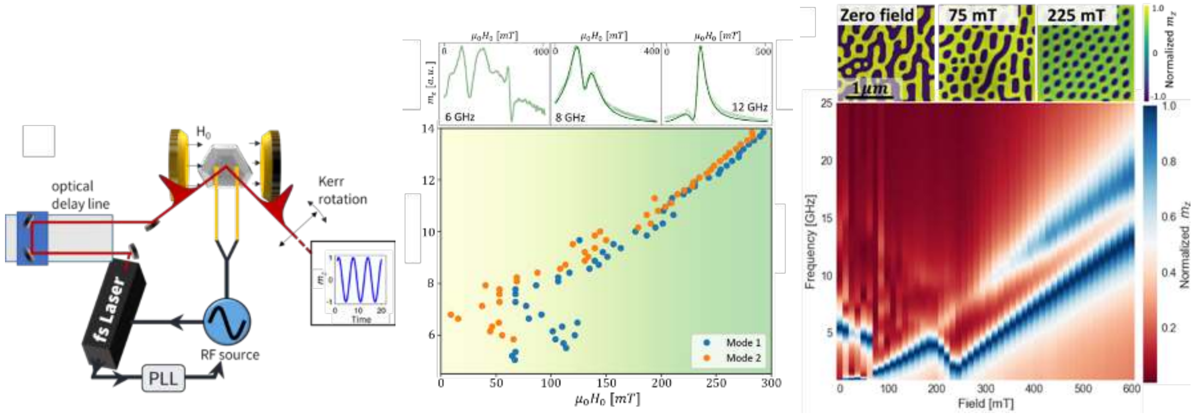
The Fe_3Sn_2 crystal is an attractive candidate for skyrmion based ultra-dense magnetic data storage and distribution applications. Recently, frustration in ferromagnetic crystals was predicted of being capable of providing the topological protection of the Skyrmion [1] without relying on the Dzyaloshinskii-Moriya interaction and the effect was immediately discovered in Fe_3Sn_2 bulk crystals [2]. Surprisingly, these Skyrmions survive even at room temperature and are controllable by electrical currents. Here were present a new technique for studying the skyrmion ferromagnetic resonance in a bulk Fe_3Sn_2 crystal where the dynamical response is excited by an AC spin torque in a fashion that is reminiscent of the spin torque ferromagnetic resonance experiment [3] (Fig. 1(a)). Using phase-locked optical pulses that probe the Skyrmion resonance response in the time-domain, we identify the counter-clockwise and breathing skyrmion modes. Furthermore, from the evolution of the mode with increasing field we can identify the magnetic phase transitions taking in the Fe_3Sn_2 crystal (Fig. 1(b)). The measurements are compared to dynamical object-oriented micromagnetic framework (OOMMF) simulations that reproduce the dynamical response (Fig. 1(c)) and reveal the phase transitions from the disordered phase through the stripe phase reaching eventually the uniform crystal lattice phase. The generality of the presented technique paves way towards resolving the spin dynamics in nonconventional magnetic crystals.



(a) (b) (c)

Figure 1: (a) The optically probed STFMR technique. An AC charge current is passed through the sample and excites the FMR which is then probed using the magneto-optical Kerr effect (MOKE). (b) Optical STFMR responses. Top panel: measured FMR spectra at 6, 8 and 12 GHz. bottom panel: evolution of resonance frequency responses for the two modes with the external field. (c) Calculation of the magnetic phase transition (top panel) and evolution of resonance frequency with the applied magnetic field (bottom panel).

REFERENCES

[1]A. O. Leonov and M. Mostovoy, “Multiply periodic states and isolated skyrmions in an anisotropic frustrated magnet”, Nature Communications **6**, 8275 (2015).

[2]Z. Hou, W. Ren, B. Ding, et al., “Observation of various and spontaneous magnetic skyrmionic bubbles at room temperature in a frustrated kagome magnet with uniaxial magnetic anisotropy”, Advanced Materials **29**, 1701144 (2017).

[3]L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, “Spin-torque ferromagnetic resonance induced by the spin hall effect”, Phys. Rev. Lett. **106**, 036601 (2011).

Contributed. C08
Monday
15:15

Phase-Resolved Optical Characterization of Nanoscale Spin Waves

Ondřej Wojewoda[1,*], **Martin Hrtoň**[1,2], **Meena Dhankhar**[1], **Jakub Krčma**[2], **Kristýna Davídková**[2],
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When the spin wave wavelengths approach the exchange length of the magnetic material or when the dimensions of the magnonic system are reduced, new phenomena such as spin unpinning condition [1] arises. Nowadays, the only possibility to image nanoscale spin waves is X-ray microscopy, requiring synchrotron radiation and making investigation of nanoscale-related phenomena very time- and resource-demanding [2].

In our approach we show that the phase of spin waves can be characterized optically with sub-diffraction resolution and nanometer precision by using Mie resonance-enhanced Brillouin light scattering [3] with array of nanoresonators (see Fig. 1a,b). The spatial restriction of the subdiffractional regions allows the light to interact with the spin waves with much shorter wavelengths, than is the wavelength of free-space light.

Presented experiments shows that we were able to get spin-wave phase with spatial step of 70 nm and get the wavelength with precission down to few nanometers (1c). We performed this experiment for several frequencies and retrieved dispersion relation in the broad wavenumber range (from 0 to 30 rad/μm) (1d).

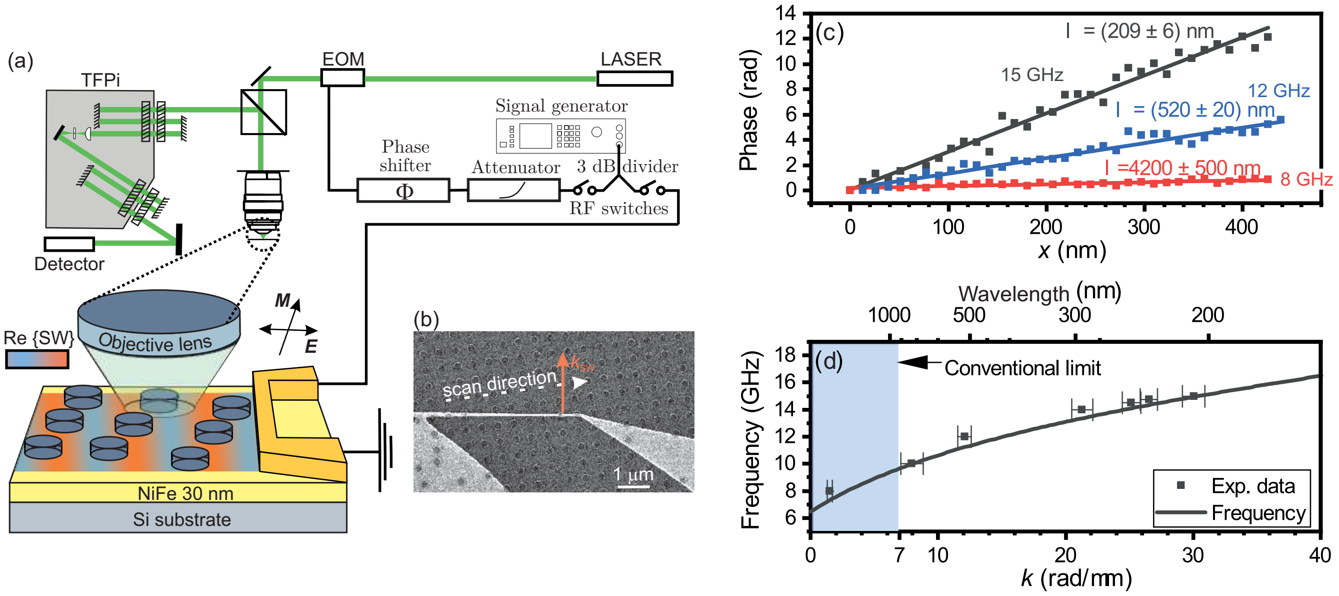

Figure 1: a, sketch of the setup. b, scanning electron microscope image of the excitation antenna and silicon disk array. c, phase evolution for 8, 12, 15 GHz. d, calculated dispersion relation using Mie nanoresonators.

REFERENCES

[1]Q. Wang, B. Heinz, R. Verba, et al., “Spin pinning and spin-wave dispersion in nanoscopic ferromagnetic waveguides”, Phys. Rev. Lett. **122**, 247202 (2019).

[2]E. Albisetti, D. Petti, G. Sala, et al., “Nanoscale spin-wave circuits based on engineered reconfigurable spin-textures”, Commun. Phys. **1**, 56 (2018).

[3]O. Wojewoda, F. Ligmajer, M. Hrtoň, et al., “Observing high-k magnons with Mie-resonance-enhanced Brillouin light scattering”, arXiv preprint arXiv:2206.05178 (2022).

Contributed. C09
Tuesday
09:30

Ultrafast Nonlinear Conversion of Magnons in an Antiferromagnet

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Propagating magnons, or spin waves, have recently attracted a lot of interest as strongly interacting potential information carriers, which do not generate Joule heating. In antiferromagnetic materials the frequencies of the magnons lie in the THz range, compared to the GHz range in ferromagnets, allowing for orders of magnitude faster information processing in antiferromagnets [1]. The first experimental demonstration of generation and detection of the coherent propagating magnons in an antiferromagnet was very recently reported [2]. The breakthrough is based on using nanoscale confinement of the laser pump pulse to excite magnons, and selective detection of them is achieved by scattering of another probe pulse. In this work we capitalise on this discovery to harness strong nonlinear coupling between magnons and realise ultrafast converter of quasi-uniform spin precession into propagating magnons with higher frequencies (energies) and wavenumbers (momenta). Our discovery enables control over the spin waves, required to make them suitable for information processing in the form of logic gates [3]. We demonstrate supressing or amplifying of THz propagating magnons, mimicking the operation of a transistor. To this end, we perform a double pump - probe experiment illustrated in figure 1. The first pump pulse launches spin dynamics, which are modulated and transformed by the second pump. The dynamics are probed magneto-optically, using the detection mechanism reported in [2]. From the 2D spectrum of the dynamics, we find that the amplitude of the detected spin wave can be controlled by the delay between the pumps (figure 1b). This amplitude modulation is intrinsically nonlinear, as we observe the features at (f_k, f_k) frequencies (interference), and around (f_0, f_k) frequencies (nonlinear conversion) (figure 1c), where f_k is the finite-k component of the freely propagating spin wave, and f_0 is the frequency of the uniform spin precession. Using the Lagrangian formalism for describing nonlinear spin dynamics [4], we can show that our experiment can be interpreted as conversion of the quasi-uniform spin precession to the finite-k magnon modes by a second light pulse. The converter enables ultrafast modulation of spin waves in an antiferromagnet, which is a major milestone in THz magnonics.

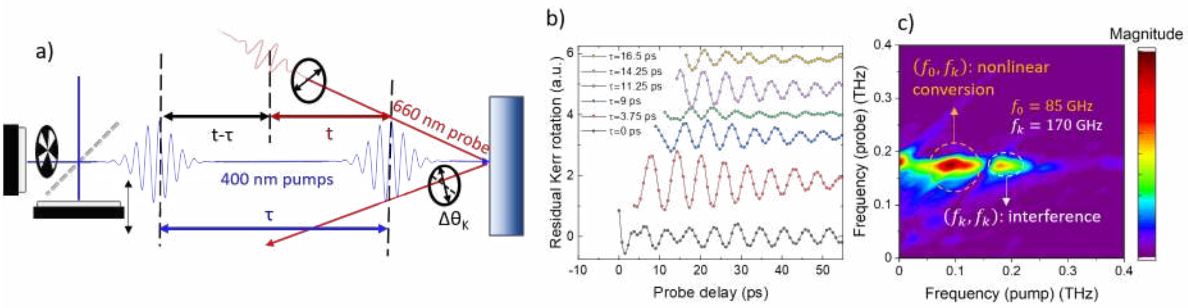

Figure 1: a) Experimental scheme. The spin dynamics is excited by the first 400 nm pump pulse and then controlled with a second 400 nm pump pulse. The ultrafast dynamics is probed magneto-optically, using a 660 nm pulse. b) Detected spin dynamics as a function of the delay τ between the two pumps. c) 2-dimensional Fourier transform of the data in b).

REFERENCES

[1] K. Zakeri, "Terahertz magnonics: feasibility of using terahertz magnons for information processing", Physica C: Superconductivity and its Applications **549**, 164–170 (2018).

[2] J. Hortensius, D. Afanasiev, M. Matthiesen, et al., "Coherent spin-wave transport in an antiferromagnet", Nature physics **17**, 1001–1006 (2021).

[3] A. Kolosvetov, M. Kozhaev, I. Savochkin, V. Belotelov, and A. Chernov, "Concept of the optomagnonic logic operation", Phys. Rev. Appl. **18**, 054038 (2022).

[4] A. Zvezdin, "Dynamics of domain walls in weak ferromagnets", Jetp Letters **29**, 605 (1979).

Contributed. C10
Tuesday
09:45

Light-Driven Control of Spin-Wave Damping in an Antiferromagnet

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Employing antiferromagnetic magnons instead of their conventional ferromagnetic counterparts in future magnonics devices promises THz rates of data processing and novel relativistic physics, but crucially lacks efficient sources of the THz spin-wave excitation [1]. Femtosecond pulses of light, the shortest and thus the most broadband stimuli in experimental condensed matter physics, have recently become a game changer in the field of antiferromagnetic magnonics. It has been shown that the light pulses can be interconverted into broadband propagating wavepackets of coherent magnons with a continuous bandwidth of more than 0.2 THz [2].

Here we investigate the many-body interaction of the light-driven magnons in prototypical antiferromagnet DyFeO3. Using femtosecond pulses of light, we excite the magnon wavepacket and show that increase in the population of the light-driven magnons leads to a dramatic suppression of the lifetime of the uniform spin precession, corresponding to the zone-center magnon. We demonstrate that the magnon lifetime can be easily reduced to more than two orders of magnitude lower than one in the equilibrium state. We argue that the stimulated processes of magnon-phonon scattering govern the renormalization of the magnon's lifetime. Our findings not only emphasize the importance of scattering processes in redistributing energy and momentum in wavepackets of antiferromagnetic magnons, but also present an opportunity for efficient control of spin-wave damping.

REFERENCES

[1] A. Barman, G. Gubbiotti, S. Ladak, et al., "The 2021 magnonics roadmap", Journal of Physics: Condensed Matter **33**, 413001 (2021).

[2] J. Hortensius, D. Afanasiev, M. Matthiesen, et al., "Coherent spin-wave transport in an antiferromagnet", Nature physics **17**, 1001–1006 (2021).

Auto-Oscillation Instability and Pattern Generation in FMR-Driven BiYIG Nanodisks

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Nonlinear ferromagnetic resonance (FMR) of low damping materials can exhibit rich and complex temporal dynamics [1]. In nanostructures, the quantization of spin-wave (SW) modes limits the available nonlinear processes, pushing back the instability thresholds at high amplitude [2]. Moreover, tuning the perpendicular magnetic anisotropy (PMA) of thin films allows the control of the nonlinear frequency shift [3].

Here, we study the high power FMR regime of BiYIG nanodisks patterned from a 30 nm thick BiYIG of high dynamical quality, where the PMA almost compensates the shape anisotropy [4]. The static magnetic field is applied out-of-plane while the microwave field of frequency 5 GHz is in the plane. Using a magnetic resonance force microscope and two-tone spectroscopy [2], we observe that, surprisingly, a frequency modulation spectrum appears beyond a relatively low threshold power. These experimental findings are reproduced by micromagnetic simulations, which reveal an auto-oscillation instability. It corresponds to a low frequency ($\sim$ 100 MHz) modulation of the magnetization dynamics (Fig.1(a)), leading to modulation patterns which sensitively depends on the bias conditions. Describing the nonlinear magnetization dynamics in terms of normal modes [5], we investigate how the nonlinear coupling between SW eigenmodes leads to the periodic oscillation of the magnetization profile (Fig.1(b-c)), responsible of the rich dynamics observed experimentally.

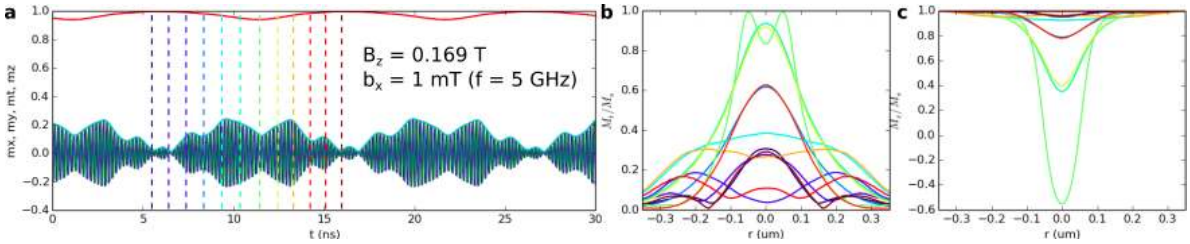

Figure 1: (a) Simulated time evolution of the average magnetization components in a BiYIG nanodisk of diameter 700 nm. Blue, green, cyan and red continuous lines respectively correspond to m_x, m_y, $m_t = \sqrt{m_x^2 + m_y^2}$ and m_z. (b) Snapshots of the transverse magnetization profiles and (c) of the longitudinal magnetization profiles at different times, indicated by vertical dashed lines in (a) of corresponding colors.

REFERENCES

[1] S. M. Rezende and F. M. de Aguiar, "Spin-wave instabilities, auto-oscillations, and chaos in yttrium-iron-garnet", Proceedings of the IEEE **78**, 893–908 (1990).

[2] Y. Li, et al., "Nutation spectroscopy of a nanomagnet driven into deeply nonlinear ferromagnetic resonance", Phys. Rev. X **9**, 041036 (2019).

[3] B. Lührmann, M. Ye, H. Dötsch, and A. Gerspach, "Nonlinearities in the ferrimagnetic resonance in epitaxial garnet films", J. Magn. Magn. Mater. **96**, 237–244 (1991).

[4] L. Soumah, et al., "Ultra-low damping insulating magnetic thin films get perpendicular", Nat. Commun. **9**, 3355 (2018).

[5] S. Perna, F. Bruckner, C. Serpico, D. Suess, and M. d'Aquino, "Computational micromagnetics based on normal modes: bridging the gap between macrospin and full spatial discretization", J. Magn. Magn. Mater. **546**, 168683 (2022).

Cavity Magnomechanics in a Synthetic Antiferromagnet with Surface Acoustic Waves

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Cavity magnomechanics [1], as an analogy to cavity optomechanics [2] and cavity optomagnonics [3], is an emerging field to study coherent phonon-magnon coupling in magnetic solids for potential quantum applications. With regard to the miniatualized micro-/nano-scale device application, a surface acoustic wave (SAW) device is attracting significant interest because of its long coherent time and high energy density. Recently, phonon-magnon coupling in a SAW resonator with a ferromagnetic thin film was experimentally and numerically studied [4]. This "on-chip SAW cavity" is a promising technology for future quantum circuit using coherent phonon-magnon interaction. For efficient quantum information processing, the phonon-magnon coupling strength should be enhanced by engineering not only ferromagnetic materials but also the film structures.

In this work, we investigate phonon-magnon coupling in a tri-layer synthetic antiferromagnet (SAF) with a non-magnetic layer sandwiched by two ferromagnetic layers integrated into a SAW cavity. The ferromagnetic layers are coupled by an antiferromagnetic interlayer exchange interaction. We use a tri-layer CoFeB/Ru/CoFeB SAF where SAW-spin wave conversion was recently reported [5]. Figure 1 shows a schematic of the study. A tri-layer CoFeB/Ru/CoFeB SAF is placed on the delay line of the SAW cavity, where SAW cavity mode couples with a magnonic mode. We employ a SAW cavity on a piezoelectric $\mathrm{LiNbO_3}$ substrate with a pair of interdigital transducers (IDTs) and Bragg reflectors as shown in Fig. 2. In the presentation, we show the phonon-magnon coupling constant in SAFs and compare the results with model calculations.

This work was supported by JSPS KAKENHI (Nos.20J20952) from JSPS, and JSR Fellowship from The University of Tokyo.

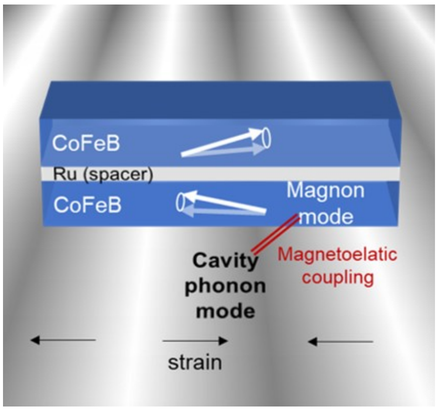

Figure 1: Schematic of the study.

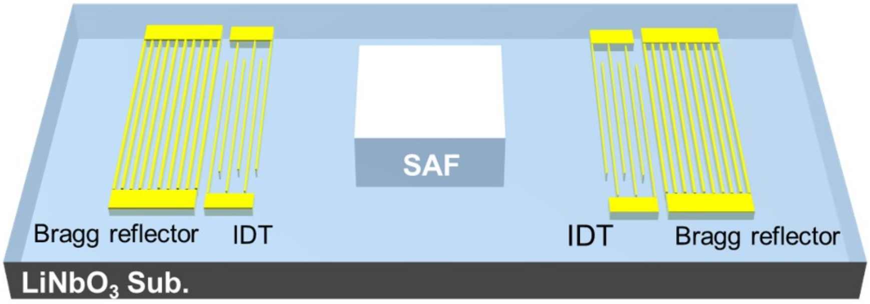

Figure 2: Schematic of the SAW cavity with a SAF.

REFERENCES

[1]X. Zhang, C.-L. Zou, L. Jiang, and H. X. Tang, "Cavity magnomechanics", Sci. Adv. **2**, e1501286 (2016).
[2]M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity optomechanics", Rev. Mod. Phys. **86**, 1391 (2014).
[3]A. Osada, R. Hisatomi, A. Noguchi, et al., "Cavity optomagnonics with spin-orbit coupled photons", Phys. Rev. Lett. **116**, 223601 (2016).
[4]D. Hatanaka, M. Asano, H. Okamoto, et al., "On-chip coherent transduction between magnons and acoustic phonons in cavity magnomechanics", Phys. Rev. Appl. **17**, 034024 (2022).
[5]H. Matsumoto, T. Kawada, M. Ishibashi, M. Kawaguchi, and M. Hayashi, "Large surface acoustic wave nonreciprocity in synthetic antiferromagnets", Appl. Phys. Express. **15**, 063003 (2022).

Hybridized Propagation of Spin Waves and Surface Acoustic Waves in a Multiferroic-Ferromagnetic Heterostructure

Jilei Chen[1,2,3*], Kei Yamamoto[4,5], Jianyu Zhang[2], Ji Ma[6], Hanchen Wang[2], Yuanwei Sun[7], Mingfeng Chen[6], Jing Ma[6], Song Liu[1,3], Peng Gao[7], Dapeng Yu[1,3], Jean-Philippe Ansermet[8], Ce-Wen Nan[6], Sadamichi Maekawa[5,9], Haiming Yu[2,3]
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Coherent coupling in magnon based hybrid systems has many potential applications in quantum information processing. Magnons can propagate in magnetically ordered materials without any motion of electrons, offering a unique method to build low-power-consumption devices and information channels free of heat dissipation. In this talk, I will present the coherent propagation of hybridized modes between spin waves and Love surface acoustic waves (SAWs) in a multiferroic $\mathrm{BiFeO_3}$ and ferromagnetic $\mathrm{La_{0.67}Sr_{0.33}MnO_3}$-based heterostructure [1]. The phase-coherent hybridized modes are observed when the dispersions of spin waves and phonons cross with each other. The magneto-elastic coupling enables a giant enhancement of the strength of the hybridized mode by a factor of 26 compared to that of the pure spin waves. A short wavelength down to 250 nm is demonstrated for the hybridized mode, which is desirable for nanoscale acousto-magnonic applications. Our combined experimental and theoretical analyses represent an important step towards the coherent control in hybrid magnonics, which may inspire the study of magnon-phonon hybrid systems for coherent information processing and manipulation.

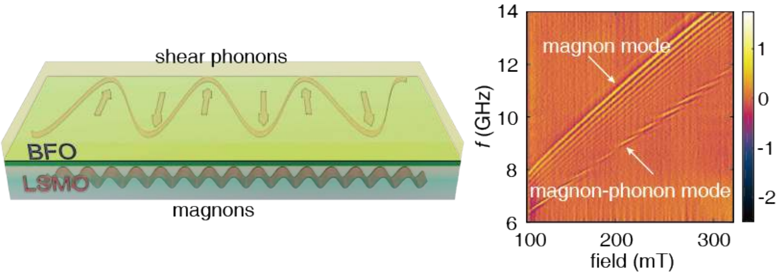

Figure 1: Coherent propagation of hybridized modes between spin waves and Love SAWs.

REFERENCES

[1] J. Chen, K. Yamamoto, J. Zhang, et al., “Hybridized propagation of spin waves and surface acoustic waves in a multiferroic-ferromagnetic heterostructure”, Physical Review Applied **19**, 024046 (2023).

Magnetooptical Investigation of Nonreciprocal Phonon-Magnon Interaction

Yannik Kunz[1,*], **Michael Schneider**[1], **Moritz Geilen**[1], **Philipp Pirro**[1], **Matthias Küß**[2], **Manfred Albrecht**[2], **And Mathias Weiler**[1]
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The coupling of surface acoustic waves (SAWs) with spin waves (SWs) intrinsically breaks the time-inversion symmetry. The resulting nonreciprocity can be exploited for applications such as miniaturized microwave isolators. SAWs can be efficiently excited and detected by interdigital transducers. Therefore, in experiments the magnetic field dependent SAW transmission induced by the coupling of SAWs and SWs is commonly detected via electrical methods [1, 2]. However, for the investigation of magnetoelastic interactions with spatial resolution, magnetooptical measurement methods are needed. We employed microfocused Brillouin light scattering spectroscopy and frequency-resolved magneto-optical Kerr effect spectroscopy [3] to map the spatial dependence of the phonon-magnon-coupling in a $LiNbO_3/Co_{40}Fe_{40}B_{20}$(10 nm)/SiN(5 nm)-structure. Enabled by the spatial resolution of our measurement methods, the increased SAW absorption by the coupling with spin waves is observed (see Figure 1 a)) and characterized by a magnetic field dependent decay rate, revealing the nonreciprocal SAW transmission. The coherent conversion of phonons to magnons is shown and by an increase in the magnon population, peaking with the maximum phonon intensity and vanishing with the decaying SAW (see Figure 1 b)).

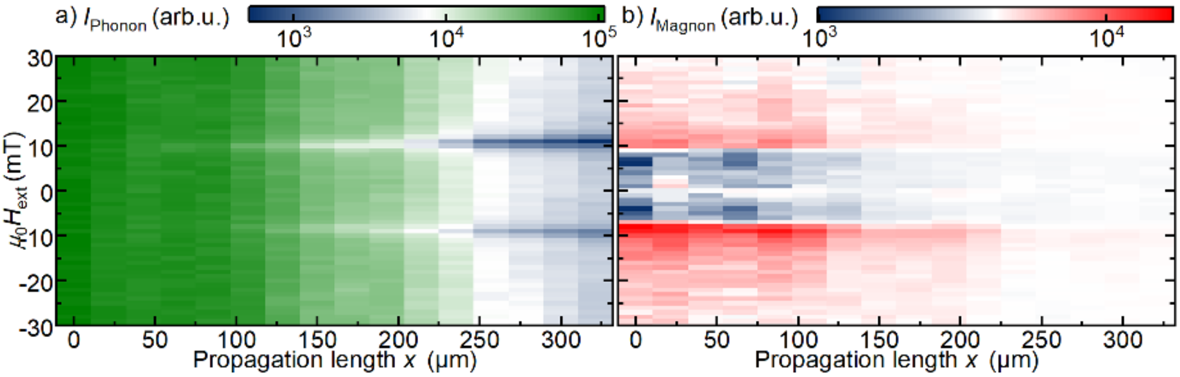

Figure 1: Spatial map of phonon (a) and magnon (b) propagation in a $Co_{40}Fe_{40}B_{20}$ film as a function of external in-plane magnetic field. The SAW is incident from the left ($x = 0$) and absorbed during propagation through the $Co_{40}Fe_{40}B_{20}$ film. Magnons are most efficiently generated at $x = 0$ where SAW amplitude is maximal.

REFERENCES

[1]M. Küß, M. Heigl, L. Flacke, et al., "Nonreciprocal Dzyaloshinskii–Moriya Magnetoacoustic Waves", Physical Review Letters **125**, `10.1103/PhysRevLett.125.217203` (2019).
[2]M. Küß, M. Hassan, Y. Kunz, et al., "Nonreciprocal magnetoacoustic waves in synthetic antiferromagnets with Dzyaloshinskii-Moriya interaction", Physical Review B **107**, `10.1103/PhysRevB.107.024424` (2023).
[3]L. Liensberger, L. Flacke, D. Rogerson, et al., "Spin-Wave propagation in Metallic $Co_{25}Fe_{75}$ Films Determined by Microfocused Frequency-Resolved Magneto-Optic Kerr Effect", IEEE Magnetics Letters **10**, `10.1109/LMAG.2019.2918755` (2019).

Contributed. C15
Wednesday
11:45

Antiferromagnetic Artificial Neuron Modeling of Biological Neural Networks

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Anatomical functions in our bodies are governed by complex neural networks consisting of thousands of interconnected neurons. Understanding the mechanisms behind these networks is a challenging task. However, by replicating these networks with artificial neurons, we can gain a deeper understanding of how biological neural networks work. Furthermore, implementing realistic artificial neural networks in modern electronics can drive the development of bioinspired artificial intelligence and robotics.

Antiferromagnetic (AFM) artificial neurons based on spin Hall oscillators have shown promise in modeling biological neural networks due to their resemblance to biological neurons [1]. When driven by a sub-threshold spin current, these devices produce ultra-short voltage spikes that closely resemble the voltage spikes generated by biological neurons in response to weak external stimuli. In this work, we use the AFM neuron model to simulate the withdrawal reflex, which is a polysynaptic spinal reflex that protects the body from harmful stimuli. This reflex causes the opposing muscles in the same limb to flex and relax in response to sensory stimuli, such as withdrawing our hand when we touch a hot surface without actively thinking about it [2].

The objective of this work is to demonstrate the efficacy of AFM neuron modeling in simulating the withdrawal reflex under various scenarios. To this end, we present the results of our simulations in Figure 1, which illustrate the response of the modeled AFM neurons to weak and strong external stimuli.

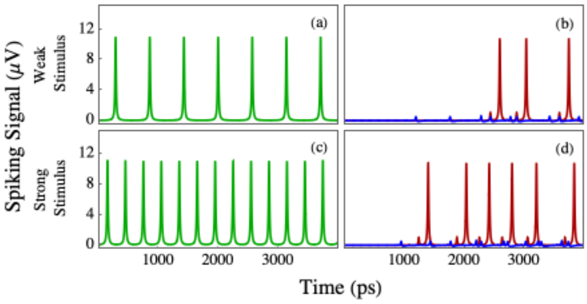

Figure 1: Response to a weak and strong stimulus. (a) Weak sensory input. (b) Motor neurons' response to a weak sensory stimulus. (c) Strong sensory input. (d) Motor neurons' response to a strong sensory stimulus.

Figure 1(a) shows the sensory input for a weak stimulus, while Figure 1(c) shows a strong stimulus. Figures 1(b) and (d) show the reaction of the motor neurons in response to the sensory input. A spike in Figures 1(b) and (d) indicates muscle contracting, while the lack of a spike means the muscle is relaxed. In both Figure 1(b) and (d), one can see that the red muscles contract while the blue muscles relax; causing the limb to move away from the harmful stimulus. Notably, the response to a strong stimulus, Figure 1(d), happens over a nanosecond faster than the response to a weak stimulus, Figure 1(b). This faster response represents the involuntary withdrawal reflex in action. The effectiveness of the withdrawal reflex neural network model demonstrated in this work highlights the potential of AFM neuron modeling for simulating other biological networks in medicine and engineering.

REFERENCES

[1]H. Bradley, S. Louis, C. Trevillian, et al., "Artificial neurons based on antiferromagnetic auto-oscillators as a platform for neuromorphic computing", AIP Advances **13**, 015206 (2023).

[2]P. T. Celena Derderian Karlie R. Shumway, *Physiology, withdrawal response*, [Updated 2022 Nov 20]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2022 Jan.

Nonlinear Chiral Magnonic Resonators: Towards Magnonic Neurons

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We explore chiral magnonic resonators [1] as building blocks of artificial neural networks. Using micromagnetic simulations and analytical modelling, we demonstrate that the first anti-symmetric confined ('dark') mode of a stripe chiral magnonic resonator may exhibit a strongly nonlinear response when resonantly excited by incident spin waves, owing to energy concentration. For modest excitation levels, the effect can be described in terms of a nonlinear shift of the resonant frequency ('detuning'), which results in amplitude-dependent transmission of monochromatic spin waves. This behaviour can be harnessed to realise a sigmoid-like activation, and thus implement artificial neurons in a network linked by spin waves propagating in a linear medium. The nonlinearity is manifested in bistability and hysteresis akin to those occurring in non-linear oscillators [2] when the excitation strength exceeds a threshold set by the decay rate of the mode. In magnonic resonators, the latter includes both the Gilbert damping and the radiative decay due to the coupling with the medium. The results of our simulations are well described by a phenomenological model in which the nonlinear detuning of the confined mode is quadratic in its amplitude, while the propagation in the medium is linear. 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 number 10039217) as part of the Horizon Europe (HORIZON-CL4-2021-DIGITAL-EMERGING-01) under grant agreement number 101070347, and from EPSRC of the UK (projects EP/L019876/1 and EP/T016574/1).

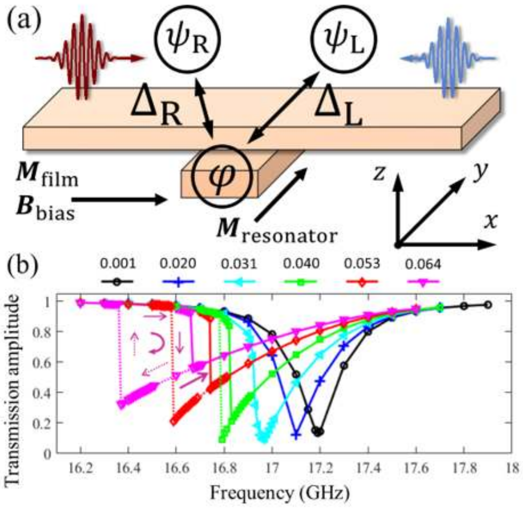

Figure 1: (a) A stripe chiral magnonic resonator under a film magnonic waveguide is shown. The magnetization of the waveguide, $M_{\texttt{film}}$, is aligned along $\hat{x}$ by the bias field, $B_{\texttt{bias}}$, while the resonator's magnetization is aligned along $\hat{y}$ by its shape anisotropy. The resonator supports a local mode $\phi(t,x)$ coupled with coupling strengths Δ_{R} and Δ_{L}, to propagating modes of the waveguide: right-going waves $\psi_{\text{R}}(t,x)$ and left-going waves $\psi_{\text{L}}(t,x)$, respectively. (b) The amplitude of transmission is shown as a function of the incident amplitude for frequencies near the dark mode resonance. In the regime of bistability, the dotted lines show the alternative transmission branch at a given excitation strength, while the arrows indicate the direction of sweeping the excitation frequency.

REFERENCES

[1] V. V. Kruglyak, "Chiral magnonic resonators: rediscovering the basic magnetic chirality in magnonics", Applied Physics Letters **119**, 200502 (2021).

[2] N. N. Bogoliubov and Y. A. Mitropolsky, "Asymptotic methods in the theory of nonlinear random oscillations", (1961).

Contributed. C17
Wednesday
12:15

A Spinwave-Based Ising Machine

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As Moore's law starts to stagnate due to physical limitations, and the amount of processing data continues to grow, alternative analog and digital computing paradigms are being investigated. A large part of modern data processing tasks consists of combinatorial optimization problems and require special purpose accelerators for fast and power efficient computing. Fortunately, Ising machines [1] have emerged as a promising non-von-Neumann computing scheme that can accelerate computation of NP-hard optimization problems.

Here we present a compact and power-efficient time-multiplexed Ising Machine (IM) exploiting spinwave phenomena [2]. The spinwave Ising Machine (SWIM) circuit is a ring oscillator operating in an RF pulsed regime with an additional feedback system implemented with microwave delay cables (Figure. 1). The main loop consists of linear and parametric amplifiers, a YIG spinwave delay line where the spinwave RF pulses propagate, and an RF switch that controls the formation of RF pulses in the ring. The feedback consists of two coupling delay lines implemented with microwave cables followed by a variable phase shifter and an attenuator. A phase-sensitive amplifier (PSA) limits conditions for stable oscillations in the SWIM ring circuit to only RF pulses at either phase 0 or π relative to a pumping reference signal at 6.25 GHz.

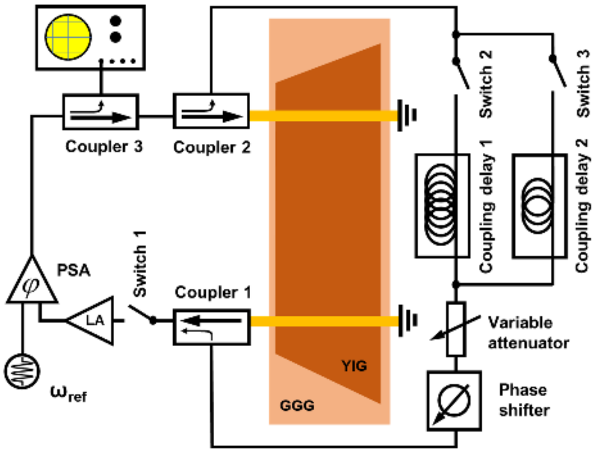

Figure 1: A schematic of a spinwave-based time-multiplexed Ising machine.

We evaluated the computational performance of the SWIM with 4-spin and 8-spin MAX-CUT optimization problems. The weak coupling of –8 dB between nearest neighbour spins is implemented with coupling delay cable 1 and 2, correspondingly. It takes 3.8 μs or 14 circulation periods for SWIM to evolve to a stable and optimal state for MAX-CUT optimization problem. The SWIM consumes only 2 W of power and, therefore, requires only 7 μJ to compute the solution of simple 4-spin and 8-spin MAX-CUT problems.

Our work creates a pathway for miniature low-power and commercially feasible Ising machines for solving a wide range of optimization problems.

REFERENCES

[1]T. Honjo, T. Sonobe, K. Inaba, et al., "100,000-spin coherent ising machine", Science Advances **7**, eabh0952 (2021).
[2]A. Litvinenko, R. Khymyn, V. H. González, et al., "A spinwave ising machine", arXiv preprint arXiv:2209.04291 (2022).

Inverse Design in Magnonics

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Magnonics is an emerging field of science in which many devices have been demonstrated recently, such as frequency (de-)multiplexers, nonlinear units, nonreciprocal diodes, circulators, and an integrated magnonic half-adder [1, 2]. However, the development of each of these devices requires specialized efforts-demanding and complex investigations. Here, we introduce the method of inverse-design magnonics, in which any functionality can be specified first, and a feedback-based computational algorithm is used to obtain the device design [3].

Figure 1a shows the color maps of the normalized spin-wave amplitude in an inverse-designed frequency demultiplexer for different input frequencies. The spin wave of the frequency f_1 = 2.6 GHz is practically entirely guided into the first output waveguide, whereas the signal of the frequency f_2 = 2.8 GHz is almost fully guided into the second output waveguide. The crosstalk between the two frequencies is low ($<$3%). The functionality of the demultiplexer is mainly realized by the multi-path interference in the design region. To analyze the frequency bandwidth of the designed device, the same structure is simulated by sweeping the frequencies from 2.5 GHz to 3 GHz. The transmission spectra at different output waveguides are shown in Fig. 1b. The transmission of frequencies f_1 and f_2 are around 96 % and 80 % and exhibits a broad 3 dB bandwidth of around 120 MHz for both center frequencies. In conclusion, we have developed an inverse-design method for magnonics and demonstrated its capabilities and potential by designing various linear, nonlinear and nonreciprocal magnonic devices.

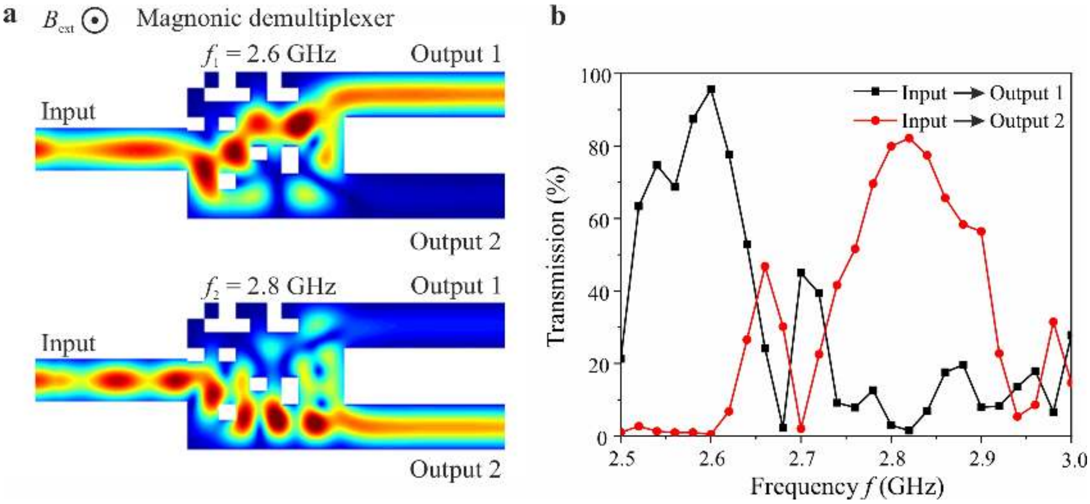

Figure 1: Working principle of inverse-designed magnonic demultiplexer. a, The normalized spin-wave amplitude map. b, The simulated transmission of spin waves towards different output waveguides as a function of frequency simulated for the same optimized structure.

REFERENCES

[1]A. V. Chumak, P. Kabos, M. Wu, and et al., “Advances in magnetics roadmap on spin-wave computing”, IEEE Transactions on Magnetics **58**, 1–72 (2022).
[2]Q. Wang, M. Kewenig, M. Schneider, and et al., “A magnonic directional coupler for integrated magnonic half-adders”, Nature Electronics **3**, 765–774 (2020).
[3]Q. Wang, A. V. Chumak, and P. Pirro, “Inverse-design magnonic devices”, Nature Communications **12**, 2636 (2021).

Exploring Nonlinear Magnon Dynamics via Amplification of Spin Waves Propagating through Mirrored Spin-Wave Concentrators

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Devices in which magnons are amplified –passively and for long durations– provide an attractive means to interface magnonic systems with current computing infrastructures. Recent studies demonstrate a doubling of the magnon signal amplitude six microns away from the amplifier[1]. While this compensates for signal decay due to damping, the current value isn't sufficient to revolutionize the field.

We fabricate funnel structures with yttrium iron garnet (YIG)[2] which concentrate spin waves to a focus, ready for further manipulation. With such concentrators, we increase the magnon signal amplitude by a factor of 22.8, an order of magnitude greater than current state-of-the-art methods (see Figure. 1.)

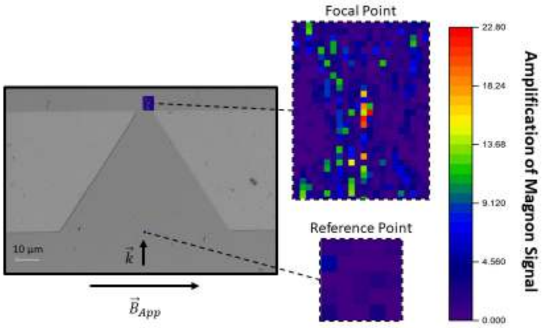

Figure 1: Measured spin-wave amplification of 22.8 through YIG spin-wave concentrator at 3.685 GHz under an applied field of 68.3 mT, relative to the reference point. The focus is 97 microns beyond the excitation antenna.

Expanding upon this spin-wave concentrator concept by mirroring two suggests a number of exciting applications (see Figure 2). For example, two counter-propagating magnon signals could interfere in the middle, allowing one to detect the phase difference between two RF antennas through a purely magnonic signal.

Figure 2: Design of the mirrored spin-wave lenses.

Another example is to use the mirrored devices to provide an efficient way to study magnonic nonlinearties. Precisely tuning the excitation frequency in situ also tunes the foci of both funnels, where they can conceivably overlap to create an extreme amplification of magnon signal. Accordingly, this geometry can effectively explore nonlinear magnon dynamics via a relatively simple device.

REFERENCES

[1]J. Gräfe, P. Gruszecki, M. Zelent, et al., "Direct observation of spin-wave focusing by a fresnel lens", Physical Review B **102** (2020).
[2]F. Heyroth, C. Hauser, P. Trempler, et al., "Monocrystalline freestanding three-dimensional yttrium-iron-garnet magnon nanoresonators", Physical Review Applied **12** (2019).

Contributed. C20
Thursday
09:30

Creation of Nonlinear Magnon Polaritons

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Polaritons are quasiparticles arising from strong coupling between electromagnetic waves and other dipole-carrying excitation. Magnon polaritons are one of them, resulting from strong interaction between electromagnetic waves (photons) and magnons. By confining photons in a microwave resonator and placing a magnet with a large filling factor, the coupling strength of photons and magnons can be strongly enhanced to form such a hybrid state. At this condition, we observe avoided crossing where hybridised states split into two, analogous to bonding and anti-bonding states of hydrogen molecules. In a rapidly growing field of cavity magnonics [1], magnon polaritons can be used for operating gradient memories, probabilistic-bits, or to distill the entanglement of interacting magnons. It also realizes (quantum) information transfer between a localized spin system and a distant superconducting qubit.

The central aim of this study is to experimentally and theoretically study how nonlinear spin-wave interactions influence the formation of magnon polaritions. Excitation of magnetic media, magnon, has nonlinear and rich dispersion relationships, distinctly different from other dynamical systems such as photons and phonons. This is due to two dissimilar magnetic interactions, dipole and exchange, each dominating the magnon dispersion in long and short wavelength limits, respectively. The magnetic dipole interaction offers directional-dependent dispersion in a thin-film magnet, being a backbone of spin-wave physics and applications, i.e. magnonics.

The magnon dispersion determines multi-magnon processes, hence equilibrium and dynamics of spin-wave states. Multi-magnon processes connect different modes in magnon spectra and facilitate nonlinear processes of spin-wave excitations associated with energy flows in individual modes. Three magnon splitting processes are one of the nonlinear spin-wave interactions where one magnon splits into two counter-propagating magnons with half the energy of the original magnon. We can experimentally control this splitting process by tuning applied magnetic field and excitation power and so it is a useful lab tool to investigate the nonlinear spin-wave interaction for any new phenomena/effects. We performed the strong coupling experiments between an on-chip microwave resonator and an yttrium iron garnet (YIG) film where the three magnon splitting can be controllably generated [2]. We successfully observe clear avoided crossing in our experiments when the photon and magnon modes are brought to resonate together. When we activate the three-magnon splitting process by increasing the excitation microwave power, we observe the change of the hybridisation gap and eventually complete gap closure at high excitation. We use the rate equation of motion for both photon and magnon modes to reproduce spectra observed experimentally and use the model to explain the underlying mechanism of our observation.

REFERENCES

[1]B. Zare Rameshti, S. Viola Kusminskiy, J. A. Haigh, et al., "Cavity magnonics", Physics Reports **979**, 1–61 (2022).
[2]O. Lee, K. Yamamoto, M. Umeda, et al., "Nonlinear magnon polaritons", Phys. Rev. Lett. **130**, 046703 (2023).

All-Electrical and Spin Seebeck Effect Driven Magnon Transport in Quasi-Two-Dimensional Antiferromagnetic Materials $CrPS_4$ and $MnPS_3$.

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Magnon spintronics studies the transport of spin currents through an insulating and magnetically ordered material using magnons[1]. Electrically and thermally induced magnons can be transported in insulating ferromagnetic[2] and antiferromagnetic materials[3]. In particular, antiferromagnetic materials have interesting properties for future spintronic applications: they possess no net magnetic moment and are therefore robust against magnetic perturbations and have ultrafast dynamics. We investigate the transport of magnons in the insulating antiferromagnetic van der Waals materials: $MnPS_3$, and $CrPS_4$. The spin currents are injected electrically, via the spin Hall effect, and thermally, via the spin Seebeck effect, and detected via the inverse spin Hall effect and inverse anomalous Hall effect using the nonlocal geometry as described in Ref.[2] and [4]. We demonstrate for the first time all-electrical long-distance magnon spin transport in $CrPS_4$ with perpendicular magnetic anisotropy. We monitor the non-local resistance as a function of an in-plane magnetic field up to 8 Tesla and observe magnon transport over distances up to at least a micron below the Neel temperature (T_N = 38 Kelvin) close to magnetic field strengths that saturate the sublattice magnetizations [5]. Furthermore, in $MnPS_3$ we show the detection of magnons generated by the spin Seebeck effect before and after the spin flop transition where the signal reversal of the magnon spin accumulation agrees with the out of plane spin polarization carried by magnon modes before and after the spin flop transition [6, 7]. These results herald the potential of 2D van der Waals magnets for scalable magnonic circuits.

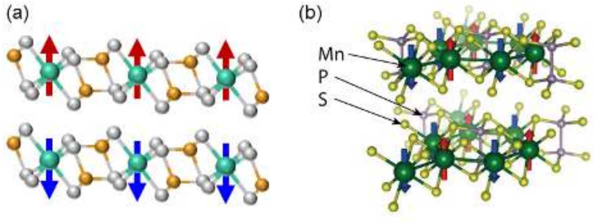

Figure 1: (a) Spin texture of $CrPS_4$, (b) Spin texture of $MnPS_3$

REFERENCES

[1] A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, “Magnon spintronics”, en, Nature Physics **11**, 453–461 (2015).

[2] L. J. Cornelissen, J. Liu, R. A. Duine, J. B. Youssef, and B. J. van Wees, “Long-distance transport of magnon spin information in a magnetic insulator at room temperature”, en, Nature Physics **11**, 1022–1026 (2015).

[3] R. Lebrun, A. Ross, S. A. Bender, et al., “Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide”, en, Nature **561**, 222–225 (2018).

[4] K. S. Das, J. Liu, B. J. van Wees, and I. J. Vera-Marun, “Efficient Injection and Detection of Out-of-Plane Spins via the Anomalous Spin Hall Effect in Permalloy Nanowires”, en, Nano Letters **18**, 5633–5639 (2018).

[5] D. K. de Wal, A. Iwens, T. Liu, et al., “Long distance magnon transport in the van der Waals antiferromagnet CrPS4”, Publisher: arXiv Version Number: 1, `10.48550/ARXIV.2301.03268` (2023).

[6] F. Feringa, G. E. W. Bauer, and B. J. van Wees, “Observation of magnetization surface textures of the van der Waals antiferromagnet FePS 3 by spin Hall magnetoresistance”, en, Physical Review B **105**, 214408 (2022).

[7] F. Feringa, J. M. Vink, and B. J. van Wees, “Spin-flop transition in the quasi-two-dimensional antiferromagnet MnPS 3 detected via thermally generated magnon transport”, en, Physical Review B **106**, 224409 (2022).

Spin Wave Assisted Switching of Permalloy Nanomagnets on Yttrium Iron Garnet

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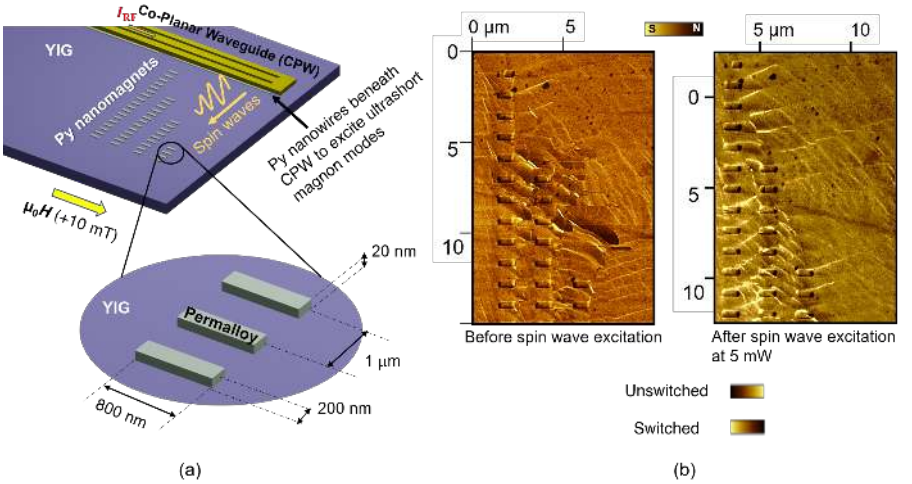
Spin wave based computing is gaining an increasing attention from the researchers working on Boolean spin wave logic as well as unconventional computing paradigms [1]. A nanoscale neural network with interference of nonlinear spin waves was recently proposed by Papp et al. [2]. The upcoming computing paradigms are linked with a key aspect, a re-configurable nonvolatile memory element. Baumgaertl et al. [3] demonstrated magnetization switching of 25 and 27 μm long Permalloy (Py) stripes when spin waves in the underlying ferrimagnet yttrium iron garnet (YIG) were excited by a microwave antenna. To realize a fully re-configurable magnonic memory, the magnetization switching of nanostructured ferromagnets needs to be achieved by propagating spin waves.

We prepared 200-nm-wide and 800-nm-long nanomagnets on 113-nm-thick YIG (Fig. 1). We systematically investigated the power-dependent sequence of switching of the 20-nm-thick nanomagnets positioned at an increasing distance from the spin-wave emitting antenna. The nanomagnets switched at a small applied field of 10 mT only when we excited spin waves between 10 MHz to 20 GHz at a certain threshold power (P_{irr}) using a Vector Network Analyzer. We observed that the distance to which the nanomagnets switched increased with increasing P_{irr} up to 5 mW. Interestingly for a higher power of $P_{\mathrm{irr}} = 10$ mW, the remanent state of some nanomagnets did not seem to change. This observation needs further investigation. Our results are a promising step towards developing a reconfigurable memory for realizing all magnon based computing devices. The work is supported by SNSF via grant 197360.



(a) (b)

Figure 1: (a) Sketch of the device investigated for the switching of Py nanomagnets (gray) using spin wave excitation in 113 nm thick YIG (purple). (b) Magnetic Force Microscopy images showing the state of the nanomagnets before (left) and after (right) spin wave excitation.

REFERENCES

[1]A. V. Chumak et al., "Advances in magnetics roadmap on spin-wave computing", IEEE Transactions on Magnetics **58**, 1–72 (2022).
[2]Á. Papp, W. Porod, and G. Csaba, "Nanoscale neural network using non-linear spin-wave interference", Nature Communications **12**, `10.1038/s41467-021-26711-z` (2021).
[3]K. Baumgaertl and D. Grundler, *Reversal of nanomagnets by propagating magnons in ferrimagnetic yttrium iron garnet enabling nonvolatile magnon memory*, 2022.

Arbitrary Quantum State Generation of Magnons

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Quantum magnonics is interesting because of its potential for magnon-based quantum computing, transducers, magnetic field sensing, etc. It is pioneered by a recent demonstration of single magnon detection by putting a magnet in a cavity quantum electrodynamics (cQED) setup consisting of a microwave cavity and a transmon [1]. Achieving quantum advantage in such applications require a controlled way to generate appropriately chosen quantum states of the magnetization, e.g. a superposition of Fock states increases the sensitivity of sensing. In [2], we discussed and numerically evaluated a protocol to deterministically create an arbitrary quantum state of the magnetization in the same setup as in [1], see Fig. 1.

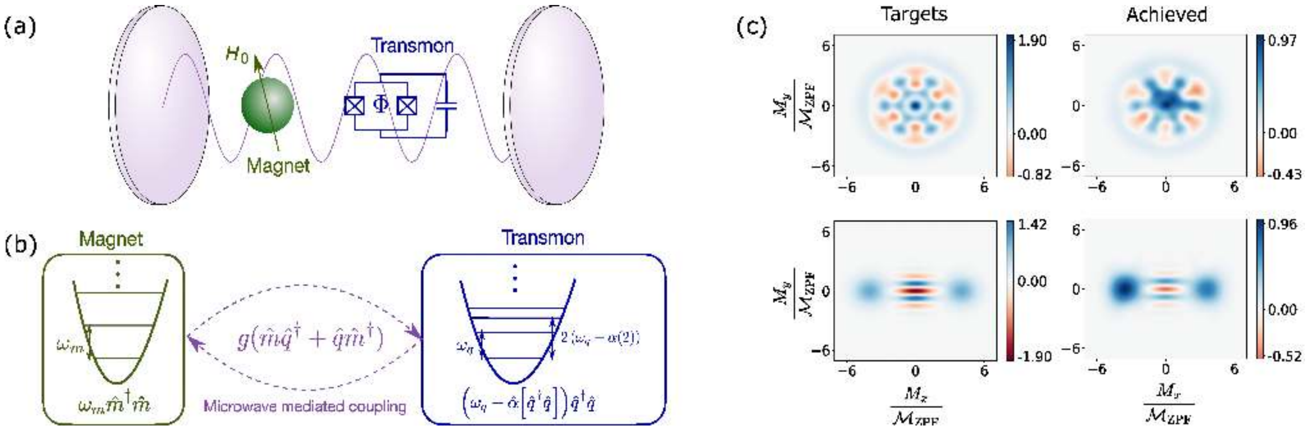

Figure 1: (a) cQED setup loaded with a magnet with H_0 being an external magnetic field and Φ being flux through the SQUID loop. (b) Effective model of a magnon (harmonic oscillator) coupled to a transmon (anharmonic oscillator) with magnon frequency ω_m, transmon frequency ω_q, transmon anharmonicity function α, and coupling g. (c) Wigner functions of target and achieved states in two cases: superposition of Fock states $|0\rangle + |6\rangle$ and superposition of coherent states $|\alpha/2\rangle + |-\alpha/2\rangle$ with $\alpha = 4$. $\mathcal{M}_{ZPF}$ is a measure of the zero-point fluctuations of the magnetization components M_x and M_y.

The protocol involves repeatedly exciting the transmon and transferring the excitations to the magnet via a microwave cavity. To avoid decay, the protocol must be shorter than the magnon's lifetime. Speeding up the protocol by simply shortening the pulses leads to non-resonant leakage of excitations to higher levels of the transmon accompanied by higher decoherence. We discuss how to correct for such leakages by applying counter pulses to de-excite these higher levels. In our protocol, states with a maximum magnon occupation of up to ~ 9 and average magnon number up to ~ 4 can be generated with fidelity > 0.75.

REFERENCES

[1] D. Lachance-Quirion, Y. Tabuchi, S. Ishino, et al., “Resolving quanta of collective spin excitations in a millimeter-sized ferromagnet”, Science Advances **3**, `10.1126/sciadv.1603150` (2017).

[2] S. Sharma, V. S. V. Bittencourt, and S. V. Kusminskiy, “Protocol for generating an arbitrary quantum state of the magnetization in cavity magnonics”, Journal of Physics: Materials **5**, 034006 (2022).

Contributed. C24
Thursday
12:00

Magnetization Dynamics Affected by Phonon Pumping

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Combining phonons with ultralow attenuation with the tunability of magnetic excitations outlines a promising path for improving magnon-based applications [1, 2]. However, to optimally merge phononics and magnonics, a full understanding of the magnon-phonon coupling needs to be established in order to engineer the coupling strength. In 2018, Streib et al. predicted that in heterostructures of a magnetic insulator and a nonmagnetic insulator an additional contribution to the magnetic damping arises from the emission of phonons into the nonmagnetic substrate, proportional to the magnon-phonon coupling strength within the magnetic insulator [3].

I will present evidence for the pumping of phonons in high-resolution ferromagnetic resonance investigations of yttrium iron garnet (YIG) on gadolinium gallium garnet (GGG) substrates, showing that these two effects are reliant on the same physical mechanism [4]. Characterizing the ferromagnetic resonance in a wide frequency range, we can observe both, the high cooperativity regime, where magnons and phonons hybridize into magnon-polarons [5], and the incoherent regime, where the pumped phonons constitute a dissipative flow of energy away from the magnetic system, verifying the predictions by Streib et al.. Additionally, we confirm that the magnon-phonon coupling can be straightforwardly understood by considering the overlap integral of the magnon and phonon amplitude profile across the film thickness [6].

REFERENCES

[1] Y. Li, C. Zhao, W. Zhang, A. Hoffmann, and V. Novosad, “Advances in coherent coupling between magnons and acoustic phonons”, en, APL Materials **9**, 060902 (2021).

[2] D. A. Bozhko, V. I. Vasyuchka, A. V. Chumak, and A. A. Serga, “Magnon-phonon interactions in magnon spintronics (Review article)”, en, Low Temperature Physics **46**, 383–399 (2020).

[3] S. Streib, H. Keshtgar, and G. E. W. Bauer, “Damping of Magnetization Dynamics by Phonon Pumping”, Physical Review Letters **121**, 027202 (2018).

[4] R. Schlitz, L. Siegl, T. Sato, et al., “Magnetization dynamics affected by phonon pumping”, en, Physical Review B **106**, 014407 (2022).

[5] K. An, A. N. Litvinenko, R. Kohno, et al., “Coherent long-range transfer of angular momentum between magnon Kittel modes by phonons”, Physical Review B **101**, 060407(R) (2020).

[6] A. Litvinenko, R. Khymyn, V. Tyberkevych, et al., “Tunable Magnetoacoustic Oscillator with Low Phase Noise”, Physical Review Applied **15**, 034057 (2021).

Magnon-Mediated Entanglement of Solid-State Spin Qubits

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Recently, spin centers in solids have attracted significant attention due to their applications to quantum information science. However, to be able to create entanglement between NVs one requires having NVs coupled to each other. Unfortunately, the bare interaction between two NV centers is week for separations > 20 nm. This creates a key challenge once NV centers cannot be optically resolvable at these distances. Therefore, providing alternative schemes to couple two NV centers over long distances became crucial to enable their use in quantum computation. Here we propose hybrid quantum systems [Fig. 1(a)] that couple and entangle spin centers over micron length scales through the quantized spin-wave excitations (magnons) of a magnetic material [1, 2]. These magnons serve as a quantum bus that transfers the information between different NV-qubits. We predict strong long-distance (μ m) NV-NV coupling via magnon modes with cooperativities exceeding unity in ferromagnetic bar, waveguide and cylindrical structures[1, 2]. Moreover, we explore and compare on-resonant transduction and off-resonant virtual-magnon exchange protocols [Fig. 1(b)], and discuss their suitability for generating or manipulating entangled states under realistic experimental conditions[2]. Due to the absence of magnon occupation decay of the off-resonant protocol, our results show this protocol is robust at temperatures up to $T \approx 150$ mK[2]. Conversely, at lower temperatures the on-resonant protocol shows a faster gate operation, and can even outperform the off-resonance protocol for small magnon damping parameters [Fig. 1(c)] [2]. Our results will guide future experiments that aim to engineer on-chip long-distance entangling gates between spin centers mediated by magnons. This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences under Award Number DE-SC0019250 (DC and MEF), the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers (DDA) and the Vannevar Bush Faculty Fellowship ONR N00014-17-1-3026 (MF and DDA).

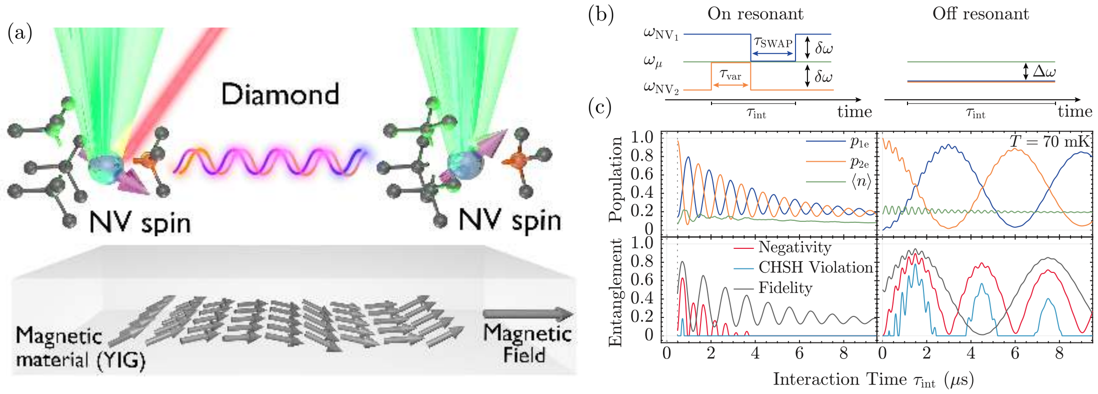

Figure 1: (a) Schematic view of the strong quantum-coherent coupling between different NV-center spins through YIG magnon mode. (b) On and off-resonant entanglement protocols. (c) Comparison of the two protocols at $T = 70$ mK. The red, sky blue, and gray curves are the entanglement negativity scaled by the Bell state's negativity, the degree of the Bell inequality violation (violated if the curve is above zero), and the fidelity to the target pure entangled states, respectively.

REFERENCES

[1] D. R. Candido, G. D. Fuchs, E. Johnston-Halperin, and M. E. Flatté, "Predicted strong coupling of solid-state spins via a single magnon mode", Materials for Quantum Technology **1**, 011001 (2020).

[2] M. Fukami, D. R. Candido, D. D. Awschalom, and M. E. Flatté, "Opportunities for long-range magnon-mediated entanglement of spin qubits via on- and off-resonant coupling", PRX Quantum **2**, 040314 (2021).

Posters

Antenna Design for Spin Wave Caustic Beams

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The manipulation of spin waves in thin ferromagnetic films is a key aspect for the development of magnonic devices [1]. Provided with unique anisotropic dispersion relations, a peculiar focused emission of spin waves, also referred to as caustic beams, occurs in in-plane magnetized films when the suitable conditions of field and frequency meets an inflection point in the dispersion relation [2]. So far, caustic beams were solely observed in geometries where a narrow spin wave conduit reaches an extended plane [3], the junction acting as a diffractive source. In this communication, we extend our model of near-field diffraction of spin waves [4] to in-plane modes, and show how caustic beams can be directly emitted from a sufficiently sharp constriction in a stripline. The obtained near-field interference patterns reproduce satisfyingly the corresponding MuMax3 micromagnetic simulations. In particular, we show that the comparison is all the better the thinner the film, as our present approach does not account for the non-reciprocity in amplitude across the thickness. This model constitutes a robust tool to explore magnon beamforming allowing probing efficiently a wide range of parameter such as field, frequency, magnetic properties, shape and scale of antenna.

This work was supported by the French ANR project ”MagFunc” and the Département du Finistère through the project “SOSMAG”.

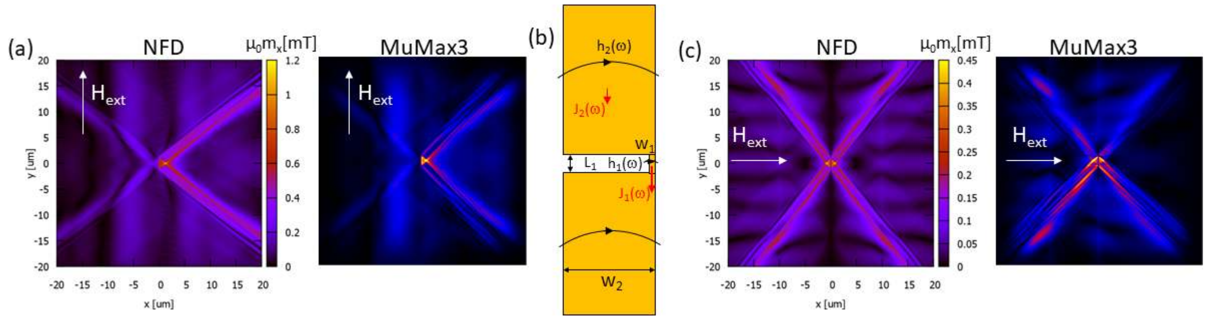

Figure 1: Near-Field diffraction (NFD) and micromagnetic (MuMax3) simulations of caustic beams from a w=200 nm wide and L=2μm long constriction for μ_0H$_{ext}$=50mT, and f=3.2GHz. (a) H$_{ext}$ is along the y-axis. (c) H$_{ext}$ is along the x-axis. (b) Sketch of the constriction geometry.

REFERENCES

[1] E. Albisetti, S. Tacchi, R. Silvani, et al., “Optically inspired nanomagnonics with nonreciprocal spin waves in synthetic antiferromagnets”, Advanced Materials **32**, 1906439 (2020).

[2] V. Veerakumar and R. E. Camley, “Magnon focusing in thin ferromagnetic films”, Physical Review B **74**, `10.1103/physrevb.74.214401` (2006).

[3] T. Schneider, A. A. Serga, A. V. Chumak, et al., “Nondiffractive subwavelength wave beams in a medium with externally controlled anisotropy”, Physical Review Letters **104**, `10.1103/physrevlett.104.197203` (2010).

[4] V. Vlaminck, L. Temdie, V. Castel, et al., “Spin wave diffraction model for perpendicularly magnetized films”, Journal of Applied Physics **133**, 053903 (2023).

Wave Vector Dependence of the Relaxation Time for Exchange Spin Waves

Loic Temdie[1,2,*], **Vincent Castel**[1,2], **Carsten Dubs**[3], **Hicham Majjad**[4], **Romain Bernard**[4], **Yves Henry**[4], **Matthieu Bailleul**[4], **Vincent Vlaminck**[1,2]
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The field of magnonic constitutes a formidable ground in the context of miniaturizing and integrating non-reciprocal microwave components such as circulators, isolators, and phase shifters [1]. Recently, unidirectional transmission of exchange spin waves down to $60\,nm$ wavelength was achieved by taking advantage of the chiral coupling between the uniform resonance of ferromagnetic nanowires coupled with thin YIG films [2, 3].
In this communication, we implement this method to study the wave vector dependence of the relaxation time of dipole-exchange spin waves over a broad range of wavevectors k=[0 - 100 $rad.\mu m^{-1}$]. We performed spin wave spectroscopy in the Damon Eshbach configuration on several devices consisting of a w=$200\,nm$ width, t=$60\,nm$ thick, and a=$400\,nm$ lattice spacing of lithographed permalloy (Ni$_{80}$Fe$_{20}$) nanowires arrays on top of a $55\,nm$ thick YIG film (see Fig. 1-a). We aligned pairs of λ_{CPW}=$5\mu m$ wavelength coplanar waveguide on top the nanowires at various distance D=[10-$20\mu m$] for the transduction of spin waves. The frequency-field mapping of the transmission spectra for these devices shown in Fig. 1-b reveals two types of non-reciprocal transmission. At higher frequency, we attribute the perfectly unidirectional transmission to the chiral excitation of wavevectors (k_{NW}) by the nanowires arrays, while at lower frequencies, the partial non-reciprocity observed suggest that these wavevectors (k_{CPW}) are directly excited by the rf field of the antenna. We then fit the separation distance (D) dependence of the amplitudes and the oscillation frequencies of theses transmission spectra in order to extract the attenuation length $L_{att}(k,H)$ and the group velocity $V_g(k,H)$ for all wavevectors [4]. Finally, we plot the k-dependence of the relaxation time defined as: $\tau(k,H)$=$L_{att}(k,H)$/$V_g(k,H)$ (see Fig. 1-c), and observe its decreases both the wavevector and the bias field increase. We obtain a good agreement with theoretical expressions of the relaxation time derived from Kalinikos-Slavin formalism.

This work was supported by the French ANR project "MagFunc" and the Departement du Finistere through the project "SOSMAG"

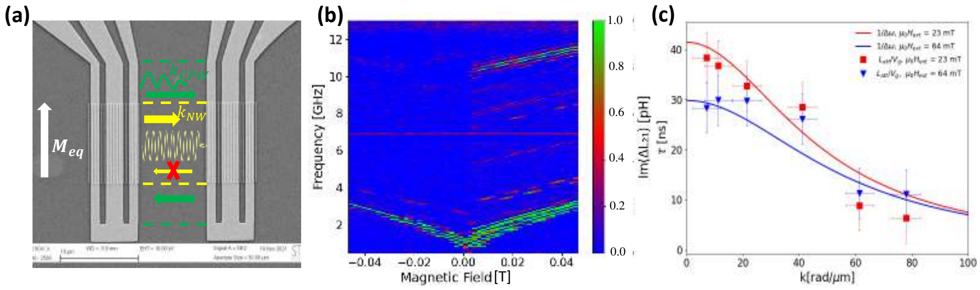

Figure 1: (a) SEM image of Ni$_{80}$Fe$_{20}$ NWA, w=$200\,nm$ width and a=$400\,nm$ lattice constant grown on top of $55\,nm$ thick YIG film. (b) Mapping of imaginary part of transmission spectra ΔL_{21}. (c) Comparison of measured relaxation time with analytical expression for 23 mT and 64 mT applied field.

REFERENCES

[1] A. B. et al., "The 2021 magnonics roadmap", Journal of Physics: Condensed Matter **33**, 413001 (2021).
[2] J. Chen and T. Y. et al., "Excitation of unidirectional exchange spin waves by a nanoscale magnetic grating", Physical Review B **100**, `10.1103/physrevb.100.104427` (2019).
[3] L. Temdie, V. Castel, C. Dubs, et al., "High wave vector non-reciprocal spin wave beams", AIP Advances **13**, 025207 (2023).
[4] N. Loayza and M. B. J. et al., "Fresnel diffraction of spin waves", Physical Review B **98**, `10.1103/physrevb.98.144430` (2018).

Poster 1. PA03
Monday
16:30

Caustic Spin Wave Beams in an Extended Thin Film Excited by a Nanoconstriction

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The ability to control the directionality of spin waves is important for magnonic logic and computing applications. Here, we demonstrate the emission of caustic-like spin waves in an extended 200 nm thick yttrium iron garnet (YIG) film from a nano-constricted rf waveguide. Caustic-like spin waves exhibit an anisotropic nature of the spin-wave dispersion which occurs when the direction of the spin wave-group velocity and spin-wave wavevector do not coincide [1].

Using spatially resolved micro-focused Brillouin light spectroscopy (BLS) in both the backward volume and the Damon-Eshbach geometry, we reveal the propagation of two directional spin-wave beams directly emitted from the nanoconstriction. We find, on one hand, that these beams are symmetric in intensity when the rf magnetic field is perpendicular to the applied magnetic field, as is shown in Fig. 1(a). On the other hand, one beam is more intense than the other when the rf magnetic field is parallel to the external field, as is shown in Fig. 1(b). We attribute this asymmetry in the latter configuration to a sign change of the perpendicular component of the wavevector with respect to the bias field direction. Namely, k_{x} remains the same when the equilibrium direction is along y, while $\mathrm{k_y}$ changes sign when $\mathrm{H_{ext}}$ is applied along the x-axis. Furthermore, we study the frequency dependence of the propagation of these caustic-like spin-wave beams. The experimental results agree well with both micromagnetic simulation, and the near-field diffraction model applied to in-plane spin-wave modes [2, 3]. Our findings have important implications for the development of switchable spin-wave splitters, passive spin-wave frequency-division demultiplexers, and magnonic interferometry.

This work was supported by the French ANR project MagFunc, the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award DE-SC0020308, and the Transatlantic Research Partnership, a program of FACE Foundation and the French Embassy.

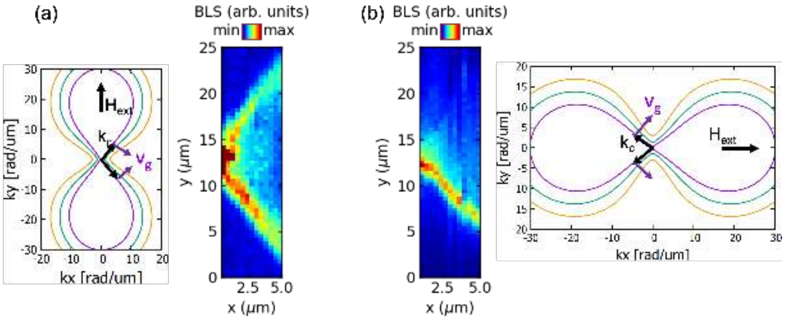

Figure 1: Spatially-resolved BLS of spin-wave caustic in an extended YIG thin film from a nano-constricted rf waveguide at 185 mT external field and 7.5 GHz frequency when rf magnetic field is (a) perpendicular and (b) parallel to the external field.

REFERENCES

[1]T. Schneider, A. A. Serga, A. V. Chumak, et al., Phys. Rev. Lett. **104**, 1 (2010).
[2]N. Loayza, M. B. Jungfleisch, A. Hoffmann, M. Bailleul, and V. Vlaminck, “Fresnel diffraction of spin waves”, Phys. Rev. B **98**, 144430 (2018).
[3]V. Vlaminck, L. Temdie, V. Castel, et al., “Spin wave diffraction model for perpendicularly magnetized films”, J. Appl. Phys. **133**, 053903 (2023).

Poster 1. PA04
Monday
16:30

Spin and Charge Pumping in the Presence of Spin-Orbit Coupling in THz Spintronics with Antiferromagnets

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The interaction of fs light pulses with magnetic materials has been intensely studied for more than two decades in order to understand ultrafast demagnetization in single magnetic layers or THz emission from their bilayers with nonmagnetic spin-orbit (SO) materials. Despite long history, microscopic understanding of ultrafast-light-driven magnets is incomplete due to numerous competing effects and with virtually no study reporting calculation of output THz radiation. This talk presents a recently developed [1] *multiscale quantum-classical formalism*—where conduction electrons are described by quantum master equation of the Lindblad type; classical dynamics of local magnetization is described by the Landau-Lifshitz-Gilbert (LLG) equation; and incoming light is described by classical vector potential while outgoing electromagnetic radiation is computed using Jefimenko equations for retarded electric and magnetic fields. We illustrate it by application to a bilayer of Weyl antiferromagnet Mn_3Sn with noncollinear local magnetization in contact with SO-coupled nonmagnetic material, revealing new mechanisms of THz radiation due to direct charge pumping by local magnetization dynamics of Mn_3Sn in the presence of its strong intrinsic SO coupling [Fig. 1(a)]. The simplest example of dynamics of magnetization leading to spin and charge pumping is that of uniformly precessing local magnetization within ferro- or antiferromagnets, which we show how to handle *in the presence of SO coupling* using the Floquet-Keldysh formalism [2] with possible first-principles Hamiltonian as an input [3]. This yields a new prediction of high harmonics [2] in pumped spin and charge currents due to peculiar motion of flowing electron spins generated by the SO coupling [Fig. 1(b)].

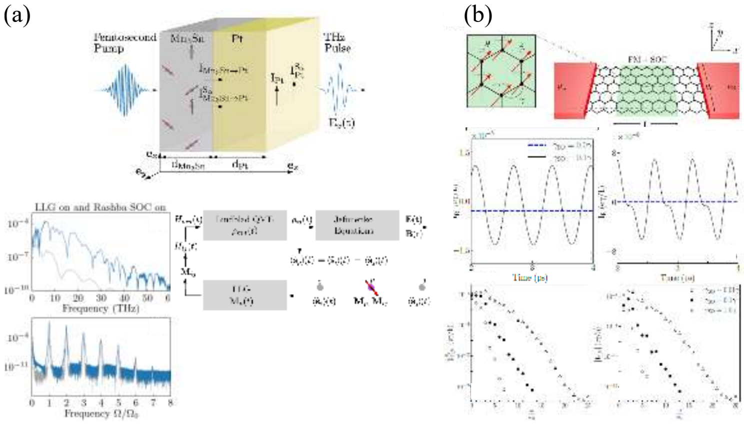

Figure 1: (a) Schematic view of ultra-fast-light driven Weyl antiferromagnet Mn_3Sn/Pt bilayer whose THz and high harmonic emission is computed using QME+LLG+Jefimenko quantum-classical formalism [1]. (b) Schematics view of two-dimensional ferromagnet whose precessing magnetization at the ferromagnetic resonance is pumping spin and charge currents at many high harmonics of the precession frequency in the presence of spin-orbit coupling [2].

REFERENCES

[1] A. Suresh and B. K. Nikolic, *Quantum-classical approach to spin and charge pumping and the ensuing radiation in thz spintronics with example of ultrafast-light-driven weyl antiferromagnet mn_3sn*, 2022.

[2] J. Varela-Manjarres and B. K. Nikolić, “High-harmonic generation in spin and charge current pumping at ferromagnetic or antiferromagnetic resonance in the presence of spin-orbit coupling”, arXiv:2112.14685, `10.48550/ARXIV.2112.14685` (2021).

[3] K. Dolui, A. Suresh, and B. K. Nikolić, “Spin pumping from antiferromagnetic insulator spin-orbit-proximitized by adjacent heavy metal: a first-principles floquet-nonequilibrium green function study”, Journal of Physics: Materials **5**, 034002 (2022).

Amplification of Electron-Mediated Spin Currents by Stimulated Spin Pumping

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Amplification of spin currents is attractive for fundamental research and practical applications. It has been recently discussed in the context of magnonic spin currents [1, 2]. However, amplification of spin currents that are mediated by electron transport is less familiar. Here we propose a stimulated spin pumping mechanism for amplifying AC electronic spin currents in a solid-state magnetic medium. The mechanism closely resembles the optical stimulated emission process during which a coherent photon is created. In the interaction, auto oscillations in a ferromagnet are excited by the DC spin Hall effect, as depicted in Fig. 1(a). Depending on the DC bias level, the pumped spin current amplifies or absorbs the injected AC spin current mimicking the operation of the optical gain medium as seen from the gain saturation characteristics in Fig. 1(b).

Our findings stimulate further connections between well-established concepts from laser physics and spintronics technology. For example, a saturable spin current absorber that gives rise to a mode-locked spin current emission capable of exerting a torque that is stronger than observed to date may be considered. Future work should relate to spatially distributed traveling wave propagation effects and, most importantly, to the experimental realization of the spin current amplifier.

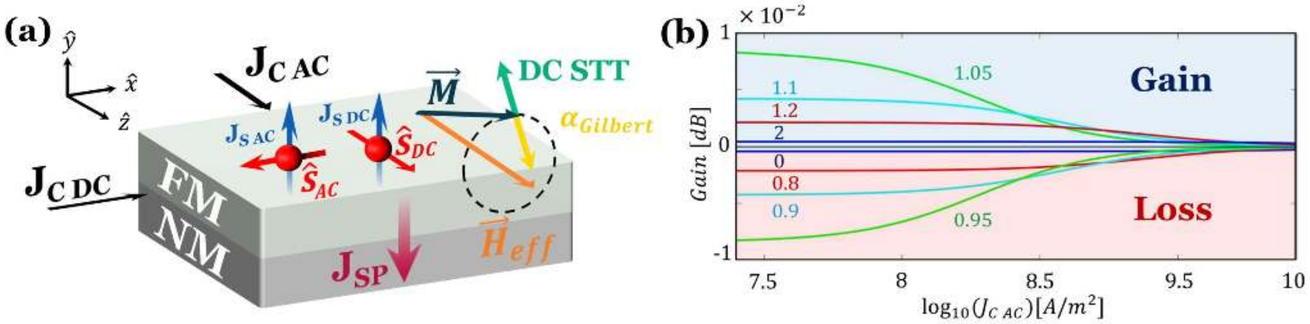

Figure 1: (a) Normal-metal / ferromagnet bilayer DC spin-transfer-torque based spin current amplification scheme. (b) Gain saturation profiles for J_{DC} of $0 - 2J_{STT}$, where J_{STT} is the DC current density required to excite self-oscillations in the ferromagnet. Symmetric J_{DC} values with respect to $J_{STT}CC$ are plotted with the same color code. Figures adopted from [3].

REFERENCES

[1]T. Brächer, P. Pirro, and B. Hillebrands, "Parallel pumping for magnon spintronics: amplification and manipulation of magnon spin currents on the micron-scale", Physics Reports **699**, 1–34 (2017).
[2]D. Malz, J. Knolle, and A. Nunnenkamp, "Topological magnon amplification", Nature Communications **10**, `10.1038/s41467-019-11914-2` (2019).
[3]B. Assouline, M. Brik, N. Bernstein, and A. Capua, "Amplification of electron-mediated spin currents by stimulated spin pumping", Physical Review Research **4**, `10.1103/physrevresearch.4.l042014` (2022).

Domain Wall Motion and DMI on Perpendicular Magnetic Anisotropy Based Spintronics Devices in Pt/CoPt, Pt/Co/X/Pt and Pt/Co/XOy/Pt Stacks

Sylvain Eimer[1,*], **Houyi Cheng**[1,2], **Pierre Vallobra**[1], **Boyu Zhang**[2], **Weisheng Zhao**[1,2]

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In recent years, the spintronic hard and flexible devices have received widespread attention because of their application in wearable devices [2] . Pt/Co multilayers with perpendicular magnetic anisotropy (PMA) have attracted great attention in high packing densiy and spintronic devices. The combination of Pt/Co with other stacks such as CoFeB/MgO can be used in the fields of magnetic memory and spintronic devices. The combination of Pt/Co with other stacks can be used in the fields of magnetic memory and spintronics sensorsiy[3]. Our group has also done some research on Pt/Co/X-based inflexible devices[4]. Recently,iy the deposition of Pt/Co multilayers on flexible substrates has become a research highlight. For example, by depositing the Pt/Co layer on polyethylene naphtha-lene dicarboxylate (PEN) substrate as a sensor, the strain direction of a flexible Giant Magneto Resistance (GMR) device can be sensed [5]. In one of previous paper[1], we report our research about perpendicular magnetic anisotropy on devices in Pt/Co stacks under different hard and flexible substrates [fig 1]. The magnetic properties in Pt/Co, Pt/Co/X/Pt and Pt/Co/XOy/Pt multilayers (X= various materials)[6], such as perpendicular magnetic anisotropy (PMA), are of particular interest for spintronic devices. In particular, it is important to obtain a strong PMA on various substrate in the field of wearable devices and structural health monitoring. However, the different stack deposition and growth conditions influence the magnetic properties of the film. Here, we investigate for example the magnetic properties in Pt/Co/Pt and Pt/Co/Ru/Pt Pt/Co/RuO2/Pt structures [fig 2] deposited by sputtering with different substrates, layer thicknesses and interlayer. An interesting way to improve or manipulate the magnetics proprieties is to use irradiation. We investigate He+ irradiation effect on our devices. We exhibited conditions for better crystallinity, enhanced PMA, homogeneous domain-wall motion (DWM) and stronger (Dzyaloshinskii–Moriya interaction) DMI.

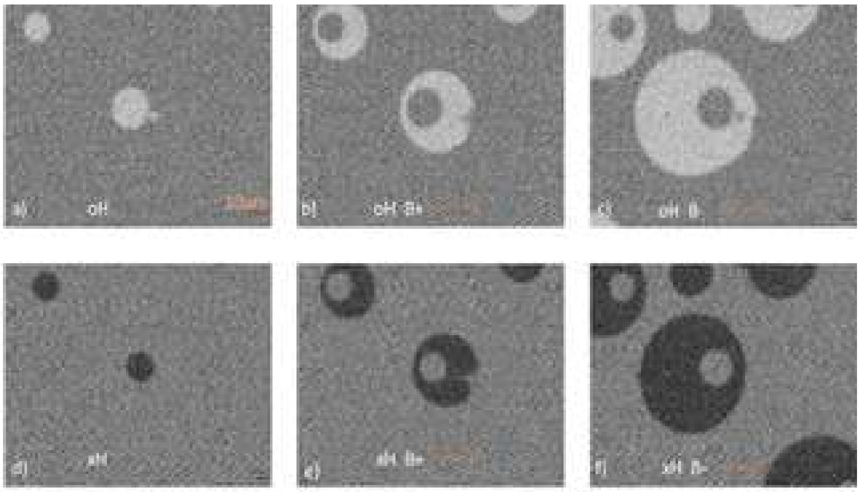

Figure 1: Kerr images of domain wall motion in Pt/Co/RuO2/Pt with a static in plane field and a pulsed out of plane field

Poster 1. PA07
Monday
16:30

Strain-Tunable Gyrotropic Dynamics in Individual Magnetic Vortices

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Magnetic vortex is a topologically protected magnetic state with curling in-plane magnetization configuration and an out-of-plane singularity in the center of the structure, known as vortex core (VC). Successfully implemented in spin-torque oscillators, magnetic vortices show great potential as building blocks of emerging microwave spintronic devices thanks to the reduced dynamical noise of the VC gyrotropic mode [1]. However, one of the major drawbacks of the VC dynamics is low tunability of the gyrotropic frequency in the linear regime. An efficient way to overcome this limitation is introducing an extrinsic magnetoelastic anisotropy energy to the VC dynamics, which leads to a sizeable change of the gyrotropic frequency due to the softening of the restoring force spring constants [2, 3].

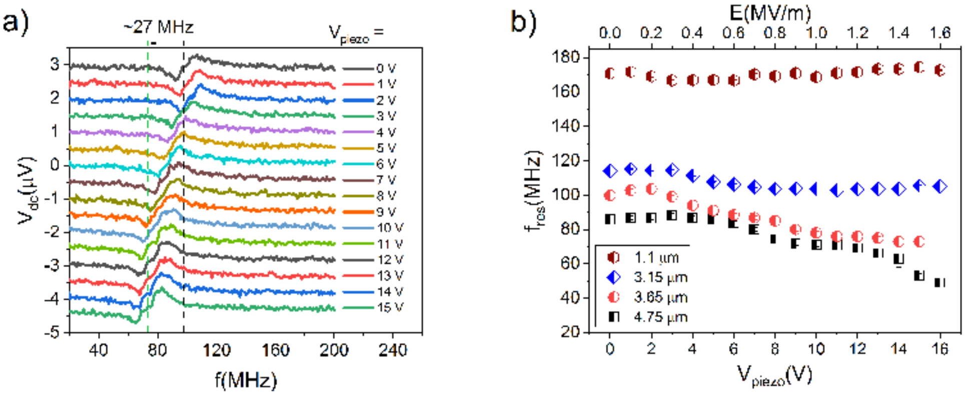

Figure 1: (a) Rectification spectra of the 30-nm-thick CoFeB disk (diameter 3.65 μm) for the different voltages applied to the PMN-PT. (b) Gyrotropic frequency vs. applied voltage (electric field) for different device sizes.

We present a study on the piezostrain-tunable gyrotropic dynamics in CoFeB vortex microstructures grown on piezoelectric PMN-PT substrates. Using spin rectification measurements, we demonstrate large frequency tunability (up to 45%) in individual disks accessed locally with low surface voltages ($\leq$16 V), and all-electrical operation. With increased voltage applied to the PMN-PT, we observe gradual decrease of the VC gyrotropic frequency associated with the strain-induced magnetoelastic energy [see Figure 1(a)]. We show that the frequency tunability strongly depends on the magnetic disk size, with increased frequency shift for the disks with larger diameter [see Figure 1(b)]. Micromagnetic simulations suggest that the observed size effects originate from the increased ratio between the strain-induced magnetoelastic and demagnetizing energies in large magnetic disks. Our results show that electrically induced piezostrain offers an extra room for the frequency tunability of the VC dynamics.

Support by the Nanofabrication Facilities Rossendorf (NanoFaRo) at the IBC is gratefully acknowledged. Financial support by the Deutsche Forschungsgemeinschaft (DFG) within the grant IU 5/2-1 (STUNNER) is acknowledged.

REFERENCES

[1] A. Litvinenko, V. Iurchuk, P. Sethi, et al., “Ultrafast Sweep-Tuned Spectrum Analyzer with Temporal Resolution Based on a Spin-Torque Nano-Oscillator”, Nano Letters **20**, 6104–6111 (2020).

[2] P. E. Roy, “In-plane anisotropy control of the magnetic vortex gyrotropic mode”, Applied Physics Letters **102**, 162411 (2013).

[3] S. Finizio, S. Wintz, E. Kirk, et al., “Control of the gyration dynamics of magnetic vortices by the magnetoelastic effect”, Physical Review B **96**, 054438 (2017).

Poster 1. PA08
Monday
16:30

Tailoring Crosstalk between Localized 1D Spin-Wave Nanochannels Using Focused Ion Beams

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Magnonic devices take advantage of purely spin-based transport and processing of information encoded in the amplitude and/or the phase of spin waves—the collective excitations of magnetization dynamics. Recently, increased efforts have been devoted to methods to reduce the lateral size of spin-wave conduits to below 100 nm [1]. One of the promising ways to tackle this goal is taking advantage of the so-called edge modes—dynamic resonances localized in extremely confined regions along the edges of a magnonic conduit [2]. In this work, we show how these modes can be efficiently tailored and, more importantly, controlled by means of local modification of the shape of the magnetic conduit by using a focused Neon ion beam (FIB) [3]. More specifically, we present a study of localized dynamical modes in a 1 µm-wide permalloy conduit probed by microresonator ferromagnetic resonance [Figure 1(a)]. We clearly observe even the lowest-energy edge mode after the FIB-assisted trimming of the microstrip. Furthermore, after trenching the microstrip along its long axis, creating consecutively ∼50 and ∼100 nm gaps [Figure 1(b)], the emerged resonances are attributed to the modes localized at the inner edges of the separated strips. To visualize the mode distribution, Brillouin light scattering microscopy was used. It shows an excellent agreement with the ferromagnetic resonance data and confirms the mode localization at the outer/inner edges of the strips [Figure 1(c)]. FIB-assisted modification of the magnetic micro- and nanostructures is a powerful tool to engineer nanoscale spin-wave channels with optimized dynamical properties.

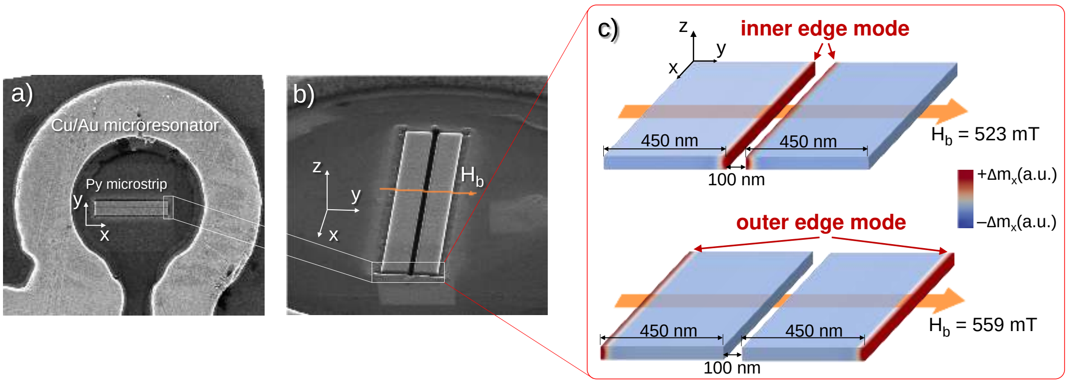

Figure 1: (a) Image of the microresonator with the 5 µm × 1 µm × 50 nm Py strip positioned in the center of the loop. (b) Close-up of the FIB-cut strip with the 100-nm-wide gap between the microstrips. (c) Illustration of the mode localization in the microstrips separated by a 100 nm gap for given magnetic field values.

Support by the Nanofabrication Facilities Rossendorf (NanoFaRo) at the IBC is gratefully acknowledged. Financial support by the Deutsche Forschungsgemeinschaft (DFG) within the programs SCHU 2922/1-1, KA 5069/1-1 and KA 5069/3-1 is gratefully acknowledged.

REFERENCES

[1] B. Heinz, T. Brächer, M. Schneider, et al., “Propagation of spin-wave packets in individual nanosized yttrium iron garnet magnonic conduits”, Nano Letters **20**, 4220–4227 (2020).
[2] A. Lara, J. Robledo Moreno, K. Y. Guslienko, and F. G. Aliev, “Information processing in patterned magnetic nanostructures with edge spin waves”, Scientific Reports **7**, 5597 (2017).
[3] V. Iurchuk, J. Pablo-Navarro, T. Hula, et al., “Tailoring crosstalk between localized 1D spin-wave nanochannels using focused ion beams”, Scientific Reports **13**, 764 (2023).

Propagation of Spin Waves in Intersecting Yttrium Iron Garnet Nanowaveguides

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In recent years, it has been shown that spin waves propagating in magnetic guiding structures provide a wide range of possibilities for the implementation of advanced nanoscale devices, including networks for nonBoolean data processing[1] and neuromorphic computing circuits[2]. We use microfocus Brillouin-light-scattering spectroscopy to directly visualize the propagation and transformation of spin waves in a magnetic cross composed of two 800-nm-wide YIG waveguides intersecting at a right angle[3]. We show that, depending on the frequency, spin waves can experience predominant reflection from the intersection region with weak tunneling of the wave in the forward direction, an efficient redirection of the wave into the side arms of the cross, or almost uniform splitting of the wave into all three arms. Additionally, we find that the rotation of the direction of the static magnetic field results in suppression of the wave redirection into the side arms and leads to a strong increase in the forward transmission. These observations are in qualitative agreement with the results of micromagnetic simulations, which indicate that the reason for suppressed redirection lies in the peculiarities of the phase profiles of spin waves.

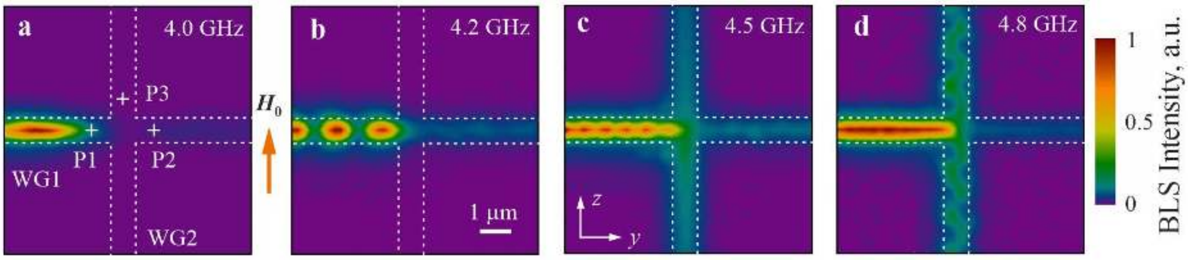

Figure 1: Representative spatial maps of spin-wave intensity recorded at different excitation frequencies.

The observed controllability is useful for steering the propagation of spin waves in complex nanoscale magnonic networks for the implementation of nontraditional computing and signal processing. The high sensitivity of the propagation regime to the frequency of spin waves provides additional opportunities for the manipulation of spin-wave propagation by nonlinear effects, such as an amplitude-dependent shift of the spinwave spectrum. This opportunity is particularly important for the realization of neuromorphic networks, where the nonlinear response plays a key role.

REFERENCES

[1] Y. Khivintsev, V. Sakharov, A. Kozhevnikov, et al., “Spin waves in yig based magnonic networks: design and technological aspects”, Journal of Magnetism and Magnetic Materials **545**, 168754 (2022).
[2] Á. Papp, W. Porod, and G. Csaba, “Nanoscale neural network using non-linear spin-wave interference”, Nature Communications **12**, `10.1038/s41467-021-26711-z` (2021).
[3] D. Raskhodchikov, J. Bensmann, K. Nikolaev, et al., “Propagation of spin waves in intersecting yttrium iron garnet nanowaveguides”, Physical Review Applied **18**, `10.1103/physrevapplied.18.054081` (2022).

Poster 1. PA10
Monday
16:30

Imaging and Phase-Locking of Non-Linear Spin-Wave Phenomena

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Non-linear processes are a key feature in the emerging field of spin-wave based information processing since they allow to convert uniform spin-wave excitations into propagating modes at different frequencies. In the last decades, non-linear processes such as three or four magnon scattering have been studied intensively in the limit of low modulation amplitudes and pushed magnonics devices closer towards competitive applications. In the strong modulation regime, the existence of non-linear magnons at higher half-integer multiples of the driving frequency has recently been predicted in $\mathrm{Ni}_{80}\mathrm{Fe}_{20}$ at low bias fields. Moreover, these higher-order processes are even predicted to dominate the non-linear response in this regime [1]. However, it is an open question under which conditions such non-linear spin waves (NLSWs) emerge coherently and how they may be used in devices. Here, we experimentally demonstrate a class of spin waves oscillating at odd half-integer harmonics. We employ the novel super-Nyquist-sampling MOKE (SNS-MOKE) [2] technique to directly image these parametrically generated magnons in micron-sized $\mathrm{Ni}_{80}\mathrm{Fe}_{20}$ elements in order to determine their wave vectors [3].

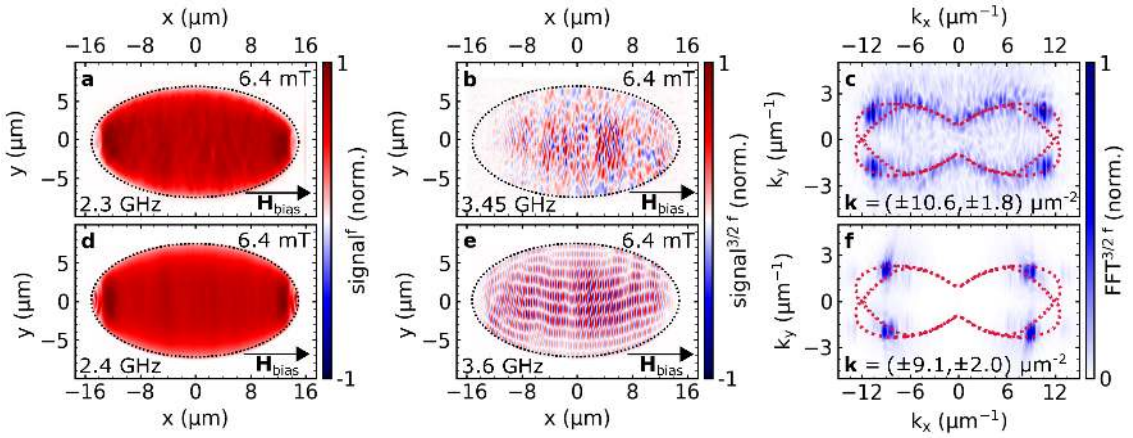

Figure 1: Spatially-resolved imaging (upper row) and micromagnetic simulations (lower row) of NLSWs analyzed at the excitation frequency and 3/2 f_{rf}. Panel **b** shows the non-linear response at the corresponding frequency component indicating a standing spin-wave pattern, while the response at the driving frequency remains uniform (see panel **a**). The 2D-FFTs in **c** and **f** demonstrate a good agreement of the wavevetors obtained from experiment and simulation.

The obtained wave vectors shown in Fig. 1 strongly differ from conventional three-magnon scattering processes indicating the different nature of the two processes. By investigating the phase stability of these NLSW's oscillating at 3/2 of the driving frequency, we demonstrate the presence of two degenerate phase states that may be selected by external phase-locking. These results open new possibilities for applications such as spin-wave sources, amplifiers and phase-encoded information processing with magnons.

REFERENCES

[1] H. G. Bauer, P. Majchrak, T. Kachel, C. H. Back, and G. Woltersdorf, "Nonlinear spin-wave excitations at low magnetic bias fields", Nature Communications **6**, 8274 (2015).
[2] R. Dreyer, N. Liebing, E. R. J. Edwards, A. Müller, and G. Woltersdorf, "Spin-wave localization and guiding by magnon band structure engineering in yttrium iron garnet", Physical Review Materials **5**, 064411 (2021).
[3] R. Dreyer, A. F. Schäffer, H. G. Bauer, et al., "Imaging and phase-locking of non-linear spin waves", Nature Communications **13**, 4939 (2022).

Poster 1. PA11
Monday
16:30

Non-Local Spin Transport Measurement in Ferrimagnetic GdCo Thin Films

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Spin current carried by spin-wave has the advantage of no Joule heat loss in comparison with the charge current. Nonetheless, it is non-conservative flows that exponentially decay to the distance, making long-distance propagation difficult. Recently, low-dissipative spin transport mechanism, spin superfluidity, has been theoretically predicted in antiferromagnets with a two-dimensional magnetic ordering [1, 2]. Ferrimagnets are also the promising candidates for spin superfluidity, which exhibit similar magnetic structure to antiferromagnets at the magnetization compensation temperature T_{M}. In addition, the spin-flop transition induced by an external magnetic field confines magnetic momentum in a two-dimensional plane. In this study, motivated by the observation of long distance spin transport via spin superfluidity, we performed non-local measurements using ferrimagnetic GdCo/Pt bilayers under the control of magnetic ordering by the external magnetic field.

A $Gd_{29}Co_{71}$ (5) /Pt (5) film (unit: nm) was deposited on a thermally oxidized Si substrate by DC magnetron sputtering, and then it was microfabricated to the device for non-local measurements. In this device, the spin transport can be observed exploiting spin Hall effect (SHE) and inverse SHE in Pt layer. Specifically, we applied charge current between A and B and detected the voltage between C and D while rotating an in-plane external magnetic field as shown in Figure 1(a). As a result, modulation of angular dependent non-local signal was observed as shown in Figure 1(b). This modulation is thought to be mainly due to the magnetoresistance effect such as anisotropic magnetoresistance (AMR) and spin Hall magnetoresistance (SMR) [3], which is consistent with the results expected from the change in magnetic ordering due to spin-flop transition. Furthermore, the increase of MR ratio induced by spin flop transition was observed, which will be discussed from the perspective of spin transport and AMR mechanism.

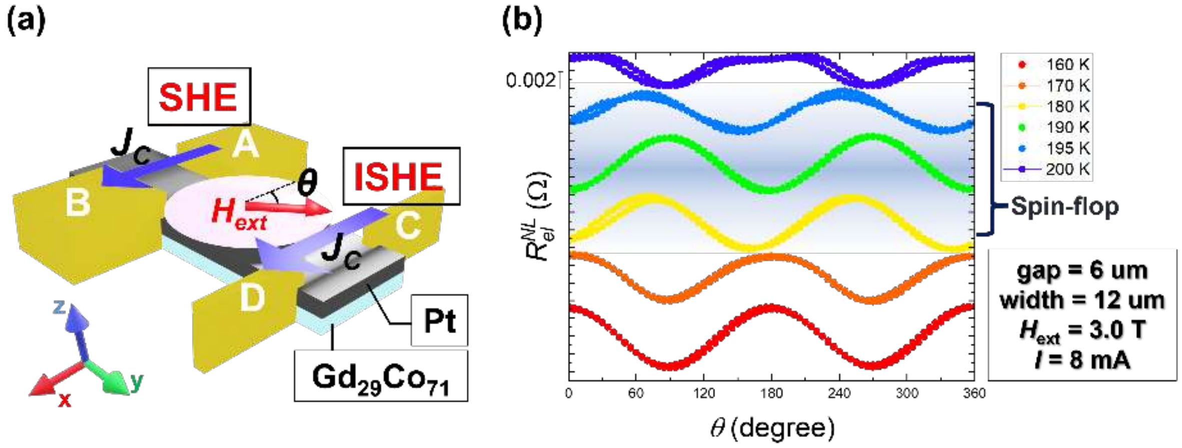

Figure 1: (a) Shematic image of non-local measurement. (b) Angular dependence of non-local resistance.

REFERENCES

[1] E. Sonin, “Spin currents and spin superfluidity”, Advances in Physics **59**, 181–255 (2010).
[2] S. Takei, B. I. Halperin, A. Yacoby, and Y. Tserkovnyak, “Superfluid spin transport through antiferromagnetic insulators”, Physical Review B **90**, 094408 (2014).
[3] W. Zhou, T. Seki, T. Kubota, G. E. W. Bauer, and K. Takanashi, “Spin-Hall and anisotropic magnetoresistance in ferrimagnetic Co-Gd/Pt layers”, Physical Review Materials **2**, 094404 (2018).

Poster 1. PA12
Monday
16:30

Magnonic Grating Coupler Effect, Magnon-Induced Nanostripe Reversal, Magnon Cooperativity and Chiral Group Velocity in Ultra-Thin YIG with Integrated NiFe Nanostripes

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Dzyaloshinskii-Moriya interaction (DMI) is known to stabilize complex spin textures with non-trivial topology and chiral dynamics. To realize chiral nanomagnonics, ultra-thin magnetic layers are important which exhibit low magnon damping and interfacial DMI (iDMI). Recently, group velocities of mainly dipolar spin waves were found to be asymmetric in magnetron-sputtered 7-nm-thick yttrium iron garnet (YIG). This observation was attributed to iDMI arising at the interface between YIG and the garnet substrate [1]. To advance the frontiers of chiral nanomagnonics it is now important to study short-waved magnon propagation in the presence of iDMI. We fabricated one-dimensional NiFe-based magnonic grating couplers (GCs) on top of 11-nm-thick YIG (Fig. 1a), that was grown by liquid phase epitaxy on the garnet substrate. Coplanar waveguides (CPWs) were patterned onto the NiFe (Py) nanostripes to excite spin waves via radiofrequency (RF) magnetic fields. By inductive spectroscopy we observe several high-frequency branches (dark color in Fig. 1b) that we explain by the magnonic grating coupler effect under RF excitation. The branch with negative slope followed by a sudden jump at $\mu_0 H \approx 40$ mT is consistent with the reversal of the NiFe nanostripe magnetization vectors, leading to the parallel alignment of the nanostripes and the underlying YIG at large H [2]. We analyze the avoided crossing at low positive fields (red box in Fig. 1b) which occurs between a magnon mode in YIG with $\lambda = 99$ nm and the NiFe fundamental mode. We estimate an average cooperativity $C = 2.26 \pm 0.11$, indicating a strong magnon-magnon coupling. In our hybrid sample, we find magnon-induced nanostripe reversal at applied RF powers ≥ -5 dBm. This value is larger than previously reported for 100-nm-thick YIG [3]. The group velocity asymmetry δv_{g} of counterpropagating magnons with $\lambda = 99$ nm (Fig. 1c) is more pronounced than reported in Ref. [1]. Further studies are required to understand its origin. Our work contributes to the progress of on-chip devices for chiral magnon excitation, detection and storage. The work was supported by SNSF via grant 197360 and by DFG via grant 271741898.

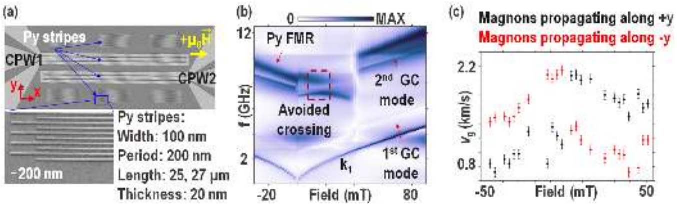

Figure 1: (a) Microscopy images of Py and CPWs on YIG. (b) Reflection spectra with avoided crossing at 18 mT and several high-frequency magnon branches. (c) Group velocities v_{g} of counterpropagating magnons with $\lambda = 99$ nm extracted from spectra measured at an RF power of -1 dBm.

REFERENCES

[1] H. Wang, J. Chen, T. Liu, et al., "Chiral spin-wave velocities induced by all-garnet interfacial dzyaloshinskii-moriya interaction in ultrathin yttrium iron garnet films", Phys. Rev. Lett. **124**, 027203 (2020).

[2] H. Wang, M. Madami, J. Chen, et al., "Tunable damping in magnetic nanowires induced by chiral pumping of spin waves", ACS Nano **15**, 9076–9083 (2021).

[3] K. Baumgaertl and D. Grundler, *Reversal of nanomagnets by propagating magnons in ferrimagnetic yttrium iron garnet enabling nonvolatile magnon memory, https://arxiv.org/abs/2208.10923*, (2022).

Poster 1. PA13
Monday
16:30

Spin Waves in Curved Magnetic Shells: Numerical Techniques and Recent Advances

Lukas Körber[1,2,*], **Roman Verba**[3], **István Kézsmárki**[4], **Jorge Otálora**[5], **Volodymyr Kravchuk**[6,7],
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The exploration of three-dimensional architectures has recently become a focus in several research fields, including the study of ferromagnets and superconductors. Depending on the underlying order parameter and interactions, twisting and bending flat samples into curved shells can lead to many emerging effects when the bending radius is comparable to the system's characteristic length scales. Curvature-induced emergent anisotropies and magnetochiral interactions have been widely studied in ferromagnetic systems, resulting in the discovery of various fascinating phenomena such as stabilizing skyrmions and merons on Gaussian and paraboloid bumps, pinning of domain walls or suppression of the Walker breakdown.

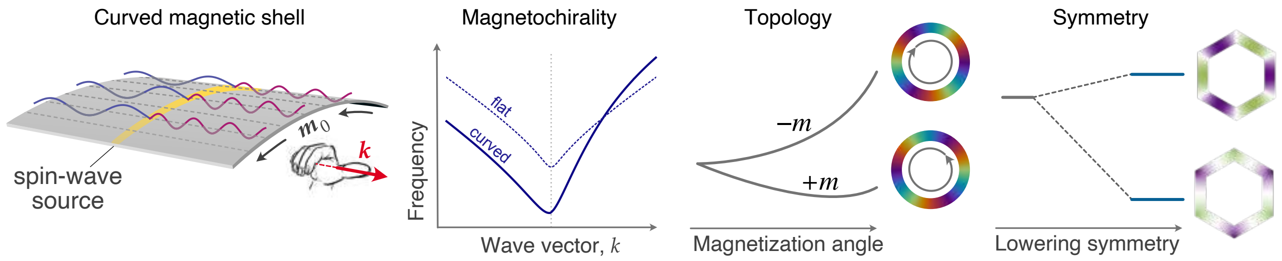

Figure 1: Examples for geometrical effects on spin-wave dynamics in curved magnetic shells (adapted from Refs. [1, 2]).

The impact of curvature and three-dimensional shape on magnetization dynamics, namely on the propagation of spin waves, manifests itself in several aspects: For example, the curvature of magnetic shells can modify the dynamic magnetic pseudo charges. As a result, magneto-chiral symmetry breaking of magnetostatic origin can lead to asymmetric spin-wave dispersion, nonreciprocal spatial mode profiles, and strongly modify nonlinear magnetization dynamics [1]. Moreover, a nontrivial topology of three-dimensional magnetic specimens can induce a topological Berry phase of spin waves or impose selection rules on the dynamics of magnetic textures. Lastly, achiral symmetry breaking, induced, for example, by lowering rotational symmetries, can lead to symmetry-governed splitting of degenerate modes [2, 3]. This talk will focus on the aforementioned geometrical effects on magnetization dynamics and introduce numerical techniques for studying spin waves in curved magnetic shells, implemented in the TetraX package (tetrax.readthedocs.org).

REFERENCES

[1] L. Körber, R. Verba, J. A. Otálora, et al., "Curvilinear spin-wave dynamics beyond the thin-shell approximation: magnetic nanotubes as a case study", Physical Review B **106**, 014405 (2022).
[2] L. Körber, I. Kézsmárki, and A. Kákay, "Mode splitting of spin waves in magnetic nanotubes with discrete symmetries", Physical Review B **105**, 184435 (2022).
[3] L. Körber, "Symmetry and curvature effects on spin waves in vortex-state hexagonal nanotubes", Physical Review B **104**, 184429 (2021).

Poster 1. PA14
Monday
16:30

Manipulating Exchange Bias with a Single Femtosecond Laser Pulse

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Ultrafast manipulation of magnetic order has challenged our understanding the fundamental and dynamic properties of magnetic materials. So far single shot magnetic switching has been limited to ferrimagnetic alloys and multilayers [1]. Whether a similar scenario can be observed in antiferromagnets remains unknown. In ferromagnetic (FM)/antiferromagnetic (AFM) bilayers, exchange bias arises from the interfacial exchange coupling between the two layers and results in a field shift (H_e) of the FM layer hysteresis loop. Exchange bias phenomena have found widespread use in fundamental scientific research and a large variety of spintronic devices, including sensors and magnetic random-access memory (MRAM) [2]. Many studies have already focused on the possibility to manipulate the exchange bias effect using thermal annealing with or without applied magnetic field and spin polarized current [3, 4]. Here we demonstrate the possibility to manipulate the exchange bias (change of the sign and amplitude of H_e) with a single femtosecond laser pulse in perpendicular to film plane magnetized IrMn/CoGd bilayers, as shown in Figure. 1. We have studied the influence of the laser fluence and the number of pulses for various IrMn thicknesses to determine the fastest and the most energy-efficient way to set the exchange bias field. Our results establish a method to set the exchange bias in a bilayer system that has potential application for ultrafast and energy-efficient spintronic devices.

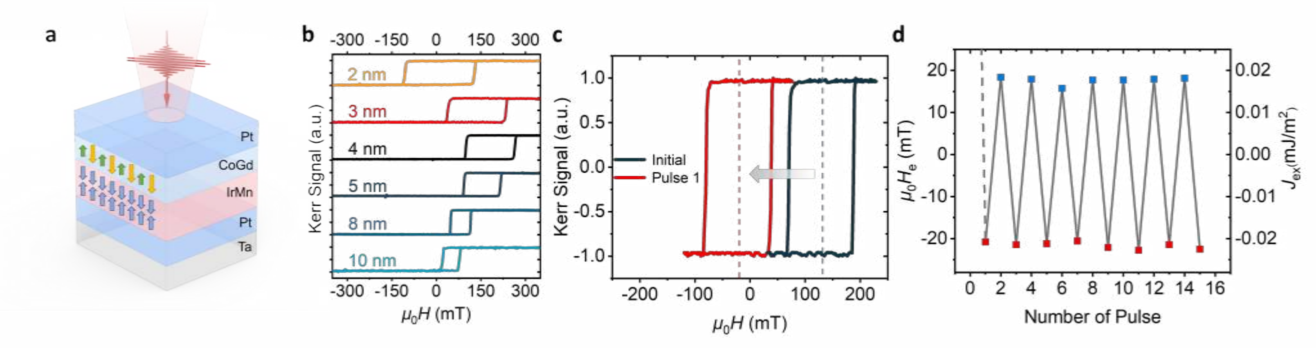

Figure 1: (a), Sketch of the IrMn/CoGd bilayer. (b), Hysteresis loops obtained on the annealed stacks for IrMn thickness from 2 to 10 nm measured by MOKE. (c), Hysteresis loop of IrMn(5)/CoGd(4) before and after exposure to a single linearly polarized laser pulse with a pulse duration of 40 fs and a fluence of 17 mJ/cm^2 (d), Modulation of the exchange bias field as a function of the number of pulses with a pulse duration of 40 fs and a laser fluence of 17 mJ/cm^2.

REFERENCES

[1] I. Radu, K. Vahaplar, C. Stamm, et al., “Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins”, Nature **472**, 205–208 (2011).

[2] J. Nogués and I. K. Schuller, “Exchange bias”, Journal of Magnetism and Magnetic Materials **192**, 203–232 (1999).

[3] I. Prejbeanu, M. Kerekes, R. C. Sousa, et al., “Thermally assisted mram”, Journal of Physics: Condensed Matter **19**, 165218 (2007).

[4] P.-H. Lin, B.-Y. Yang, M.-H. Tsai, et al., “Manipulating exchange bias by spin-orbit torque”, Nature Materials **18**, 335–341 (2019).

Magnonics 2023
July 30th - August 3rd
Le Touquet - Paris - Plage, France

Poster 1. PA15
Monday
16:30

Significant Suppression of Magnon Damping in Ultrathin Co Films by Modulating Interfacial Magnetic Anisotropy at the Interface of Co/nonmagnet

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Ultrathin ferromagnetic metals (FMs) has attracted attention because of its gate-tunability of magnetism [1]. To realize gate-tunable magnon systems, the study on magnetization dynamics in ultrathin FM films is inevitable. In FM thin films, the surface contribution to magnon damping, two-magnon scattering (TMS) [2]., is dominant, which have hampered study on magnetization dynamics and magnon in ultrathin FM films. TMS was reported to be dependent on the surface state of FM films such as surface morphology and uniaxial magnetic anisotropy [2]. In addition, the modulation of interfacial magnetic anisotropy at FM/nonmagnetic metal (NM) with various NM layer via inducing interfacial spin-orbit interaction was reported [3].. Here, we investigated the magnon damping in ultra-thin Co film on various NM layers. Through the control experiment with changing NM layer, we established the guiding principle for realization of low-magnon damping in ultrathin FM film.

In this study, we selected Ti, Cu and Al as NM layers. As shown in Figure 1, the samples of Co film with NM buffer layers were prepared by electron beam deposition, and the thickness of Co film (tCo) varies from 2 nm to 20 nm. Here, we measured ferromagnetic resonance (FMR) of these samples with applying DC magnetic field along the in-plane direction to estimate the Gilbert damping constant α as magnon relaxation. Figure 2 shows the Co thickness dependence of α. The thickness dependence of α is expressed by the following equation [4]., $\alpha = \alpha_{\text{int}} + \alpha_{\text{SP}} t_{\text{Co}}^{-1} + \beta_{\text{TMS}} t_{\text{Co}}^{-2}$,where α_{SP}, α_{SP}, and β_{TMS} are intrinsic, spin pumping, and TMS contributions, respectively. TMS contributions with various NM films are shown in Fig. 2 as the quadratic factor in broken lines. The TMS contribution was greatly suppressed in the samples with Ti layer, but not in the samples with Cu and Al. The NM layer dependence of the TMS contribution can be explained by the interfacial magnetic anisotropy at Co/NM interfaces [5].

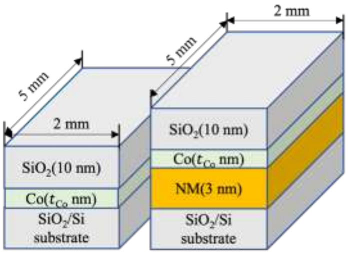

Figure 1: Composite

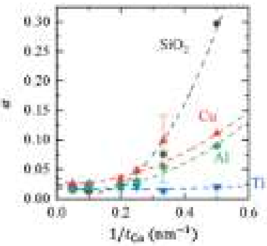

Figure 2: Gradation

REFERENCES

[1] D. Chiba, S. Fukami, K. Shimamura, et al., “Electrical control of the ferromagnetic phase transition in cobalt at room temperature”, Nature Materials **10**, 853–856 (2011).
[2] R. Arias and D. L. Mills, “Extrinsic contributions to the ferromagnetic resonance response of ultrathin films”, Physical Review B **60**, 7395–7409 (1999).
[3] A. J. Lee, A. S. Ahmed, B. McCullian, et al., “Interfacial rashba-effect-induced anisotropy in nonmagnetic-material–ferrimagnetic-insulator bilayers”, Physical Review Letters **124**, `10.1103/physrevlett.124.257202` (2020).
[4] L. Zhu, D. C. Ralph, and R. A. Buhrman, “Effective spin-mixing conductance of heavy-metal–ferromagnet interfaces”, Physical Review Letters **123**, `10.1103/physrevlett.123.057203` (2019).
[5] S. Yoshii, K. Kato, E. Shigematsu, et al., “Significant suppression of two-magnon scattering in ultrathin co by controlling the surface magnetic anisotropy at the co/nonmagnet interfaces”, Physical Review B **106**, `10.1103/physrevb.106.174414` (2022).

Poster 1. PA16
Monday
16:30

Zero-Frequency Chiral Magnonic Edge States Protected by Non-Equilibrium Topology

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Topological Magnon Insulators (TMIs) are magnonic realizations of topological insulators, where instead of electrons magnons are the carriers of information. However, topological bosonic excitations must, in contrast to their fermionic counterparts, appear at finite energies. This is a key challenge for TMIs, as it prevents straightforward excitation and detection of topologically-protected magnonic edge states and their use in magnonic devices.

In this talk, we propose a general strategy to access the topologically protected edge states in a magnon Chern insulator [1]. We show that the chiral edge states can be tuned in frequency by considering magnon excitations on top of a magnetization that is pointing against the applied external magnetic field [2]. In this non-equilibrium state, stabilized by spin-transfer torques, the topologically-protected chiral edge modes lie at zero frequency, while the bulk modes remain gapped, as shown in Fig. 1. Using numerical Landau-Lifshitz-Gilbert simulations we show that the chiral edge states can be excited with microwave fields at GHz-frequencies. Furthermore, we demonstrate that in a propagating spin wave spectroscopy experiment the edge states can be directly detected, even in the presence of disorder.

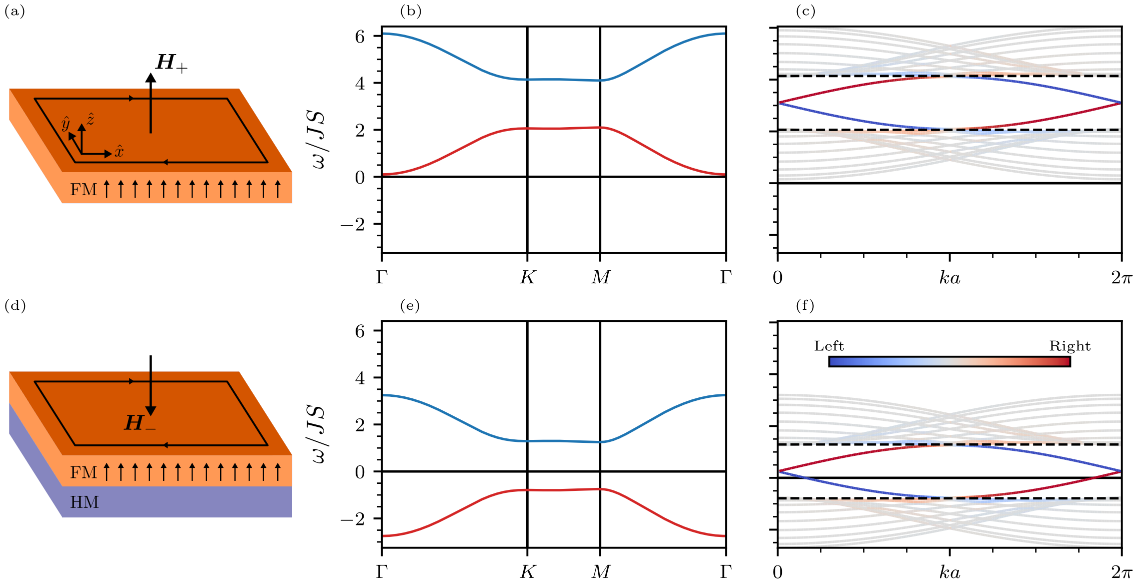

Figure 1: Zero-frequency chiral magnonic edge states in a magnon Chern insulator ferromagnet, comparing the uniform magnetization and magnetic field $\boldsymbol{H}_\pm$ aligned parallel (a-c) and anti-parallel (d-f). (b,e) Bulk magnon band structure. (c,f) Magnon band structure of an armchair edge ribbon. In equilibrium the edge states lie at high frequencies, but they are lowered down to zero frequency in non-equilibrium.

REFERENCES

[1]P. M. Gunnink, J. S. Harms, R. A. Duine, and A. Mook, *Zero-frequency chiral magnonic edge states protected by non-equilibrium topology*, (2023) `https://arxiv.org/abs/2302.06597`.
[2]J. S. Harms, H. Y. Yuan, and R. A. Duine, *Antimagnonics*, (2022) `https://arxiv.org/abs/2210.16698`.

Poster 1. PA17
Monday
16:30

Three Magnon Processes in Spin-Wave Scattering on Localised Modes for Controllable Frequency and Trajectory Modulation.

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Spin waves (SWs) are a fascinating research object and are considered a promising information carrier. One of the potential advantages of using SWs is an easily achieved non-linearity, e.g., processes such as confluence and splitting. Here we study the interaction of an incident SW beam with SW modes localised on the edge of the ferromagnetic film. The nonlinear interaction of the incident SW beam with the localised mode at the edge leads to the creation of new beams with shifted frequencies due to confluence and stimulated splitting processes. We consider two approaches for localizing the edge modes. First, by using the demagnetising field [1] and in the second method, we place a ferromagnetic strip directly over the edge of the film. The second approach is a realization of the magnonic Gires-Tournois interferometer [2–4], whose geometric dimensions influence the localised mode properties. In our research, we compare the efficiency of the nonlinear processes for both systems and investigate the scope of inelastically scattered SW beams' lateral displacement along the interface with respect to the incident beam point (SW analogue to the Goos-Hanchen effect for inelastically scattered SWs). For both methods of mode localization, we show that the splitting process is more efficient than the confluence process and that the lateral shift of inelastically scattered beams depends on edge mode frequency. Our research contributes to a better understanding of inelastic scattering of SWs, which will be used in magnonic circuits e.g., for modulating SW frequency and redirecting SW beams by changing localised mode frequency.

REFERENCES

[1] P. Gruszecki, K. Y. Guslienko, I. L. Lyubchanskii, and M. Krawczyk, "Inelastic spin-wave beam scattering by edge-localized spin waves in a ferromagnetic thin film", Physical Review Applied **17**, 044038 (2022).

[2] K. Sobucki, W. Śmigaj, J. Rychły, M. Krawczyk, and P. Gruszecki, "Resonant subwavelength control of the phase of spin waves reflected from a gires–tournois interferometer", Scientific Reports **11**, 4428 (2021).

[3] K. Sobucki, P. Gruszecki, J. Rychły, and M. Krawczyk, "Control of the phase of reflected spin waves from magnonic gires–tournois interferometer of subwavelength width", IEEE Transactions on Magnetics **58**, 1–5 (2021).

[4] K. Sobucki, W. Śmigaj, P. Graczyk, M. Krawczyk, et al., "Advanced magnon-optic effects with spin-wave leaky modes", arXiv preprint arXiv:2302.11507 (2023).

Poster 1. PA18
Monday
16:30

Probing the Internal Texture of Skyrmions through Spin Waves with a Quantum Sensor

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NV centers are defects in diamond which can be used as quantum sensors to probe magnetism at the nanoscale when integrated in an atomic force microscope. Such a measurement relies on the spin $S = 1$ of the NV center: the static stray field produced by a magnetic state induces a Zeeman shift on the spin sublevels, which can be detected optically. In addition, NV centers are also sensitive to spin waves, as the magnetic noise originating from thermally activated spin waves accelerates its spin relaxation.

In the latter case, the enhanced relaxation leads to a decrease of the photoluminescence emitted by the NV center [1], which allows an easy localization of spin waves interacting with magnetic textures. We applied this approach to the study of Co-based perfectly compensated synthetic antiferromagnetic layers [2], in which we were able to observe spin waves channeled inside the domain walls [3].

We report here on a more detailed investigation of skyrmions in synthetic antiferromagnetic layers, revealing a spatial distribution of the noise contrast around their boundary. Both the noise distribution and its intensity appear to be linked to the skyrmion's internal structure.

REFERENCES

[1]M. Rollo, A. Finco, R. Tanos, et al., "Quantitative study of the response of a single NV defect in diamond to magnetic noise", Physical Review B **103**, 235418 (2021).
[2]W. Legrand, D. Maccariello, F. Ajejas, et al., "Room-temperature stabilization of antiferromagnetic skyrmions in synthetic antiferromagnets", Nature Materials **19**, 34–42 (2020).
[3]A. Finco, A. Haykal, R. Tanos, et al., "Imaging non-collinear antiferromagnetic textures via single spin relaxometry", Nature Communications **12**, 767 (2021).

All-Optical Helicity-Independent Switching State Diagram in Gd-Fe-Co Alloys

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Ultrafast magnetization switching induced by a single femtosecond laser pulse, under no applied magnetic field has attracted a lot of attention in the last 10 years because of its high potential for low-energy and ultrafast memory applications. Single-pulse helicity-independent switching has mostly been demonstrated for Gd-based materials. It is now necessary to optimize the pulse duration and the energy needed to switch a Gd-Fe-Co magnet depending on the alloy thickness and composition.

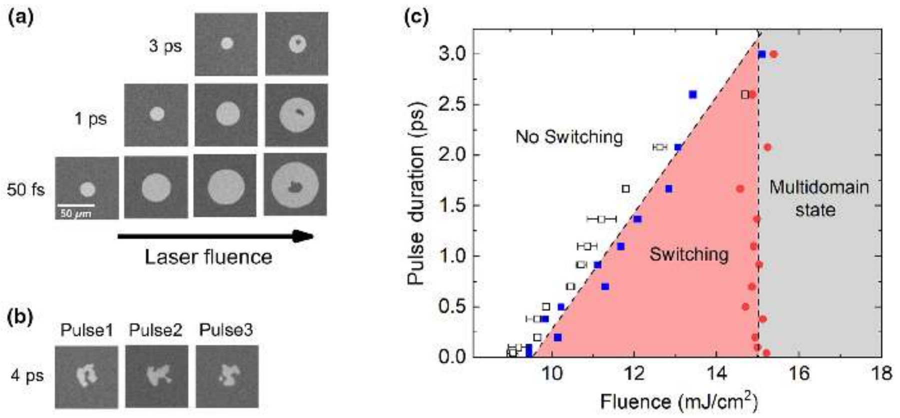

Figure 1: Magneto-optical images and all-optical helicity-independent switching (AO HIS) state diagram for a 20-nm $Gd_{24}(FeCo)_{76}$ film. (a) Magneto-optical images of $Gd_{24}(FeCo)_{76}$ after exposure to a single linearly polarized laser pulse with a pulse duration of 50 fs, 1 ps, and 3 ps, and with various fluences ranging from 9.5 to 15 mJ/cm^2. (b) Magneto-optical images of $Gd_{24}(FeCo)_{76}$ after exposure to a single linearly polarized laser pulse with a pulse duration of 4 ps and a fluence of 17 mJ/cm^2. (c) AO HIS state diagram: switching fluence F_{switch} (open black square and full blue square) and multidomain fluence F_{multi} (full red dot) as a function of the pulse duration for a single linearly polarized laser pulse. The blue full squares represent the switching fluences F_{switch} recorded when the diameter of switched area reaches around 10 μm. The open squares are the fitting results obtained via the method proposed by Liu *et al.* [1]. The spatial FWMH of laser beam is around 70 μm.

Here we experimentally report state diagrams showing the magnetic state obtained after one single pulse depending on the laser pulse duration and fluence for various Gd-Fe-Co thin films with different compositions and thicknesses (Figure 1). We demonstrate that these state diagrams share similar characteristics: the fluence window for switching narrows for longer pulse duration and for the considered pulse-duration range the critical fluence for single-pulse switching increases linearly as a function of the pulse duration while the critical fluence required for creating a multidomain state remains almost constant. Calculations based on the atomistic spin model qualitatively reproduce the experimental state diagrams and their evolution. By studying the effect of the composition and the thickness on the state diagram, we demonstrate that the best energy efficiency and the longest pulse duration for switching are obtained for composition around the magnetic compensation[2].

REFERENCES

[1]J. M. Liu, “Simple technique for measurements of pulsed gaussian-beam spot sizes”, Optics Letters **7**, 196 (1982).
[2]J. Wei, B. Zhang, M. Hehn, et al., “All-optical helicity-independent switching state diagram in gd-fe-co alloys”, Physical Review Applied **15**, 054065 (2021).

Poster 1. PA20
Monday
16:30

Selective Resonant Triggering of the Skyrmion by Higher-Order Spin-Wave Modess

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In magnetism, particularly in magnonics, studying the interactions between spin waves and spin textures, specifically skyrmions, can be an intriguing research area [1–3]. Spin-wave propagation can also be controlled in this field, as well as brain-inspired computing systems can be developed [4]. Skyrmion-waveguide systems have mainly been studied for the skyrmion's movement and dynamics within waveguides. A potential application of such systems to race-track memories motivates this research [5].

Our study utilized micromagnetic simulations to investigate a three-layered hybrid system in the absence of an external magnetic field. Among the components of the system are: a permalloy waveguide; a thin circular nanodot with a stable Néel-type skyrmion and made of a material with perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya interactions; and a non-magnetic separation layer between them. As part of this study, we examined (i) the static coupling between the nanodot and the waveguide, [6] (ii) whether propagating spin waves can be used to induce skyrmion dynamics, (iii) the effects of a skyrmion in nanodot and its imprint on spin-wave transmission through a waveguide [7]. Shape anisotropy maintains magnetic saturation along the waveguide's long axis. A skyrmion imprint appears below the nanodot due to magnetostatic interactions between the nanodot and the waveguide. Through this mutual interaction, the skyrmion in the nanodot loses its circular symmetry and becomes deformed. By using a heterostructure consisting of a nanoresonator in the skyrmion state dipole-coupled to a waveguide, we were able to achieve long propagation of spin waves. The presence of skyrmion in nanodot and imprint in waveguide affects spin-wave flow.

Using broadband excitation, we studied spin-wave transmission over a wide range of frequencies. A skyrmion and its imprint affect the transmission spectrum differently. Imprint at low frequencies exhibit significant amplitude, meanwhile, skyrmion excitations become dominant around 10 GHz. Excitation of the skyrmion leads to appearing of azimuthal modes at the edge and standing waves in the skyrmion core. Moreover, the skyrmion stimulates very low-frequency modes by coupling with higher-frequency modes, which origin is still under debate. Due to coupling with the nanodot, these excitations are also visible in the imprint spectrum.

In order to control spin waves, we have found that coupling them to the resonant modes of the skyrmion-imprint hybrid system is a viable approach, making it a promising technique for various applications.

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REFERENCES

[1] Z. Wang, H. Yuan, Y. Cao, et al., “Magnonic frequency comb through nonlinear magnon-skyrmion scattering”, Physical Review Letters **127**, 037202 (2021).

[2] C. Schütte and M. Garst, “Magnon-skyrmion scattering in chiral magnets”, Physical Review B **90**, 094423 (2014).

[3] J. Iwasaki, A. J. Beekman, and N. Nagaosa, “Theory of magnon-skyrmion scattering in chiral magnets”, Physical Review B **89**, 064412 (2014).

[4] S. Li, W. Kang, X. Zhang, et al., “Magnetic skyrmions for unconventional computing”, Materials Horizons **8**, 854–868 (2021).

[5] A. Fert, V. Cros, and J. Sampaio, “Skyrmions on the track”, Nature nanotechnology **8**, 152–156 (2013).

[6] M. Zelent, M. Moalic, M. Mruczkiewicz, et al., “Stabilization and application of asymmetric n\’eel skyrmions in hybrid nanostructures”, arXiv preprint arXiv:2204.05620 (2022).

[7] K. A. Kotus, M. Moalic, M. Zelent, M. Krawczyk, and P. Gruszecki, “Scattering of spin waves in a multimode waveguide under the influence of confined magnetic skyrmion”, APL Materials **10**, 091101 (2022).

Coherent Magnetization Dynamics in Strongly Quenched Systems

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The laser-induced modulation of the spin system on ultrashort timescales [1] is an important step towards time-efficient writing of data and therefore has been investigated in various material systems over the last decades. In this context, it has been shown that spin waves become especially dominant during the slower remagnetization processes [2, 3], indicating their contribution to the angular momentum transfer during the process. In our work, we investigate the influence of strong demagnetization induced by ultrashort laser pulses on the coherency and phase of the excited spin waves and whether the coherency is influenced by the degree of demagnetization.

Figure 1(a) shows the magnetization traces for multiple laser pump powers in a Ni film, where a quenching from a few percent up to almost full demagnetization of the sample was achieved.

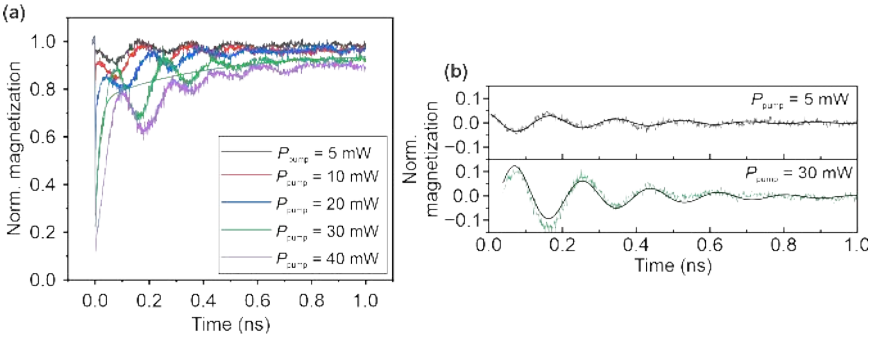

Figure 1: (a) The time-resolved magnetization curves are normalized with respect to the initial magnetization level for selected pump powers. The fast de- and remagnetization are followed by the precession movement of the magnetization around the effective field. (b) The resulting oscillation after removing the exponential background of the ultrafast de- and remagnetization is shown, fitted with a damped sine function.

The largest amplitude of the coherent spin waves is observed for demagnetizations of about 90%, which implies that the coherency of the spin system is still conserved for strongly quenched systems. Interestingly, the phase of the coherent oscillations relative to the initial laser pulse is strongly dependent on the laser fluence, as it is shown in Fig.1(b). Since the demagnetization happens quasi-instantly on the time scale of the coherent precession, this delay must be caused during the remagnetization process. A possible explanation could be that due to the quasi-instant excitation of the system, the magnetization needs to remagnetize to a certain level to allow linear coherent oscillations. Further investigation of this time-dependent behavior will give insight into the generation process of spin waves after ultrafast demagnetization and its related angular momentum transfer.

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REFERENCES

[1] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, "Ultrafast spin dynamics in ferromagnetic nickel", Physical Review Letters **76**, 4250–4253 (1996).

[2] S. Mondal and A. Barman, "Laser controlled spin dynamics of ferromagnetic thin film from femtosecond to nanosecond timescale", Physical Review Applied **10**, `10.1103/physrevapplied.10.054037` (2018).

[3] M. van Kampen, C. Jozsa, J. T. Kohlhepp, et al., "All-optical probe of coherent spin waves", Physical Review Letters **88**, `10.1103/physrevlett.88.227201` (2002).

Spin Dynamics of Skyrmion Lattices in a Chiral Magnet Resolved by Micro-Focused Brillouin Light Scattering

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Chiral magnets provide an innovative framework to study non-collinear spin textures and their associated magnetization dynamics. They include helical and conical magnetic textures that are spatially modulated with a wavevector k_h as well as the topologically non-trivial skyrmion lattice (SkL) phase. So far, different techniques have been used to probe the magnetization dynamics of the latter SkL phase. Whereas magnetic and spin wave resonance spectroscopy are sensitive to magnons with wavevectors $k \ll k_h$, only recently inelastic neutron scattering experiments on MnSi achieved to study the magnon spectra away from the center of the magnetic Brillouin zone for wavevectors $k > k_h$ [1].

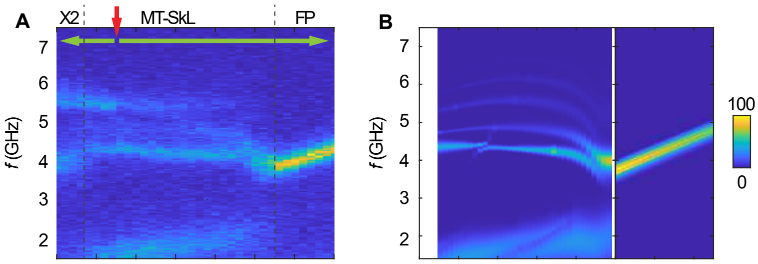

Figure 1: BLS intensity map obtained from the experimental data (A) and the theoretical calculation (B).

Here, we show that Brillouin light scattering (BLS) is ideally suited to probe the complementary range of wavevectors $k \leq k_h$. We study both theoretically and experimentally BLS from bulk spin waves in the SkL phase of Cu$_2$OSeO$_3$ with helix wavevector $k_h = 105\,\text{rad}/\mu m$. Generalizing the theory of Refs. [1, 2], we provide parameter-free predictions for the BLS cross section and compute both the resonances and their spectral weights. We limit ourselves here to the high temperature range where cubic anisotropies are known to be small and negligible [3, 4]. The theoretical results are compared to BLS experiments in the backscattering geometry that probe magnons with a wavevector $k = 48\,\text{rad}/\mu m < k_h$ (*see Figure 1*). The clockwise, counterclockwise and breathing modes already known from magnetic resonance spectroscopy are clearly resolved. Due to the finite wavevector k of the magnon excitations, finite spectral weights are theoretically predicted also for other resonances. Experimentally, at least one additional resonance can be clearly identified.

REFERENCES

[1] T. Weber, D. M. Fobes, J. Waizner, et al., “Topological magnon band structure of emergent landau levels in a skyrmion lattice”, Science **375**, 1025–1030 (2022).

[2] N. Ogawa, L. Köhler, M. Garst, et al., “Nonreciprocity of spin waves in the conical helix state”, Proceedings of the National Academy of Sciences **118**, `10.1073/pnas.2022927118` (2021).

[3] A. Chacon, L. Heinen, M. Halder, et al., “Observation of two independent skyrmion phases in a chiral magnetic material”, Nature Physics **14**, 936–941 (2018).

[4] R. Takagi, M. Garst, J. Sahliger, et al., “Hybridized magnon modes in the quenched skyrmion crystal”, Physical Review B **104**, `10.1103/physrevb.104.144410` (2021).

Poster 1. PA23
Monday
16:30

The Asymmetry Quantification of Spin-Wave Dynamics in Single and Double Confined Rectangular Ni$_{80}$Fe$_{20}$ Microstrips

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Research of the spin-wave (SW) dynamics in confined rectangular microstructures is important for the their potential use for information transport and processing [1]. The design of a microstructure can affect the SW behavior, which can be used as a manipulating mechanism [2, 3]. The development of planar microresonators/microantennas with a micro-coil (loop) allows for measuring FMR of a single ferromagnetic microstrip including resonance lines corresponding to the SW excitations [4, 5]. TR-STXM [6] with the use of the planar microresonators enables direct, time-dependent imaging of the spatial distribution of the precessing magnetization across the nm-thin microstrips during FMR excitation at the GHz frequency range with elemental selectivity [7, 8].

In the present work, the focus is put on a fundamental understanding of the SW behavior in confined rectangular structures under a uniform excitation depending on the mutual positioning of two adjacent microstrips [8]. The SW dynamics were simulated, measured, and imaged over a range of external static magnetic field values at the fixed excitation frequency of 9.43 GHz. In general, the confinement of the structure leads to the quantization of SW k-vectors in the direction of confinement [9]. Under the uniform excitation only SW eigenmodes with an odd number of nodes are expected. This results in a symmetric interference pattern. Changes in the geometry of the structure, such as a presence of an additional rectangular microstrip, can cause the ”breaking” of the symmetry [2]. In this work the asymmetry quantification by an asymmetry parameter (AP) of SW dynamics in confined rectangular microstrips is suggested and applied to the TR-STXM results and micromagnetic simulations. The AP indicates a deviation of a central profile of an interference pattern from the mirror-symmetric state. This indicates an asymmetry in the interference pattern itself. A mirror-symmetric profile here is a profile, which is invariant under a reflection about the central axis. An AP for a profile consisting of normalized data values $\{x_n\}_{n=1}^{N}$ is calculated as follows:

$$AP = \frac{1}{[N/2]} \sum_{n=1}^{[N/2]} \mid x_n - x_{N-n+1} \mid, \qquad (1)$$

where one half of the profile is subtracted from the other one point by point. Then the mean of the absolute values of all differences is taken. If the profile is symmetric, $AP = 0$. In this work profiles of the out-of-plane component of the dynamic magnetization ($m_{oop}(t)$) are analyzed [8]. The central region of the strips is used to calculate the profiles. For the excitation, a uniform microwave field at a frequency of 9.43 GHz was considered, while the external static magnetic field was varied. The results show a higher asymmetry for double microstrips indicating the influence of the additional microstructure placed in close proximity to the analyzed structure.

REFERENCES

[1]A. V. Chumak et al., IEEE Transactions on Magnetics **58**, 1–72 (2022).
[2]P. Clausen et al., Appl. Phys. Lett. **99**, 162505 (2011).
[3]A. V. Sadovnikov et al., Applied Physics Letters **106**, 192406 (2015).
[4]R. Narkowicz et al., J. Magn. Reson **175**, 275–284 (2005).
[5]A. Banholzer et al., Nanotechnology **22**, 295713 (2011).
[6]H. Stoll et al., Front. Phys. **3**, 26 (2015).
[7]S. Pile et al., Appl. Phys. Lett. **116**, 072401 (2020).
[8]S. Pile et al., Phys. Rev. B **105**, 094415 (2022).
[9]C. Bayer et al., Phys. Rev. B **72**, 064427 (2005).

Modification of Three-Magnon Splitting by In-Plane Magnetic Fields

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Over the past few decades, extensive research has been conducted on magnetic vortices due to their fundamental physical properties and potential applications as magnetic storage devices or resonators. Information can be encoded in the polarity or gyrotropic motion of the vortex core. Moreover, magnetic vortices offer a versatile spectrum of radial and azimuthal magnon modes, which exhibit interesting linear and nonlinear dynamics. One notable example is three-magnon splitting, where one mode can spontaneously split into two secondary magnon modes when excited above a threshold power. Three-magnon splitting follows specific selection rules, with the split modes having distinct frequencies and mode numbers to fulfill energy and angular momentum conservation [1]. Magnetic vortices offer the potential to stimulate these processes below their intrinsic threshold powers [2, 3], making them promising candidates for novel computing approaches such as reservoir computing.

In this study, we demonstrate that the application of in-plane magnetic fields in the order of a few mT can efficiently modify three-magnon splitting [4]. Using micromagnetic simulations and Brillouin-light-scattering microscopy, we show that the deformation of the vortex results in additional secondary butterfly modes that follow the same selection rules as the regular modes but exhibit different localization (Figure. 1) and much lower three-magnon splitting threshold powers.

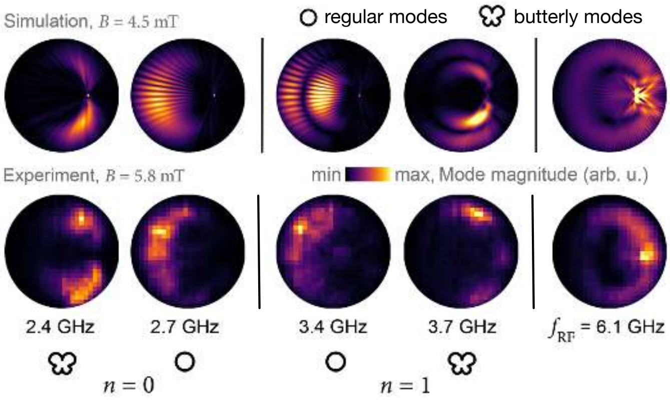

Figure 1: Magnon modes profiles in a displaced magnetic vortex obtained by micromagnetic simulations (top line) and experimentally measured by Brillouin light scattering microscopy (bottom line). Figure adapted from [4].

REFERENCES

[1] K. Schultheiss, R. Verba, F. Wehrmann, et al., “Excitation of Whispering Gallery Magnons in a Magnetic Vortex”, Physical Review Letters **122**, 097202 (2019).

[2] L. Körber, K. Schultheiss, T. Hula, et al., “Nonlocal Stimulation of Three-Magnon Splitting in a Magnetic Vortex”, Physical Review Letters **125**, 207203 (2020).

[3] L. Körber, C. Heins, T. Hula, et al., “Pattern recognition with a magnon-scattering reservoir”, arXiv **2211.02328** (2022).

[4] L. Körber, C. Heins, I. Soldatov, et al., “Modification of three-magnon splitting in a flexed magnetic vortex”, Applied Physics Letters **122**, 092401 (2023).

Poster 1. PA25
Monday
16:30

On the Nature of the Ferromagnetic Resonance Excitations in Cobalt Stripe Domain Structures

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We use a newly developed two-dimensional version of our numerical spin-wave normal mode analysis method [1] to determine the exact nature of the ferromagnetic resonance (FMR) excitations in hcp(0001) Co films, which host magnetic stripe domains [Fig. 1(a)]. Among the modes with moderate frequencies [Fig. 1(b)] none is found to involve strong precession inside the main out-of-plane magnetized domains (so-called domain resonances). On the contrary, all of them are spin-texture confined modes, that is, modes where magnetization dynamics essentially occur within domain walls of various types [Fig. 1(c)]. Several modes show gyration of the Bloch wall cores while others exhibit flexures of the Bloch wall sections. All involve breathing or shearing of the Néel caps.

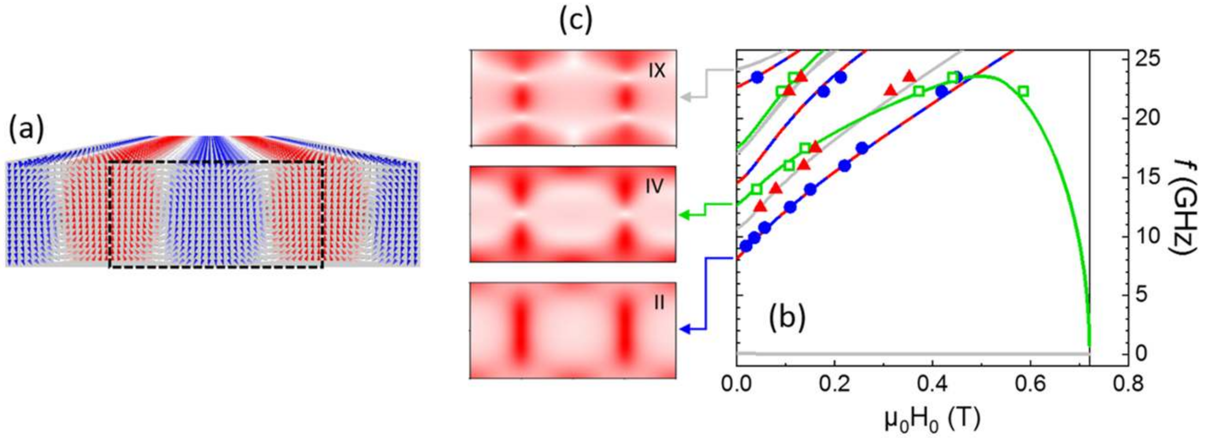

Figure 1: (a) Stripe domain configuration in a Co film with thickness 76 nm as obtained from micromagnetic simulations. Colors correspond to the out-of-plane component of magnetization. (b) Frequency versus longitudinal applied field relations for the FMR modes in the same film. Symbols and lines correspond to results from experiments (Ref. [2]) and numerical simulations, respectively. (c) Cross-sectional maps of the amplitude of the dynamic magnetization in some of the modes.

Additionally, we evidence that FMR modes of stripe domain patterns exhibit unsuspected complexity. Periodicity in the equilibrium magnetic configuration [Fig. 1(a)] produces lateral (perpendicular-to-stripe) finite-size and spin-wave quantization effects. However, because magnetization possesses a large longitudinal (parallel-to stripe) component, especially at the cores of the Bloch walls, usual standing wave pattern cannot form. As a consequence of dynamic dipolar interactions, travelling spin waves form instead, which propagate perpendicular to the stripes, in opposite direction in the top and bottom halves of the films. This phenomenon bears some resemblance with the pseudopropagation evidenced for spin waves confined in a chiral system [3] and in obliquely magnetized films [4].

REFERENCES

[1] Y. Henry, O. Gladii, and M. Bailleul, “Propagating spin-wave normal modes: a dynamic matrix approach using plane-wave demagnetizating tensors”, arXiv: **1611.06153**.

[2] U. Ebels, P. E. Wigen, and K. Ounadjela, “Probing domain wall structures in co(0001) thin films using ferromagnetic resonance”, Europhysics Letters (EPL) **46**, 94–100 (1999).

[3] B. W. Zingsem, M. Farle, R. L. Stamps, and R. E. Camley, “Unusual nature of confined modes in a chiral system: directional transport in standing waves”, Physical Review B **99**, 214429 (2019).

[4] D. A. Bozhko, H. Y. Musiienko-Shmarova, V. S. Tiberkevich, et al., “Unconventional spin currents in magnetic films”, Physical Review Research **2**, 023324 (2020).

Poster 1. PA26
Monday
16:30

Modal Analysis of Axially Symmetric Magnetic Textures

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The linear response of a magnetic texture is accurately determined by its eigen-solution [1], which calculation can be greatly simplified in the presence of a spatial symmetry. This is specially relevant for a large class of complex textured problems (vortex, magnetic bubble, skyrmions etc...), which exhibits axial symmetry. Then one can exactly map the 3D problem onto a 2D one by projection over the azimuthal harmonic functions *i.e.*, $\exp^{i\ell\phi}$, where ℓ is an integer index and ϕ is the azimuthal angle. We have developed a micromagnetic simulation code which allows to exploit such simplification. We use it to calculate the modal solutions of the lowest energy part of the spectrum. The benefits are *i)* a tremendous improvement in the precision of the solutions, *ii)* an inherent classification of the modes by their azimuthal symmetry, and *iii)* the extension of the feasible simulation range to very large sized objects in relation to the micromagnetic length scale.

As an example, we show in Fig.1 the evolution of the azimuthal dispersion of the magnon localized inside a 2 μm diameter and 100 nm thickness YIG disk [2–4], when a normal magnetic field is applied. At low fields, the equilibrium magnetic texture is a vortex state (core radius 15 nm) while at high magnetic field a uniform state along the normal direction is established. The observed evolution points to a continuous morphing of a trivial spectrum, which can be calculated analytically [1] in the saturated state, into a more complex spectral structure when the vortex emergence induces in particular a large split between the modes ($\ell = -1, 0$) conceptually related to the appearance of Goldstone and Higgs modes upon a spontaneous symmetry breaking [5].

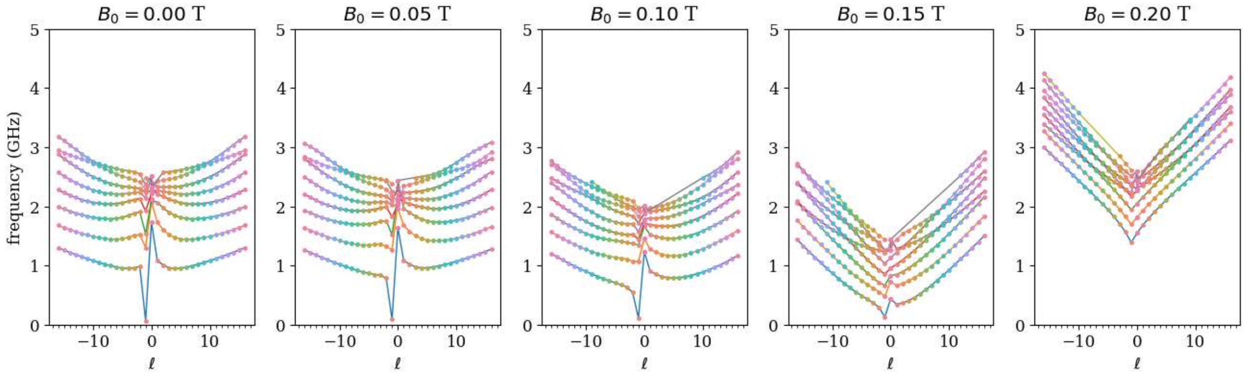

Figure 1: Evolution of the magnon dispersion inside a YIG disk of 2 μm diameter and 100 nm thickness as a function of a normal magnetic field. The abscissa is the azimuthal index ℓ of the eigen-vectors.

REFERENCES

[1]V. V. Naletov, G. de Loubens, G. Albuquerque, et al., “Identification and selection rules of the spin-wave eigenmodes in a normally magnetized nanopillar”, Physical Review B **84** (2011).

[2]K. Y. Guslienko, A. N. Slavin, V. Tiberkevich, and S.-K. Kim, “Dynamic origin of azimuthal modes splitting in vortex-state magnetic dots”, Physical Review Letters **101** (2008).

[3]B. Taurel, T. Valet, V. V. Naletov, et al., “Complete mapping of the spin-wave spectrum in a vortex-state nanodisk”, Physical Review B **93** (2016).

[4]M. Mruczkiewicz, P. Gruszecki, M. Krawczyk, and K. Y. Guslienko, “Azimuthal spin-wave excitations in magnetic nanodots over the soliton background: vortex, bloch, and néel-like skyrmions”, Physical Review B **97** (2018).

[5]M. Grassi, M. Geilen, K. A. Oukaci, et al., “Higgs and goldstone spin-wave modes in striped magnetic texture”, Physical Review B **105** (2022).

Noncommutativity of Parametric Spin Wave Excitations in YIG Disks

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Parametric pumping is an efficient way to populate individual spin wave modes in magnetic microstructures. For mode-based computing, it is important to understand how the existence of an excited mode can influence the generation of another. We examined this question in simulation for 1-μm diameter YIG disks at 300 K, whereby we investigated the transient mode population dynamics which were computed with MuMax3 [1] by projecting the magnetization dynamics onto precomputed eigenmode profiles [2] [Fig. 1(b)]. The figure highlights the main features for two modes, $k = 8, 13$, with frequencies of $f_8 = 2.813$ GHz and $f_{13} = 2.980$ GHz, respectively. Fig. 1(c) shows the evolution of the mode populations when the system is driven at $f_A = 2f_8$ and $f_B = 2f_{13}$ separately, where for the former the $k = 8$ mode dominates while for the latter $k = 13, 14$ modes are excited equally. When these driving frequencies are combined using the toggle sequence in Fig. 1(d), we see from the mode spectrogram that the order of the frequency toggle has a strong bearing on the overall dynamics. We observe mode inhibition, suppression and transitions as the sequence evolves, which differs markedly from the case of single frequency excitation. Such noncommutativity in the nonlinear processes could be exploited for information processing. This work is supported by the Horizon2020 Framework Programme of the European Commission under contract number 899646 (k-Net).

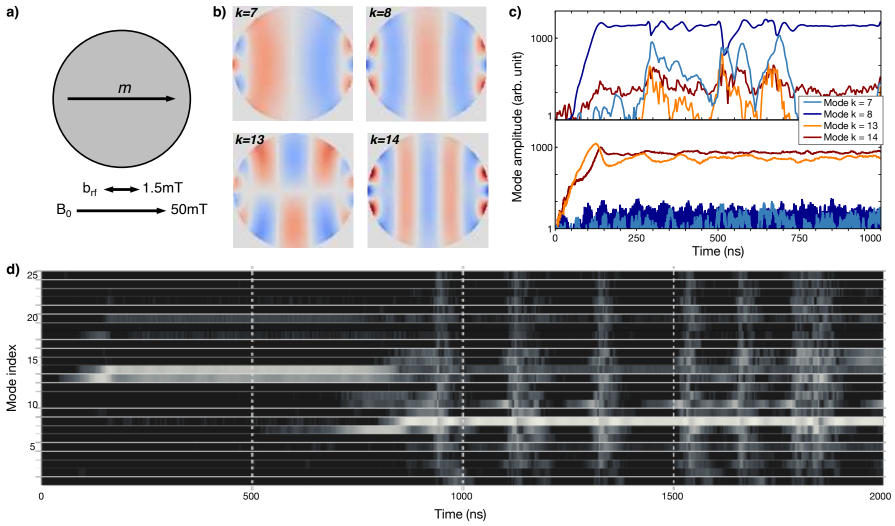

Figure 1: a) Geometry. b) Eigenmode profiles. c) Mode population versus time under a driving frequency of $f_A = 2 \times 2.813$ GHz (top) and $f_B = 2 \times 2.980$ GHz (bottom). d) Pohttps://fr.overleaf.com/project/63f359a0d026f5a4baf19b67pulations of the first 25 modes under the pulse sequence f_A, $f_A + f_B$, f_B, $f_B + f_A$, where the duration of each pulse is 500 ns.

REFERENCES

[1]A. Vansteenkiste, J. Leliaert, M. Dvornik, et al., "The design and verification of mumax3", AIP advances **4**, 107133 (2014).

[2]M. d'Aquino, C. Serpico, G. Miano, and C. Forestiere, "A novel formulation for the numerical computation of magnetization modes in complex micromagnetic systems", Journal of Computational Physics **228**, 6130–6149 (2009).

Spin-Wave Transport in Two-Dimensional Partially-Compensated Ga:YIG Structures

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The idea of using spin waves as data carriers in future computing devices has been developing over the years [1]. However, complex magnonic circuits require efficient guidance of spin waves between data processing and memory units in two dimensions. Even the simplest 90° bend of a magnetic conduit is a challenge due to spin-wave anisotropy in the in-plane magnetised structures or due to the necessity in applying large magnetising fields in the out-of-plane geometry. Several solutions have already been proposed [2, 3].

Here we investigate spin-wave transmission through a 90° bent conduit made of partially compensated Ga:YIG in in-plane and out-of-plane magnetisation geometries. Ga:YIG opens access to operation with fast and isotropic exchange spin waves and has a pronounced uniaxial out-of-plane anisotropy leading to an out-of-plane easy axis. [4] The 500 nm wide and 69 nm thick Ga:YIG waveguide with 90° curvature (Fig. 1a) was fabricated using argon ion beam etching and positive CSAR 62 resist as a hard mask. Spin waves were excited by RF cw or pulsed microwave signals applied to the CPW antenna and detected by space- and time-resolved microfocused Brillouin light scattering (BLS) spectroscopy. The 2D spatial map of spin-wave intensity measured in the out-of-plane magnetisation geometry shows the efficient spin-wave transmission through the curved region - see Fig. 1b. The intensity of the spin waves extracted from the central region of the waveguide after the bent region (Fig. 1c) shows the oscillating pattern associated with the interference between the higher spin-wave width modes [5]. The transmission efficiency is investigated as a function of the width of the nanowaveguide, the curvature of the bent, the magnetisation orientation as well as the spin-wave wavelength. The 2D Ga:YIG structures are great candidates for the implementation in complex magnonic circuits.

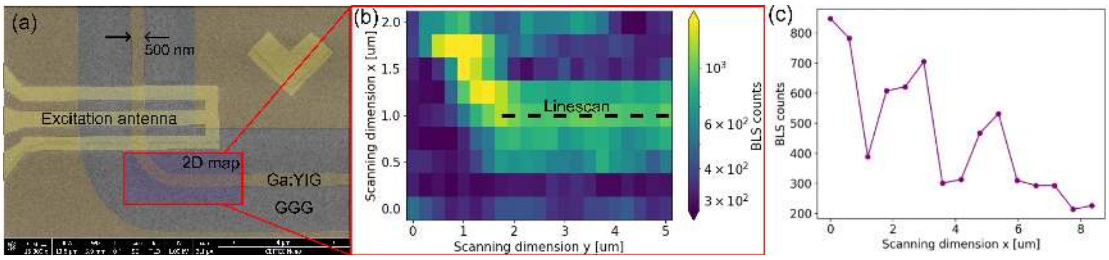

Figure 1: (a) SEM picture of the waveguide under study and the excitation antenna; (b) BLS 2D intensity map in the bent region; (c) spin-wave intensity linescan after passing the bend - position indicated in (b).

REFERENCES

[1] A. V. Chumak, P. Kabos, M. Wu, et al., "Advances in magnetics roadmap on spin-wave computing", IEEE Transactions on Magnetics **58**, 1–72 (2022).
[2] X. Xing, Y. Yu, S. Li, and X. Huang, "How do spin waves pass through a bend?", Scientific reports **3**, 1–6 (2013).
[3] K. Vogt, H. Schultheiss, S. Jain, et al., "Spin waves turning a corner", Applied Physics Letters **101**, 042410 (2012).
[4] T. Böttcher, M. Ruhwedel, K. Levchenko, et al., "Fast long-wavelength exchange spin waves in partially compensated ga: yig", Applied Physics Letters **120**, 102401 (2022).
[5] P. Clausen, K. Vogt, H. Schultheiss, et al., "Mode conversion by symmetry breaking of propagating spin waves", Applied Physics Letters **99**, 162505 (2011).

Poster 1. PA29
Monday
16:30

Long-Distance Coherent Propagation of High-Velocity Antiferromagnetic Spin Waves

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Antiferromagnetic (AFM) magnonics attracts world-wide scientific and industrial interests due to their potential applications in information processing with high speed, low power and high stability [1]. However, zero magnetic moment and high resonance frequency for AFM makes this challenging. Recently, advanced microwave technology based on solid-state extenders enabled frequency multiplication of conventional GHz source into sub-THz generators for all-electrical AFM magnon excitation [2]. Until now, coherent AFM spin waves are electrically excited only with k =0, viz., antiferromagnetic resonance with zero group velocity in canted AFM [3, 4]. High-velocity propagating AFM exchange spin waves with electrical excitation has not yet been realized.

In this work, we demonstrate coherent propagation of AFM exchange spin waves in a canted AFM α-Fe$_2$O$_3$ with Dzyaloshinskii-Moriya interaction (DMI) using all-electrical spin wave spectroscopy. By measuring a series of devices with different propagation distances, we find that the observed AFM spin waves can propagate over a long distance (10 μm) at room temperature with unprecedented high group velocities (up to 22.5 km/s) [5]. We derive analytically an AFM spin-wave dispersion in the presence of DMI which accounts for our experimental data. AFM spin waves excited by nanoscale antennas with large wavevectors enter the exchange regime and follow a quasi-linear dispersion. By fitting experimental data with our theoretical model, we extract an AFM exchange stiffness length of 1.7 Å. In addition, we suggest some other measurements that can further be done in ferrimagnetic or antiferromagnetic insulators systems to build on these results.

Note added– During the revision of this manuscript, we became aware that recent reports on spin-wave dispersion of hematite studied by Brillouin light scattering [6] and nonreciprocial propagation of spin waves in hematite [7] have been posted.

REFERENCES

[1]R. Lebrun, A. Ross, S. Bender, et al., "Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide", Nature **561**, 222–225 (2018).
[2]J. Li, C. B. Wilson, R. Cheng, et al., "Spin current from sub-terahertz-generated antiferromagnetic magnons", Nature **578**, 70–74 (2020).
[3]I. Boventer, H. T. Simensen, A. Anane, et al., "Room-temperature antiferromagnetic resonance and inverse spin-Hall voltage in canted antiferromagnets", Physical Review Letters **126**, 187201 (2021).
[4]H. Wang, Y. Xiao, M. Guo, et al., "Spin pumping of an easy-plane antiferromagnet enhanced by Dzyaloshinskii–Moriya interaction", Physical Review Letters **127**, 117202 (2021).
[5]H. Wang, R. Yuan, Y. Zhou, et al., "Long-distance coherent propagation of high-velocity antiferromagnetic spin waves", Physical Review Letters **130**, 096701 (2023).
[6]M. Hamdi, F. Posva, and D. Grundler, "Spin wave dispersion of ultra-low damping hematite (α-Fe$_2$O$_3$) at GHz frequencies", arXiv preprint arXiv:2212.11887 (2022).
[7]A. E. Kanj, O. Gomonay, I. Boventer, et al., "Evidence of non-degenerated, non-reciprocal and ultra-fast spin-waves in the canted antiferromagnet α-Fe$_2$O$_3$", arXiv preprint arXiv:2301.06329 (2023).

Micromagnetic Study of Parallel Pumping of Spinwaves into CoFeB/By Bilayer with Non Reciprocal Propagation

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Parallel pumping (PP), where the excitation field b_{PP} is applied parallel to the magnetization, is an alternative way to usual thin transverse antennas for inducing propagating spinwaves into thin films. The process of PP results in the generation of pairs of magnons (f_-,k_-) and (f_+,k_+) under frequency $f_{PP} = f_+ + f_-$ and momentum conservation $k_+ + k_- = k_{PP}$ with k_{PP} the wavevector of the pumping field [1]. For a wide antenna, $k_{PP} \approx 0$ so that these two magnons have opposite wavevectors $k_+ = -k_-$.

The CoFeB/Py bilayer previously investigated [2] presenting a highly non reciprocal dispersion curve $f(k)$ (displayed left at the figure) leads to a large frequency splitting for the pair of $primary$ magnons $f_+ - f_- = f(k) - f(-k)$. Surprisingly, our micromagnetic simulations show that $secondary$ magnons having propagating k vectors corresponding to some other eigenmodes at f_+ and f_- frequencies can also be induced. We have determined all potential $primary$ and $secondary$ k vectors assuming $k_{PP} = 0$ using the dispersion curves $f(k)$ of the bilayer first eigenmode. MuMax3 [3] simulations of the parallel pumping have been performed for an infinite CoFeB(20 nm)/Py(26 nm) bilayer using a 16.4 μm wide antenna of constant excitation field b_{PP} [1]. A fair agreement is exhibited since the symbols, corresponding to the (f,k) points get from a time and space Fourier analysis of the outgoing spinwave signal, fit on the curves. We will also discuss the contribution of the second mode which overlaps with the first one over a large range of frequencies. These results confirm that the combination of parallel pumping and non reciprocal dispersion curves results in a rich magnonic behaviour.

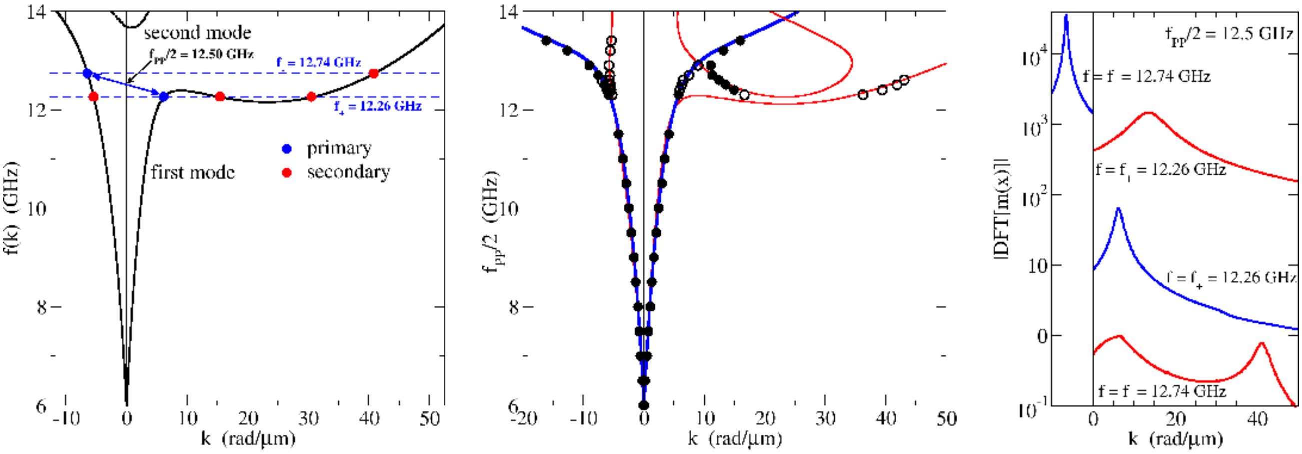

Figure 1: (left) Dispersion curves f(k) for the two first eigenmodes and position of $primary$ (blue circles) and $secondary$ (red circles) magnons derived for $f_{PP}/2 = 12.5$ GHz. (center) Plot of all potential k vectors in the case of a wide parallel pumping at frequency f_{PP} determined from $f(k)$ shown left (blue curves for the $primary$ magnons and red curves for the $secondary$ magnons) and plot of the k values obtained by discret Fourier transform (DFT) from the micromagnetic calculation (symbols). (right) DFT of the outgoing spin wave signal at $f_+ = 12.26$ GHz and $f_- = 12.74$ GHz for $f_{PP}/2 = 12.5$ GHz.

REFERENCES

[1] T. Braecher, P. Pirro, and B. Hillebrands, “Parallel pumping for magnon spintronics: amplification and manipulation of magnon spin currents on the micron-scale”, Physics Reports **699**, 1–34 (2017).

[2] M. Grassi, M. Geilen, D. Louis, et al., “Slow-wave-based nanomagnonic diode”, Phys. Rev. Appl. **14**, 024047 (2020).

[3] A. Vansteenkiste, J. Leliaert, M. Dvornik, et al., “The design and verification of Mumax3”, AIP Advances **4**, 107133 (2014).

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[1] The field b_{PP} has been estimated by requiring that the average reduced parallel magnetization is equal to 0.9999 under the antenna.

Poster 1. PA31
Monday
16:30

Development of a NV-Center Microscope for Spin-Wave Spectroscopy

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Collective spin excitations, or spin-waves, inside a magnet provide a unique spectroscopic signature on the nature of the magnetic material as well as the magnetic texture present inside. The magnetic texture can be either a heterogeneity in the equilibrium configuration (point defect, skyrmion, magnetic bubble, vortex, Bloch point ect...) or the dynamical one (non-linear soliton, bullet mode, or spin-wave droplet). So far, the spectral signature is still mostly incomplete because most of the spin-wave eigen-modes remain undetected due to the difficulties to couple them with spatially averaged quantities. To circumvent this difficulty requires to use a local probe.

To achieve precisely this, we are currently developing a home-made NV-center microscope, whose purpose is to image with nanometer precision the spatio-temporal profile of spin-wave eigen-modes inside a magnetic object [1, 2]. The technical originality of our development is that the NV centre microscope seats between the poles of a 1.4 T electromagnet, as shown in Figure. 1. In addition the originality of our setup is that the field of the electromagnet is defined and stabilised at ppm resolution in order to study ultra narrow spectral features. As a first goal, we want to use this instrument to study the influence of the dynamical pattern on the relaxation process. In magnetic system, the processes of dissipation are generally poorly known, while they are key to several functions exploiting the very long relaxation time of magnetic resonance.

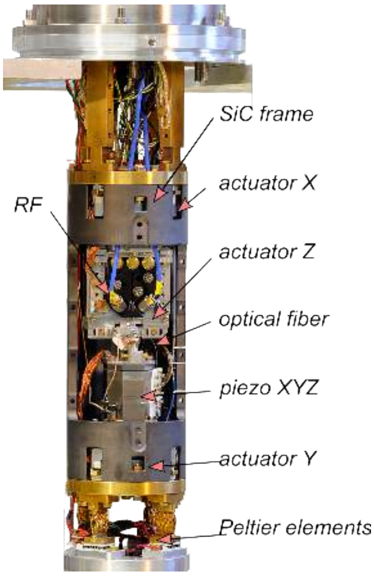

Figure 1: Picture of the NV center microscope developed at Spintec. A SiC frame supports XYZ actuators covering a field of ±2.5mm with a precision of about 10 pm. The non-magnetic assembly is inserted in a 1.4T electromagnet. This preliminary version operates at room temperature.

REFERENCES

[1] Gruber.A, Dräbenstedt.A, Tietz.C, et al., “Scanning confocal optical microscopy and magnetic resonance on single defect centers”, Science **276**, 2012–2014 (1997).

[2] Gross.I, Akhtar.W, Garcia.V, et al., “Real-space imaging of non-collinear antiferromagnetic order with a single-spin magnetometer”, Nature **549**, 252–256 (2017).

Growth of Perpendicular Magnetic Anisotropy in Gallium-substituted Yttrium Iron Garnet Thin Films (Ga:YIG)

K. Lenz[1,*], **Olga Gladii**[1], **Javier Pablo-Navarro**[1], **Antje Oelschlägel**[1], **Jürgen Lindner**[1], **Oleksii Surzhenko**[2], **Carsten Dubs**[2]
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The continuously growing interest on high-quality thin yttrium iron garnets (YIG) as materials with large potential application in different areas of modern physics, motivates enormous researches of its magnetic, optic, and microwave properties. Possessing an extremely low Gilbert-damping parameter, this material is the premier candidate for magnon-based devices, allowing for the coherent propagation of magnons over long distances [1, 2]. The properties of the thin film certainly depend on the growth technique and conditions, but in addition, they can be modified on demand by ion doping and substitution in order to obtain desirable properties for some specific applications. In particular, a lot of attempts have been focused on the modification of magnetic easy axis direction, where the main approach is related to the strain-induced magnetoelastic anisotropy as a result of the lattice mismatch between substrate and film [3, 4]. On the other hand, a significant perpendicular anisotropy can be also achieved by epitaxial tensile strain, which arises from substituting Fe with other elements like Tm [5] or Bi [6].

In this study, we investigate the effect of Ga substitution on the magnetic properties of nanometer-thin YIG films grown by liquid phase epitaxy (LPE). Vibrating sample magnetometry and broadband ferromagnetic resonance (VNA-FMR) measurements were performed to extract the static and dynamic magnetic characteristics of the Ga-substituted YIG (Ga:YIG, $Y_3Fe_{5-x}Ga_xO_{12}$). The content of Ga ions was varied between 1.1–1.3% in samples with variable film thickness from 30 to 230 nm. Our study shows, that the presence of Ga ions induces a strong reduction of the remanent magnetization. It also leads to an increased tensile strain caused by the growing lattice mismatch. In turn, these two factors result in a considerable enhancement of the out-of-plane uniaxial anisotropy making thin Ga:YIG films perpendicularly magnetized. We also demonstrate that, independent of the thickness and of the substrate used (GGG(111) or GGG(001)), the perpendicular magnetic anisotropy gradually increases by increasing the Ga-content, resulting in a 14 times larger perpendicular anisotropy for 1.3% Ga-content compared to pure YIG. This implies that the magnetic anisotropy can be easly tuned by simply varying the Ga concentration. The Gilbert-damping slightly increases with the amount of Ga.

Therefore, our investigation noticeably complements existing studies on magnetic materials with on demand growing perpendicular anisotropy, using the concept of structural modification by ion doping.

REFERENCES

[1] J. J. Carmiggelt, O. C. Dreijer, C. Dubs, O. Surzhenko, and T. van der Sar, “Electrical spectroscopy of the spin-wave dispersion and bistability in gallium-doped yttrium iron garnet”, Appl. Phys. Lett. **119**, 202403 (2021).
[2] T. Böttcher, M. Ruhwedel, K. O. Levchenko, et al., “Fast long-wavelength exchange spin waves in partially compensated Ga:YIG”, Appl. Phys. Lett. **120**, 102401 (2022).
[3] G. Li, H. Bai, J. Su, et al., “Tunable perpendicular magnetic anisotropy in epitaxial $Y_3Fe_5O_{12}$ films”, APL Mater. **7**, 041104 (2019).
[4] M. Kubota, A. Tsukazaki, F. Kagawa, et al., “Stress-induced perpendicular magnetization in epitaxial iron garnet thin films”, Appl. Phys. Expr. **5**, 103002 (2012).
[5] O. Ciubotariu, A. Semisalova, K. Lenz, and M. Albrecht, “Strain-induced perpendicular magnetic anisotropy and gilbert damping of $Tm_3Fe_5O_{12}$ thin films”, Sci. Rep. **9**, 17474 (2019).
[6] L. Soumah, N. Beaulieu, L. Qassym, et al., “Ultra-low damping insulating magnetic thin films get perpendicular”, Nat. Comms. **9**, 3355 (2018).

Poster 1. PA33
Monday
16:30

Inversion of the Polarity of Angular Velocity inside a Precessing Magnet

Giovanni Olivetti[1,*], **Thierry Valet**[1], **Grégoire De Loubens**[2], **Kei Yamamoto**[3], **Yoshichika Otani**[4,5], **Benjamin Pigeau**[6], **Olivier Klein**[1]
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Recent progress in magneto-acoustic effect have demonstrated the benefits of using circularly polarized vector fields to excite the magnetization dynamics [1–3]. In this case, a discrimination occurs depending on the sense of gyration and it is often assumed that the proper polarity of angular velocity is uniquely set by the direction of equilibrium magnetization and the sign of the gyromagnetic ratio.

Using an axisymmetric eigen-solver (see T. Valet abstract), we have found numerically that the above statement is in general not true and the angular velocity can spatially changes its sign relative to the magnetization vector. It emerges in finite size object due to self-demagnetizing effect, where a spin-wave minimizes its magnetostatic energy by inverting its sense of gyration. This leads to the spatial segregation of the magnetization dynamics in different regions with opposite angular velocity.

As an example we compare in Fig.1 the dynamics of two Walker modes propagating either clockwise or counter-clockwise along the edge of a normally magnetized disk. For each eigen-value, ω_0, the eigen-solver associates two eigen-vectors $\mathbf{m}_{0^\circ}$ and $\mathbf{m}_{90^\circ}$, respectively the phase and the quadrature, which allows to reconstruct the time evolution of the dynamical magnetization $\mathbf{m} = \mathbf{m}_{0^\circ} \cdot \cos(\omega_0 t) - \mathbf{m}_{90^\circ} \cdot \sin(\omega_0 t)$. Using the colormap shown in the legend, we plot the spatial variation of the angle between $\mathbf{m}_{0^\circ}$ and $\mathbf{m}_{90^\circ}$ for two indices $\ell = \pm 8$. Here a change of color indicates a change in the direction of rotation.

The implications of our findings are relevant to the conservation of total angular momentum inside a magnetic system.

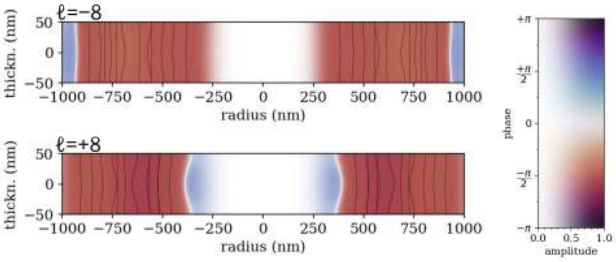

Figure 1: Comparison of the dynamics of two Walker modes with azimuthal indices $\ell = \pm 8$ propagating along the edge of disk. The figure is a view along a sagittal section. The colormap shows the angle between $\mathbf{m}_{0^\circ}$ and $\mathbf{m}_{90^\circ}$ respectively the phase and quadrature eigen-vectors.

REFERENCES

[1]M. Xu, K. Yamamoto, J. Puebla, et al., "Nonreciprocal surface acoustic wave propagation via magneto-rotation coupling", Science Advances **6** (2020).
[2]K. An, A. N. Litvinenko, R. Kohno, et al., "Coherent long-range transfer of angular momentum between magnon kittel modes by phonons", Physical Review B **101** (2020).
[3]K. An, R. Kohno, A. Litvinenko, et al., "Bright and dark states of two distant macrospins strongly coupled by phonons", Physical Review X **12** (2022).

Spin-Wave Dynamics in Curved Magnets

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Spin waves, also known as magnons, are fascinating in the field of condensed matter physics, where they play a key role in the dynamics of magnetic materials. Recent research in this area has focused on the study of spin waves in low-dimensional systems, such as thin films, nanowires, and two-dimensional materials [1]. In this context, new developments are spin waves in curved magnetic geometries [2].

Recent research has predicted a curvature-induced spin wave non-reciprocity effect in ferromagnetic nanotubes and curved magnetic thin shells in magnetic vortex state (VS) [3, 4]. This effect arises due to dipolar interaction and the curvature-induced symmetry breaking. To observe this asymmetric dispersion, magnetic half-pipe structures as shown in figure 1 are being investigated and characterized.

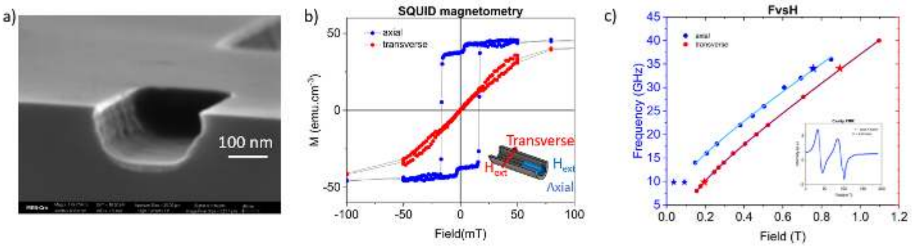

Figure 1: a) SEM imaging of cross-sectional view of a magnetic half pipe on a silicon susbtrate. b) SQUID measurements of an array of Permalloy half pipes c) Ferromagnetic resonance in configuration H_{ext} $\perp$ and $||$ to the axis of the half pipe. Circles: coplanar waveguide FMR, stars: cavity FMR, inset: cavity FMR spectrum at 34GHz in transverse configuration.

We fabricate half-pipe structures using pre-patterned intrinsic silicon substrate and permalloy (Py=Ni80Fe20) as shown in figure 1. Isotropic etching was achieved through reactive ion etching using SF_6 [5], resulting in the formation of the desired structures. We conducted magnetic characterization using SQUID magnetometry and ferromagnetic resonance (coplanar waveguide and cavity FMR) in both the axial and transverse configurations. All measurements show a sizeable uniaxial magnetic anisotropy with easy axis along the half-pipe.

REFERENCES

[1] A. B. et al., “The 2021 magnonics roadmap”, Journal of Physics: Condensed Matter **33**, 413001 (2021).
[2] R. Streubel, F. Kronast, P. Fischer, et al., “Retrieving spin textures on curved magnetic thin films with full-field soft x-ray microscopies”, Nature Communications **6**, `10.1038/ncomms8612` (2015).
[3] J. A. Otálora, M. Yan, H. Schultheiss, R. Hertel, and A. Kákay, “Curvature-induced asymmetric spin-wave dispersion”, Physical Review Letters **117**, `10.1103/physrevlett.117.227203` (2016).
[4] L. Körber, R. Verba, J. A. Otálora, et al., “Curvilinear spin-wave dynamics beyond the thin-shell approximation: magnetic nanotubes as a case study”, Physical Review B **106**, `10.1103/physrevb.106.014405` (2022).
[5] P. Panduranga, A. Abdou, Z. Ren, R. H. Pedersen, and M. P. Nezhad, “Isotropic silicon etch characteristics in a purely inductively coupled sf$_6$ plasma”, Journal of Vacuum Science & Technology B **37**, 061206 (2019).

Poster 1. PA35
Monday
16:30

Static and Dynamic Magnetic Properties of Two-Dimensional Van Der Waals Materials: Vanadium-Based Transition-Metal Dichalcogenides, $\mathrm{VX_2}$ for $\mathrm{X}=$ S, Se, and Te.

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There is currently a great interest in two-dimensional (2D) Van der Waals magnetic materials, and many various groups of these materials have already been synthesized. In this presentation we will describe basic magnetic properties of one group of such materials, referred to as Vanadium-based transition-metal dichalcogenides, $\mathrm{VX_2}$ (where X = S, Se, Te). These materials became interesting due to their potential for use in future electronic and spintronic devices, such as atomically thin spin valves, non-volatile memory elements, or gates for information processing [1–3].

To determine the magnetic properties of these materials, we have employed two different methods; (i) the Density Functional Theory (DFT), and (ii) spin Wave theory in the case of magnetic excited states. More specifically, we calculated the spin-resolved band structures for both monolayers and bilayers of these materials (which were found to be in excellent agreement with previous results [4–6]), and then we utilized these results to determine important parameters describing magnetic properties, such as magnetic anisotropy constants and exchange parameters between Vanadium atoms. These parameters have been then used to calculate the Curie temperatures, hysteresis curves, and especially frequency (energy) of spin wave excitations. The latter has been determined from the numerical Quantum ATK code package [7] as well as from the spin wave theory based on the corresponding effective spin Hamiltonian. Results obtained from these two methods are in good agreement as shown in Figure below. Interestingly, we have found that the Curie temperature for $\mathrm{VTe_2}$ monolayers and bilayers is below the room temperature, especially for bilayers, whereas for $\mathrm{VS_2}$ and $\mathrm{VSe_2}$ it is close to or above the room temperature, which is consistent with available experimental data. This indicates that these materials (especially $\mathrm{VTe_2}$) could be useful for some applications, including advanced spintronic devices.

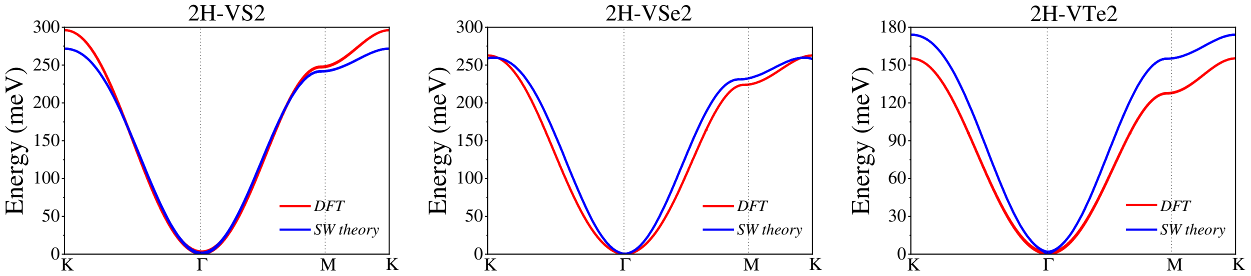

Figure 1: Spin waves obtained from numerical calculations within the ATK package (red line) and from spin wave theory based on the corresponding effective spin Hamiltonian (blue line).

This work has been supported by the Norwegian Financial Mechanism 2014- 2021 under the Polish-Norwegian Research Project NCN GRIEG "2Dtronics" no. 2019/34/H/ST3/00515.

REFERENCES

[1] A. Fert, Reviews of Modern Physics **80**, 1517 (2008).
[2] E. Montoya et al., Physical Review Letters **113**, 136601 (2014).
[3] J. Moodera et al., Physical Review Letters **61**, 637 (1988).
[4] H.-R. Fuh et al., Scientific Reports **6**, 32625 (2016).
[5] M. Jafari et al., Journal of Magnetism and Magnetic Materials **548**, 168921 (2022).
[6] Y. Ma et al., ACS nano **6**, 1695–1701 (2012).
[7] S. Smidstrup et al., Physical Review B **96**, 195309 (2017).

Poster 1. PA36
Monday
16:30

Scattering of Magnetostatic Surface Modes of Ferromagnetic Films by Geometric Defects

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A problem of interest in the area of Magnonics is the propagation of spin waves in thin ferromagnetic films or stripes. Presently this interest is related with the possibility of using spin waves as a practical mechanism of transferring information within nano-devices, either coded in their amplitudes or phases. In particular, to elucidate the effect of geometric obstacles or simply roughness in their propagation is of relevance for practical applications. The present study focuses on the scattering of particular spin wave modes in a particular geometry of interest: the propagation of magnetostatic Damon-Eshbach surface waves [1] in ferromagnetic films, these are modes that propagate perpendicularly to the magnetization and that may have high group velocities. We consider that the surfaces of the films have localized geometric modulations perpendicular to the direction of propagation of the waves, that may be of arbitrary shape, but in particular we consider in this study bumps and depressions. The analysis of the effect of the obstacles in the spin wave flow of energy allows to define transmission and reflection coefficients of the scattering process. These coefficients may be simply obtained in terms of phase shifts of even and odd modes that describe the scattering solutions of the same frequency. We determine these spin wave modes with symmetry properties through the Green-Extinction theorem [2, 3], that renders sets of integral equations for the modes evaluated on the geometrically modified surfaces: at the end a standard matrix eigenvalue problem renders the frequencies, shape of the modes and their phase shifts. Depending on the shape of the obstacles, from the band of surface modes we do see emerging localized modes: these emerge from the highest frequency of the band, that corresponds to the frequency of surface modes in semi-infinite media. Also, depending on the shape of the obstacles the transmission coefficient presents frequency dependent regions of high transmission, that are associated with resonant modes of the geometry.

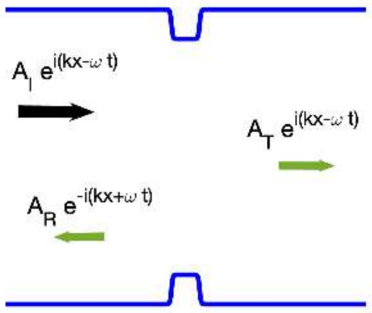

Figure 1: Scattering waves

REFERENCES

[1] R. Damon and J. Eshbach, “Magnetostatic modes of a ferromagnet slab”, Journal of Physics and Chemistry of Solids **19**, 308–320 (1961).
[2] R. Arias and D. L. Mills, “Magnetostatic modes in ferromagnetic nanowires”, Phys. Rev. B **70**, 094414 (2004).
[3] R. E. Arias, “Spin-wave modes of ferromagnetic films”, Phys. Rev. B **94**, 134408 (2016).

Poster 1. PA37
Monday
16:30

Spin Waves in Ferrimagnets at and around the Angular Magnetization Compensation Temperature: A Micromagnetic Study

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Magnon propagation in antiferromagnetic (AFM) and/or ferrimagnetic (FiM) insulators has drawn attention recently due to the benefits as opposed to their ferromagnetic (FM) counterparts, such as higher fundamental frequency and insensitivity to external magnetic field perturbations. Spin wave (SW) propagation in these materials connects magnonics with spintronics, since spin current is mainly transported by magnons.

Here, SW propagation along a FiM strip with out-of-plane magnetization is studied by means of micromagnetic simulations. The FiM material is considered as formed by two antiferromagnetically coupled sublattices, each having its own temperature dependent saturation magnetization. Two critical temperatures can be defined for such systems: that of magnetization compensation (T_M) and that of angular momentum compensation (T_A), both different due to distinct Landé factors for each sublattice. SWs in the strip are promoted by a spin current injected at one of its edges. This current is modulated as to determine the dispersion curves shown in Figure. 1.

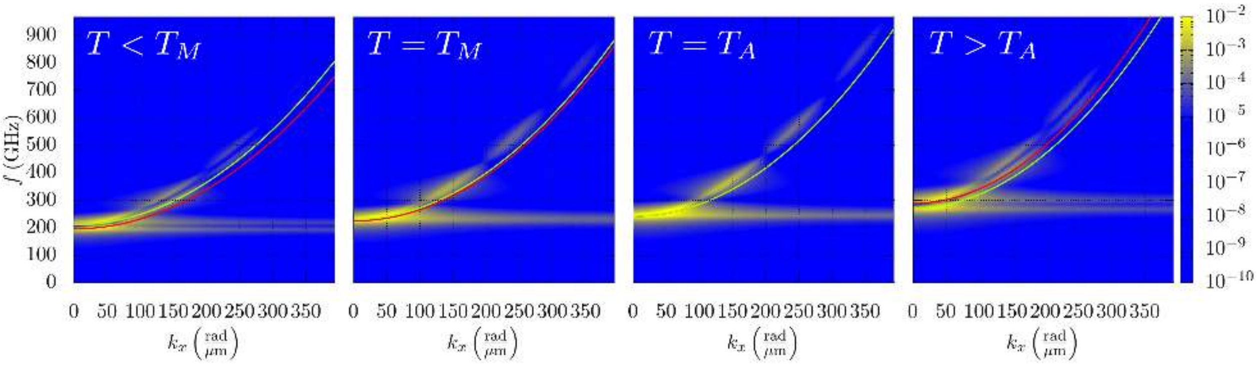

Figure 1: Dispersion curves for a FiM at different temperatures, including the relevant cases of both magnetization and angular momentum compensation.

From the figure, the exchange-dominated character of the SWs can be verified, in the form of a k^2-dependent mode frequency. Solid curves show the fitting to the data from Kalinikos and Slavin's theory[1], when each sublattice magnetization is modeled as of separate effective FM. These curves reveal that SWs travel with different phase velocities through each sublattice except at T_A. As a result, the in-plane components of the Neel vector describes elliptic trajectories where the orientation of their axes is found to be position dependent whereas their eccentricity is determined by the temperature. Consequently, different positions are subjected to different torques, not only by the amplitude fading but because this reorientation effect. Therefore, fine control of magnetization by means of SWs in FiM materials must take into account the reported effect.

REFERENCES

[1] B. A. Kalinikos and A. N. Slavin, "Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions", Journal of Physics C: Solid State Physics **19**, 7013–7033 (1986).

Poster 1. PA38
Monday
16:30

Spin Wave Properties of CoFeB Grown on Piezoelectric Substrates

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The elastic coupling between a magnetic film and the substrate is desired in SAW-FMR devices [1–3] and in magnetoacoustics [4] when one harness the interaction between a surface acoustic wave (SAW) hosted by a piezoelectric substrate and the ferromagnetic resonance (FMR) of the magnetic film. We study CoFeB single films grown on various crystalline orientations of $\mathrm{LiNbO_3}$ substrates and on oxidized silicon [5]. We identify the annealing conditions that are appropriate to induce or suppress uniaxial anisotropy. Anisotropy fields can be increased by annealing up to 11 mT when using substrates with anisotropic surfaces. They can be decreased to below 1 mT when using isotropic surfaces. In the first case, the increase in anisotropy originates from the biaxial strain in the film caused by the anisotropic thermal contraction of the substrate when back at room temperature after strain relaxation during annealing. In the second case, anisotropy is progressively removed by applying successive orthogonal fields that are assumed to progressively suppress any chemical ordering within the magnetic film. The method can be applied to CoFeB/Ru/CoFeB synthetic antiferromagnets (SAFs) but the tuning of the anisotropy comes with a decrease of the interlayer exchange coupling and a drastic change of the exchange stiffness. Particularly, vanishing anisotropy is required for resonant coupling between the SAW and the spin waves in SAFs [6].

We have also combined broadband FMR and FMR microscopy techniques to study spin waves properties in the magnetic films grown on $\mathrm{LiNbO_3}$ substrates. We were particularly interested on the coupling between the acoustic media and the magnetic films.

REFERENCES

[1] M. Weiler, L. Dreher, C. Heeg, et al., “Elastically driven ferromagnetic resonance in nickel thin films”, Phys. Rev. Lett. **106**, 117601 (2011).
[2] P. Kuszewski, J.-Y. Duquesne, L. Becerra, et al., “Optical probing of rayleigh wave driven magnetoacoustic resonance”, Phys. Rev. Appl. **10**, 034036 (2018).
[3] P. Rovillain, J.-Y. Duquesne, L. Christienne, et al., “Impact of spin-wave dispersion on surface-acoustic-wave velocity”, Phys. Rev. Appl. **18**, 064043 (2022).
[4] M. Küß, M. Albrecht, and M. Weiler, “Chiral magnetoacoustics”, Front. Phys. **10**, `https://doi.org/10.3389/fphy.2022.981257` (2022).
[5] R. Lopes Seeger, F. Millo, A. Mouhoub, et al., “Effect of annealing on magnetic properties of cofeb thin films grown on various substrates”, in preparation (2023).
[6] R. Verba, V. Tiberkevich, and A. Slavin, “Wide-band nonreciprocity of surface acoustic waves induced by magnetoelastic coupling with a synthetic antiferromagnet”, Phys. Rev. Appl. **12**, 054061 (2019).

Resonant Dynamics of Three-Dimensional Skyrmionic Textures in Thin Film Multilayers

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The rich and diverse eigen-excitations of non-collinear magnetic textures called skyrmions, in the GHz range, can offer a multitude of exploitable properties for magnonics [1–3]. While their dc current-driven dynamics in thin films have been extensively studied, their microwave response remains largely unexplored owing to large damping coefficients.

Here, we discuss the resonant dynamics of skyrmionic textures in thin-film multilayers of Pt/FeCoB/AlOx at room temperature [4], in particular, the observation of a high-frequency mode (> 12 GHz), which is made possible by a comparatively low Gilbert damping constant of ∼0.02. Magnetic force microscopy measurements reveal a variety of domain states as the field is swept, including skyrmion lattices, where they are found via micromagnetic simulations to comprise complex three-dimensional structures driven by the magnetic interactions in these multilayers. From broadband ferromagnetic resonance experiments (Figure. 1a), we identify modes at low (< 2 GHz) and intermediate frequencies ($2 - 8$ GHz), which represent localized excitations and the precession of the uniform background magnetization, respectively. The high-frequency mode involves the coherent precession of the skyrmion cores (Figure. 1b). Strikingly, this precession generates spin waves with wavelengths in the 50–80 nm range, which flow into the uniformly magnetized background. Our findings suggest new avenues to explore spin wave generation in the deep submicron regime, along with microwave processing schemes using reconfigurable arrays of solitons on the nanoscale.

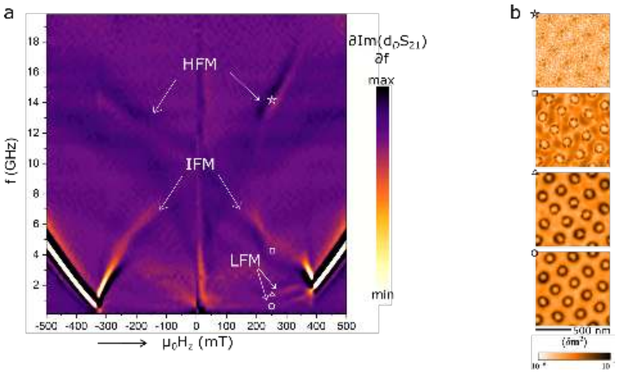

Figure 1: (a) Frequency-field dispersion measured by FMR over a frequency range of 0.1 to 20 GHz with an out-of-plane field. (b) Simulations: Time-averaged dynamic response of the norm of the transverse component $\langle \delta m^2 \rangle$ in response to the in-plane excitation field at four different resonant frequencies marked by symbols on the resonance map in (a).

REFERENCES

[1]H. Yu, J. Xiao, and H. Schultheiss, “Magnetic texture based magnonics”, Physics Reports **905**, 1–59 (2021).
[2]M. Garst, J. Waizner, and D. Grundler, “Collective spin excitations of helices and magnetic skyrmions: review and perspectives of magnonics in non-centrosymmetric magnets”, J. Phys. D Appl. Phys. **50**, 293002 (2017).
[3]A. Fert, N. Reyren, and V. Cros, “Magnetic skyrmions: advances in physics and potential applications”, Nat. Rev. Mater. **2**, 17031 (2017).
[4]T. Srivastava, Y. Sassi, F. Ajejas, et al., “Resonant dynamics of skyrmion lattices in thin-film multilayers: localised modes and spin wave emission”, `10.48550/arXiv.2111.11797` (2021).

Damping in Garnet Microdisks Coupled to Microwave Antennas

Gabriel Soares[1,*], **Rafael Lopes Seeger**[1], **Amel Kolli**[1], **Igor Ngouagnia**[1], **Titiksha Srivastava**[1],
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Magnetic garnet thin films, with thicknesses of 10 to 100 nm, damping parameters in the 10^{-4} range, and tunable anisotropy can now be routinely grown by liquid phase epitaxy (LPE) [1] and pulsed laser deposition (PLD) [2]. For magnonic applications, these films often have to be patterned at the (sub)micron-scale and coupled to microwave antennas. As such, it is important to monitor the damping after these stages [3]. In this work, we use MRFM to study the evolution of the damping as a function of the diameter of microdisks patterned from 30 nm thick PLD BiYIG and 52 nm thick LPE YIG films. Narrow microwave antennas made of Ti/Au are integrated either on top of or beside the disks. When the antenna is directly patterned on top of the disks (keeping the e-beam resist mask), we observe an increased damping as the diameter decreases, due to spin pumping at the disk periphery between the YIG and Ti/Au. Inserting an insulating layer between the YIG microdisks and the metallic antenna leads to the opposite behavior: a reduced damping as the diameter goes down (Fig. 1b). We ascribe it to radiation damping [4], which scales up with the volume of the magnetic sample. We also verify that the microdisks beside the antenna have smaller inductive coupling, and therefore a smaller damping. This work has received financial support from the Horizon 2020 Framework Programme of the European Commission under FET-Open grant agreement no. 899646 (k-NET).

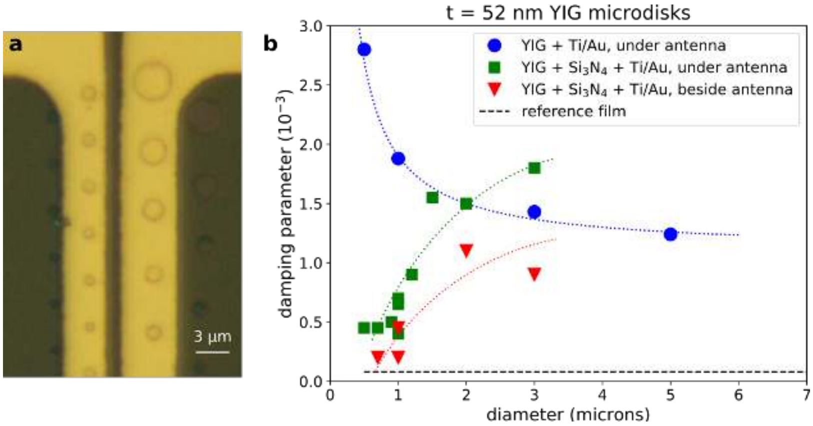

Figure 1: (a) Optical image of the 52 nm thick YIG microdisks and integrated antennas. (b) Dependence of the damping parameter on diameter in different configurations. Dotted lines are guides to the eye.

REFERENCES

[1] N. Beaulieu, et al., “Temperature dependence of magnetic properties of a ultrathin yttrium-iron garnet film grown by liquid phase epitaxy: effect of a Pt overlayer”, IEEE Magn. Lett. **9**, 1–5 (2018).

[2] L. Soumah, et al., “Ultra-low damping insulating magnetic thin films get perpendicular”, Nat. Commun. **9**, 3355 (2018).

[3] C. Hahn, et al., “Measurement of the intrinsic damping constant in individual nanodisks of $Y_3Fe_5O_{12}$ and $Y_3Fe_5O_{12}$|Pt”, Appl. Phys. Lett. **104**, 152410 (2014).

[4] M. A. W. Schoen, et al., “Radiative damping in waveguide-based ferromagnetic resonance measured via analysis of perpendicular standing spin waves in sputtered permalloy films”, Phys. Rev. B **92**, 184417 (2015).

Spin Dynamics with Inertia in Ultrathin Permalloy Films

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The dynamics of spins is usually described by the well-known Landau–Lifshitz–Gilbert (LLG) equation. However, recent theoretical studies have found another term, corresponding to the inertia of spin and the LLG equation is reformulated including this term with the new abbreviation inertial LLG (ILLG) equation [1],

$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H}_{\text{eff}} + \frac{\alpha}{M_{\text{S}}} \vec{M} \times \frac{d\vec{M}}{dt} + \gamma \vec{M} \tau \frac{d^2\vec{M}}{dt^2} \tag{1}$$

The ILLG equation predict the occurance of spin nutation, at a much higher frequency (in the sub-terahertz range) than that for spin precessions (typically in the gigahertz range). We have studied the spin dynamics of $\mathbf{Ni_{80}Fe_{20}}$ films (thicknesses of 2.8 nm and 5 nm) by time-resolved magneto optical Kerr effect (TR-MOKE) technique. We first study the precessional dynamics followed by fs laser induced ultrafast demagnetization. We observe that the precessional relaxation time increases with increase of applied magnetic field and decreases with increase of pump fluence. With lowering magnetic fields and increasing pump fluence, the probability of excitation of incoherent magnons in ultrathin films becomes more as compared to the coherent magnons, leading to a lower value of precessional relaxation time due to two-magnon scattering or multi magnon scattering.

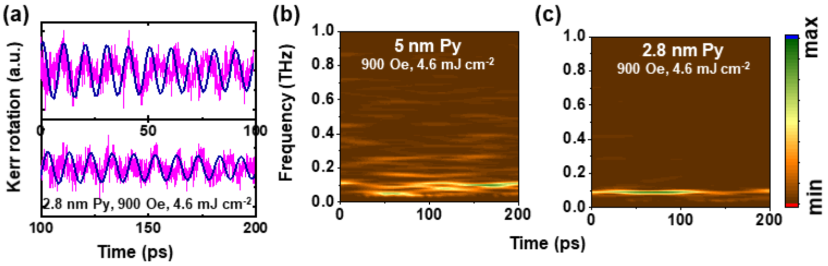

Figure 1: (a) Time-resolved data set at different time scales for Py (2.8 nm) sample measured at 900 Oe magnetic field and 4.6 mJ cm^{-2} pump fluence. Frequency vs. time plot for (b) 5 nm Py and (c) 2.8 nm Py measured at same condition as (a)

On short time scales, the usual precession behaviour is enriched by nutation as predicted theoretically. To verify this experimentally, we record the time-resolved data up to 300 ps with much higher resolution and subtract the FMR background. We scanned the time-resolved traces (with an interval of 100 ps), and performed FFT in each successive time window. The resulting frequency vs. time profile show a clear mode at ~ 0.1 THz in all cases (Fig. 1), which we assign to the nutation of spins[1, 2]. The nutation frequency has a negligible dependence on magnetic field and film thickness.

The authors acknowledge the support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through No. TRR 173-268565370 (Project B11).

REFERENCES

[1] M.-C. Ciornei, J. M. Rubì, and J.-E. Wegrowe, "Magnetization dynamics in the inertial regime: nutation predicted at short time scales", Phys. Rev. B **83**, 020410 (2011).
[2] V. Unikandanunni, R. Medapalli, M. Asa, et al., "Inertial spin dynamics in epitaxial cobalt films", Phys. Rev. Lett. **129**, 237201 (2022).

Micromagnetic Simulations of Magnon Nonlinear Interactions in a YIG Disk Magnetic Vortex

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Several approaches are being researched to reduce energy consumption in data processing. One such approach is reservoir computing, which involves using a nonlinear dynamic system to perform computational tasks [1]. In particular, the nonlinear interactions between magnons can be utilized to perform reservoir computing in modal space [2]. This work presents micromagnetic simulations to study these nonlinear interactions in YIG disks in a vortex state. We use MuMax3, a software that utilizes finite difference discretization of space, to perform the micromagnetic simulations. The disks have a thickness of 65 nm and a diameter ranging from 500 nm to 5 μm.To investigate the effect of the disk size on the magnon frequencies, we excite the disks in the r.f. range by using a spatially uniform cardinal sine function perpendicular to the disk plane. This allows to obtain the linear response of the magnons - see central panel of Fig 1 - as well as the mode profiles with some examples of these in the side panels of Fig 1. As the size of the magnetic disk decreases, the mode frequencies and the spacing between them increase because the magnons experience stronger magnetostatic confinement. The first two modes with low power spectral density (PSD) behave like azimuthal modes due to the in-plane anisotropy. The confinement and the anisotropy affect the spatial profiles. Applying an r.f. magnetic field amplitude of 0.1 mT to the 500 nm disk corresponds to the onset of the nonlinear interactions. At 2.92 GHz excitation frequency which corresponds to the first radial mode number in Fig.1, we observe four modes distributed equally around the directly excited magnons with a frequency spacing of 170MHz. Studying the evolution of the in plane component of the magnetization with time gives a gyration of the vortex with a frequency of 170 MHz. Increasing the r.f. field excitation to 0.5 mT, we distinguish a higher number of modes. Broadening this work to higher frequencies as well as larger disks is required to determine the reason of the gyration motion and to identify if another type of interaction will appear.

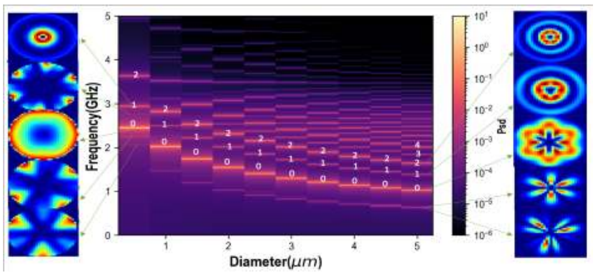

Figure 1: The power spectral density map at different excitation frequencies for YIG disks with different diameters with some spatial profiles. The numbers in the central panel represent the radial number.

ACKNOWLEDGEMENT

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)] and by the European Commission under FET-Open Grant No. 899646 (K-NET).

REFERENCES

[1]G. Tanaka et al., Neural Networks **115**, 100–123 (2019).
[2]L. Körber et al., arXiv preprint arXiv:2211.02328 (2022).

Poster 1. PA43
Monday
16:30

Efficient Spin-Wave Transmission in YIG/Pt-Interfaced Structures

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Magnonics and magnon spintronics address the transfer and processing of information using Spin Waves (SW) and their quanta, magnons. One of the main challenges for this field is the limited lifetime of magnons, even in a low-damping material such as single-crystal Yttrium Iron Garnet (YIG). A possible way to overcome this problem is the compensation of the SW damping via the transfer of a spin torque to a magnetic medium using a spin-polarized electron current in an adjacent non-magnetic metal layer. Such magnetic heterostructures, consisting of single crystal YIG films coated with platinum (Pt), are widely used in spin-wave experiments related to spintronic phenomena such as the spin-transfer-torque, spin Hall, and spin Seebeck effects. However, spin waves in YIG/Pt bilayers experience much stronger attenuation than in bare YIG films.

To understand the nature of this decay we performed a systematic study of the influence of a thin Pt film (2.5-10 nm) on SW propagation in a 6.7-μm-thick YIG waveguide. Spin waves were excited and detected by 50-μm-wide microstrip antennas at frequencies around 6.5 GHz. We have found that the SW amplitude decreases due to the resistive losses attributed to the eddy currents induced in a Pt film by a propagating SW. With the help of a novel excitation configuration in which the YIG film faces the metal plate of the microstrip antenna structure (Fig. 1a), the eddy currents in Pt are shunted and the transmission of the surface SW is greatly improved (Fig. 1b) [1].

The theoretical analysis carried out within the framework of the electrodynamic approach reveals how the Pt nanolayer and the nearby highly conductive metal plate affect the group velocity and the lifetime of the surface SW and how these two wavelength-dependent quantities determine the transmission characteristics of the SW device. The novel excitation configuration allows the application of direct or alternating electric currents to the Pt-layer. Thus, the proposed structure has a good potential for use in magnonic and spintronic devices.

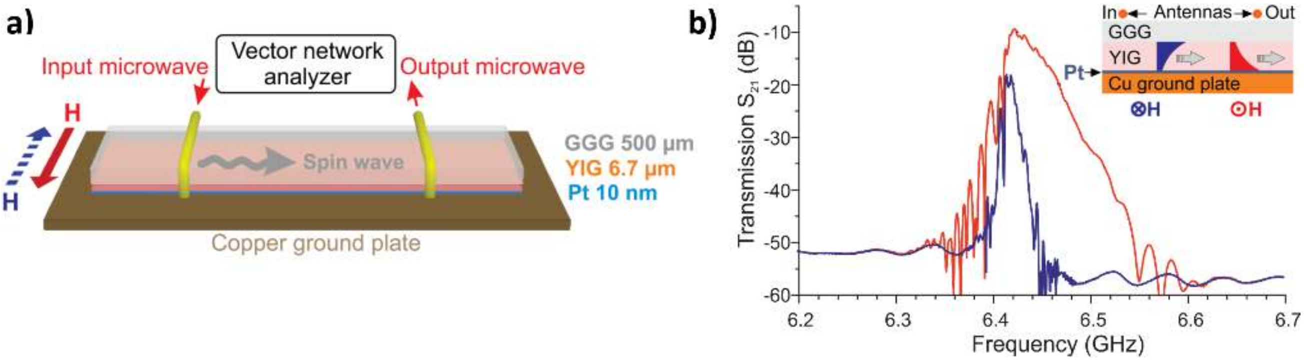

Figure 1: a) Inverted spin-wave excitation configuration—-the YIG/Pt bilayer is close to the ground plate of the microstrip structure. b) S_{21} transmission characteristics of the YIG waveguide covered with a 10 nm Pt layer.

REFERENCES

[1] R. O. Serha, D. A. Bozhko, M. Agrawal, et al., “Low-damping spin-wave transmission in YIG/Pt-interfaced structures”, Adv. Mater. Interfaces **9**, 2201323 (2022).

Poster 1. PA44
Monday
16:30

Confinement of Bose–Einstein Magnon Condensates in Adjustable Complex Magnetization Landscapes

Matthias R. Schweizer[1,*], **Franziska Kühn**[1], **Alexander J.E. Kreil**[1], **Georg von Freymann**[1, 2], **Burkard Hillebrands**[1], **Alexander A. Serga**[1]
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We demonstrate the capability to control a room-temperature magnon Bose–Einstein condensate (BEC) by spatial modulation of the saturation magnetization. We use laser heating in combination with a phase-based wavefront modulation technique to create adjustable temperature patterns in an yttrium-iron-garnet film. The increase in temperature leads to a decrease of the local saturation magnetization and in turn to the modification of the corresponding BEC frequency. Over time, a phase accumulation between different BEC-areas arises, leading to phase-driven magnon supercurrents.

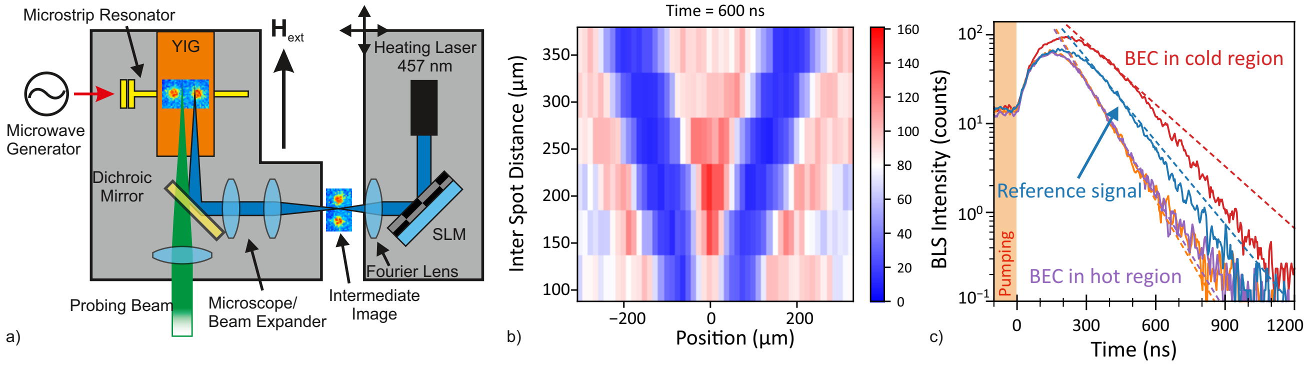

Figure 1: Dynamics of magnon BEC confined in complex magnetization landscapes. (a) The experimental setup. (b) Spatial distribution of magnon BEC density at different inter-spot distances. Two local minima of the magnon density at the hot spots and a local maximum in between are observed for all observed distances. (c) BEC density time traces taken at different positions. The dashed lines show the regression of exponential decay.

The BEC is created by microwave parametric pumping and probed by Brillouin light scattering (BLS) spectroscopy. We observe a strong magnon accumulation effect caused by magnon supercurrents for several distances between heated regions. This accumulation effect manifests in the confinement of the magnon BEC, which exhibits an enhanced lifetime due to the continuous influx of magnons [1].

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center–TRR 173/2–268565370 “Spin+X” (project B04)

REFERENCES

[1] M. R. Schweizer, A. J. E. Kreil, G. von Freymann, B. Hillebrands, and A. A. Serga, “Confinement of Bose–Einstein magnon condensates in adjustable complex magnetization landscapes”, Journal of Applied Physics **132**, 183908 (2022).

Poster 1. PA45
Monday
16:30

Negative Energy Modes in Antiferromagnets for Amplification and Analogue Gravity

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Magnonic black holes [1] – analogue event horizons for the spin-wave collective excitations of ordered magnets - can be used for fundamental research, for example for investigating Hawking radiation, but also for technological applications of spin waves, such as sensors[2], amplifiers[3], performing logical operations. Here we will show how to engineer magnonic black holes in antiferromagnets[4], which have the attractive feature of fast magnetization dynamics. Our approach is both classical and quantum. We consider the set-up in Figure 1. The set-up consists of two antiferromagnets that are weakly coupled by exchange, and have different uniaxial magnetocrystalline anisotropies, magnetic fields, pumping mechanisms of angular momentum, i.e. Spin Orbit Torque (SOT) or Spin transfer Torque(STT). We compute the values of parameters to have amplification of spin waves and moreover we individuate which configuration is more suitable for analogue gravity research purposes. Particular attention is paid to the differences between the classical and quantum regimes and on the challenges in observing the quantum effects.

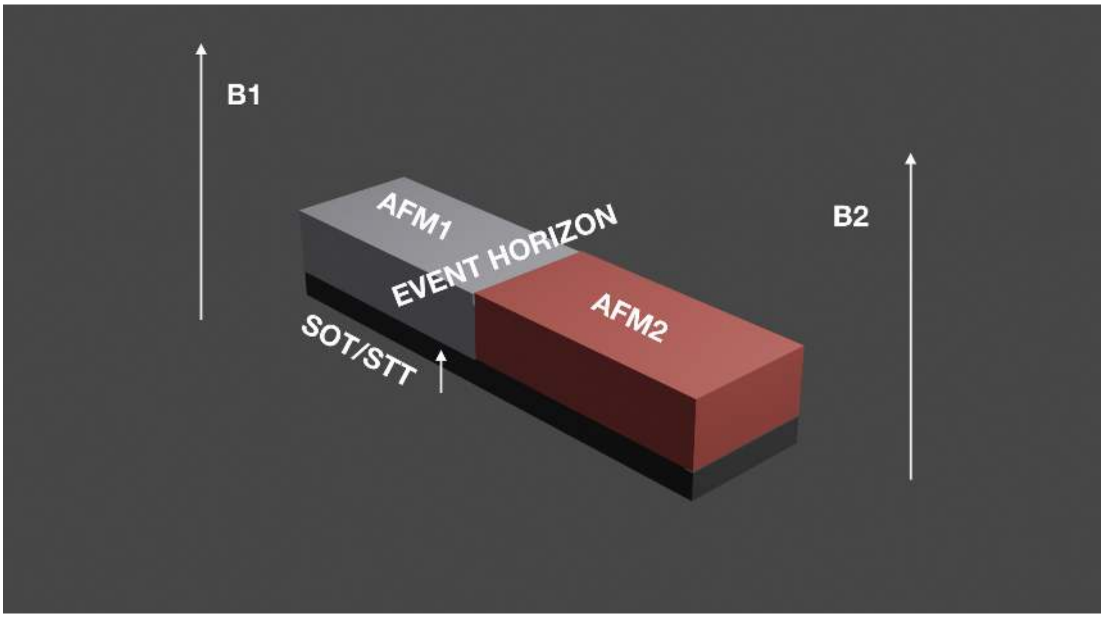

Figure 1: The set-up we study, in which uniaxial magnetocrystalline anisotropies, magnetic fields, angular momentum pumping mechanisms are varied between the two antiferromagnets.

REFERENCES

[1] A. Roldán-Molina, A. S. Nunez, and R. Duine, “Magnonic black holes”, Physical review letters **118**, 061301 (2017).

[2] R. Duine, V. Errani, and J. Harms, “Non-linear dynamics near exceptional points of synthetic antiferromagnetic spin-torque oscillators”, `10.48550/arXiv.2302.07607` (2023).

[3] J. S. Harms, H. Y. Yuan, and R. A. Duine, *Enhanced magnon spin current using the bosonic klein paradox*, 2021.

[4] T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich, “Antiferromagnetic spintronics”, Nature nanotechnology **11**, 231–241 (2016).

Poster 1. PA46
Monday
16:30

PT Symmetry Breaking and Topological Features in Dissipatively Coupled Spin Dynamics

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In recent decades, it has become clear that unconventional degeneracies are common in magnetic systems. Over the past several years, the development of non-hermitian theories has provided new tools for understanding the finer details of non spin-conserving dynamics of coupled magnetic systems. We present here our theoretical investigation of dynamically coupled spin systems, such as in the form of Eq. (1), for both the case of dissipative and non-dissipative dynamical interactions. A consequence of our treatment is the emergence of exceptional points signifying PT symmetry breaking of our non-hermitian dynamical system. We explore the physical consequences of this phenomenon in the case of an interacting bilayer as well as nearest neighbor interactions in larger geometries and the topological features of the resultant magnonic excitations. Finally, we explore the effects of magnon-antimagnon dynamical coupling, possibly realizable via the inclusion of a heavy metal layer.

$$\frac{\partial \mathbf{M_i}}{\partial t} = -\gamma \mathbf{M_i} \times \mathbf{H}_{\text{eff}} + \alpha \left(\mathbf{M_i} \times \frac{\partial \mathbf{M_i}}{\partial t} \right) + \hat{G}(\mathbf{M_i}, \mathbf{M_j}) \frac{\partial \mathbf{M_j}}{\partial t} \quad \mathbf{i}, \mathbf{j} \in \{1, 2\} \tag{1}$$

Poster 2. PB01
Wednesday
16:30

Magnonic Spectral Symmetry-Breaking in a Trilayered Artificial Spin-Vortex Ice

Jack C. Gartside[1,*], **Troy Dion**[2], **Kilian D. Stenning**[3,1], **Holly H. Holder**[1], **Alex Vanstone**[1],
Rawnak Sultana[4], **Mojtaba Taghipour Kaffash**[4], **Takashi Kimura**[2], **Hidekazu Kurebayashi**[1,3],
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In this talk we'll examine the benefits of moving nanomagnetic arrays from quasi-2D, single magnetic layer systems[1-3] into architectures with strongly-coupled magnetic elements in all three dimensions.

As demonstrated by fantastic recent work by groups including Sam Ladak's [4] 3D artficial spin ice, Claire Donnelly's [5] stunning 3D magnetic imaging and Gubbiotti and Adeyeye's [6] trilayered nanosystems, many unexpected and exciting phenomena appear when moving magnetic nanostructures beyond 2D.

We have harnessed some of these phenomena for magnonics, and used them to engineer a host of complex behaviours: reconfigurable control of magnonic acoustic/optical mode hybridisation, many GHz-scale mode-frequency shifts and chiral spectral symmetry breaking. We introduce new methodologies for reconfigurable chiral selectivity using elegant, easy-to-implement 3D microstate engineering.

We then explore leveraging these behaviours for functional processing including neuromorphic computing[2,3].

[1] Gartside, Jack C., et al. ”Reconfigurable magnonic mode-hybridisation and spectral control in a bicomponent artificial spin ice.” Nature Communications 12.1 (2021): 1-9.

[2] Gartside, Jack C., et al. ”Reconfigurable Training and Reservoir Computing via Spin-Wave Fingerprinting in an Artificial Spin-Vortex Ice.” Nature Nanotechnology (2022)

[3] Stenning, Kilian D., Gartside, Jack C. et al. ”Adaptive programmable networks for in materia neuromorphic computing.” arXiv preprint arXiv:2211.06373 (2022).

[4] Ladak, Sam, Amalio Fernández-Pacheco, and Peter Fischer. ”Science and technology of 3D magnetic nanostructures.” APL Materials 10.12 (2022): 120401.

[5] Donnelly, Claire, et al. ”Three-dimensional magnetization structures revealed with X-ray vector nanotomography.” Nature 547.7663 (2017): 328-331.

[6] Gubbiotti, G., Adeyeye, A. et al. ”Collective spin waves in arrays of asymmetric and symmetric width nanowires: Effect of the film layering sequence.” Journal of Physics D: Applied Physics 53.13 (2020): 135001.

Toward Larger-Area Magnonic Platform Materials: 3-Inch, Nanometer-Thin YIG Films

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Nanometer-thin yttrium iron garnet (YIG) films represent a potential base material for future nanoscale devices that could be used as building blocks for magnonic networks for spin-wave-based data processing [1]. In addition to the unique magnetic and microwave properties, the fact that it is already possible to increase the usable film surface area of this material up to 3-inch diameters makes them interesting for fabrication of a multitude of nanoscale spin-wave devices on the same wafer. One the one hand, in the academic field, this enables an investigation of the spin-wave properties of different chip designs on the same material. On the other hand, it could bridge to the engineering and fabrication domain to achieve the required high technology readiness levels (TRL) of three or more for such devices [2]. It has already been demonstrated that magnonic adder architectures [3, 4], spin-wave optical elements [5] or spin-wave converters [6] can be designed and fabricated based on 1D functional YIG films. However, it is a prerequisite that the YIG film material is homogenous over the entire wafer diameter and maintains its unique properties compared to small sample geometries fabricated up to date [7, 8]). Recently, we were able to grow 3-inch YIG films with a thickness of 20 nm on GGG substrate wafers by liquid phase epitaxy (LPE) for the first time. To evaluate the homogeneity and perfection of such films the topological and FMR properties have to be investigated over the entire wafer diameter. Here we report the thickness homogeneity, surface roughness and FMR linewidth, as well as Gilbert damping of 3-inch YIG films with different thicknesses of 100 nm, 55 nm and 22 nm. First investigations show that it is possible to achieve films with properties comparable to those for 1-inch diameter ($\delta_{FWHM} = 2$ Oe $@ \ 6.5$ GHz, $\alpha = 10^{-4}$) which are among the samples with the best microstructural and microwave properties [8]. Thus, if real devices for integrated logic circuits can be designed on a planar layer platform without the need of 3D intersections, the LPE technique provides a simple and cost-effective tool to their fabrication.

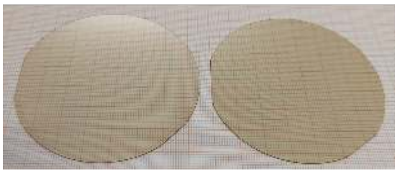

Figure 1: nm-thin 3-inch YIG films.

REFERENCES

[1] A. V. Chumak, P. Kabos, M. Wu, et al., “Advances in magnetics roadmap on spin-wave computing”, IEEE Transactions on Magnetics **58**, 1–72 (2022).

[2] B. Dieny, I. L. Prejbeanu, K. Garello, et al., “Opportunities and challenges for spintronics in the microelectronics industry”, Nature Electronics **3**, 446–459 (2020).

[3] Q. Wang, M. Kewenig, M. Schneider, et al., “A magnonic directional coupler for integrated magnonic half-adders”, Nature Electronics **3**, 765–774 (2020).

[4] F. Schulz, F. Groß, J. Förster, et al., “Realization of a magnonic analog adder with frequency-division multiplexing”, AIP Advances **13**, 015115 (2023).

[5] M. Kiechle, L. Maucha, V. Ahrens, et al., “Experimental demonstration of a spin-wave lens designed with machine learning”, IEEE Magnetics Letters **13**, 1–5 (2022).

[6] Q. Wang, R. Verba, B. Heinz, et al.

[7] C. Dubs, O. Surzhenko, R. Thomas, et al., “Low damping and microstructural perfection of sub-40nm-thin yttrium iron garnet films grown by liquid phase epitaxy”, Physical Review Materials **4**, `10.1103/physrevmaterials.4.024416` (2020).

[8] J. Ding, T. Liu, H. Chang, and M. Wu, “Sputtering growth of low-damping yttrium-iron-garnet thin films”, IEEE Magnetics Letters **11**, 1–5 (2020).

Nonlinear Multi-Magnon Scattering in Ensembles of Nanomagnets

M. Benjamin Jungfleisch[1,*], **Sergi Lendinez**[1], **Mojtaba T. Kaffash**[1], **Olle Heinonen**[2,3],
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Artificial spin ices (ASI) are magnetic metamaterials where magnetic domains can be mapped onto a spin-lattice model . Recently, ASI has been discussed in the context of functional magnonic materials, where an interplay between geometry, material properties, and reconfigurability determines the magnon spectrum [1–5]. Magnons are the fundamental quantum-mechanical bosonic excitations of magnetic solids, whose number does not need to be conserved in scattering processes. Microwave-induced parametric magnon processes have been believed to occur in magnetic thin films only, where quasi-continuous magnon bands exist.

Here, we reveal the existence of such nonlinear magnon-magnon scattering processes and their coherence in ensembles of magnetic nanostructures [6]. We find that the ASI systems exhibit effective scattering processes akin to those observed in continuous magnetic thin films. A combined microwave and micro-focused Brillouin light scattering measurement approach was used to investigate the evolution of their modes. Scattering events occur between discrete bands whose resonant frequencies are determined by each nanomagnet's mode volume and profile. Comparison with numerical simulations reveals that parametric pumping leads to scattering from bulk modes into edge modes. Our results suggest that tunable directional scattering is possible in ASI structures.

This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering under Award DE-SC0020308.

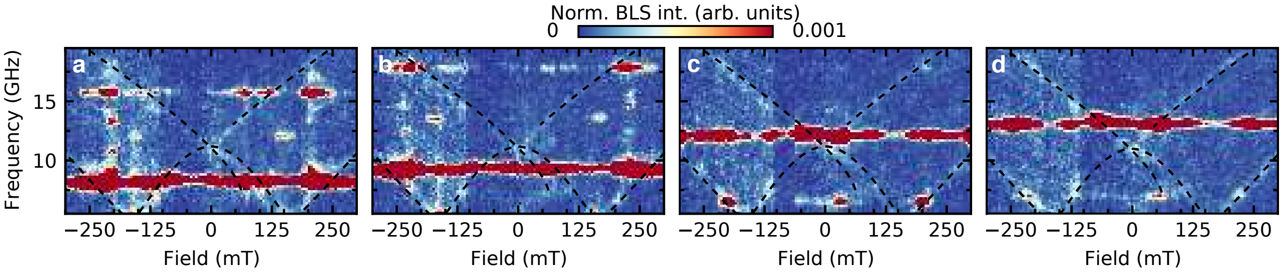

Figure 1: Measured spectra under microwave excitation. Driving microwave frequency-dependent magnon spectra in the nonlinear regime at P_{applied}= 2 W and microwave frequencies of **a** 7.25 GHz, **b** 8.25 GHz, **c** 11 GHz, and **d** 12 GHz. The intense nearly-field independent band corresponds to the directly excited frequency. However, if there are states available at $2f$ or $f/2$, magnon scattering is observed as indicated by an increased Brillouin light scattering (BLS) intensity.

REFERENCES

[1] S. Gliga, E. Iacocca, and O. G. Heinonen, "Dynamics of reconfigurable artificial spin ice: toward magnonic functional materials", APL Materials **8**, 040911 (2020).

[2] M. T. Kaffash, S. Lendinez, and M. B. Jungfleisch, "Nanomagnonics with artificial spin ice", Physics Letters A **402**, 127364 (2021).

[3] W. Bang, J. Sturm, R. Silvani, et al., "Influence of the vertex region on spin dynamics in artificial kagome spin ice", Phys. Rev. Appl. **14**, 014079 (2020).

[4] S. Lendinez, M. Taghipour Kaffash, and M. B. Jungfleisch, "Observation of mode splitting in artificial spin ice: a comparative ferromagnetic resonance and brillouin light scattering study", Applied Physics Letters **118**, 162407 (2021).

[5] S. Lendinez, M. T. Kaffash, and M. B. Jungfleisch, "Emergent spin dynamics enabled by lattice interactions in a bicomponent artificial spin ice", Nano Letters **21**, 1921–1927 (2021).

[6] S. Lendinez, M. Kaffash, O. Heinonen, et al., "Nonlinear multi-magnon scattering in artificial spin ice", `10.21203/rs.3.rs-1636046/v1` (2022).

Poster 2. PB04
Wednesday
16:30

Electrical Evidence and Modeling of the Unidirectionnality of the Energy Flow Carried by the Spin Waves of a Synthetic Antiferromagnet

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Non-reciprocal (NR) microwave components providing a unidirectional flow of energy are essential for signal processing. Spin waves (SWs) are commonly harnessed to design NR components. However these components are presently bulky: more compact systems are desirable. Synthetic antiferromagnet (SAF) films with strong dipole-dipole interactions have been proposed [1] as a versatile platform on which strongly NR behaviors could be obtained at micron-scale dimensions.

We have studied the NR behavior of SWs in stripes of CoFeB /Ru /CoFeB SAFs using propagative spin wave spectroscopy. Inductive antennas are used to generate/collect the spin waves using a network analyzer. We determine the forward and backward transmission parameters for variable field-to-wavevector orientations. When the SAF is in the scissors state, all directions show substantial frequency non-reciprocities, except when the wavevector is perpendicular to the applied field. Unidirectionnal energy flow is achieved when harnessing acoustical spin waves of wavevector parallel to an applied field that sets the SAF in the scissors state. The direction of unidirectional energy flow can be reversed by setting the SAF in the other scissors state (Fig. 1).

We model this behavior by computing the dispersion relation of the spin waves and their sensitivity to the radio frequency (RF) fields of the antenna, as well the inductive transduction back to the electrical domain. Analytical approximations can be derived to clarify the respective role of the direction of the wavevector of the SWs versus the role of the direction of the energy flow carried by the SWs. For spin waves with a linear dispersion relation in the range of wavevectors allowed by the antenna geometry –like in our experimental situation– all wavevectors (positive and negative) can have a positive group velocity such that even if one emits bidirectional spin waves, the energy of the wavepackets propagate in only one direction. This happens for the acoustical spin waves of synthetic antiferromagnets when the wavevector is close to parallel to the applied field. Our formalism offers a simple and direct method to understand, design and optimize devices harnessing propagating spin waves, including when a unidirectional energy flow is desired.

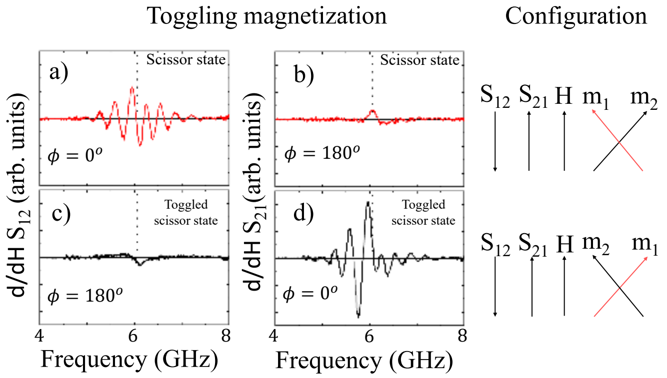

Figure 1: Transmission parameters near the frequency of acoustical spin waves of a SAF in the scissors state fro wavevector parallel to the applied field. a) and b): Forward and backward transmission for one scissors state. c) and d) idem of toggling the two magnetizations to achiever the other scissors state.

REFERENCES

[1]M. Ishibashi, Y. Shiota, T. Li, et al., “Switchable giant nonreciprocal frequency shift of propagating spin waves in synthetic antiferromagnets”, en, Sci. Adv. **6**, eaaz6931 (2020).

Traveling Salesman Problem Solution Using Magnonic Combinatorial Device

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Traveling Salesman Problem (TSP) is a decision-making problem that is essential for a number of practical applications. Today, this problem is solved on digital computers exploiting Boolean-type architecture by checking one by one a number of possible routes. In this work, we describe a special type of hardware for the TSP solution. It is a magnonic combinatorial device comprising magnetic and electric parts connected in the active ring circuit. There is a number of possible propagation routes in the magnetic mesh made of phase shifters, frequency filters, and attenuators. The phase shifters mimic cities in TSP while the distance between the cities is encoded in the signal attenuation. The set of frequency filters makes the waves on different frequencies propagate through the different routes. The principle of operation is based on the classical wave superposition. There is a number of waves coming in all possible routes in parallel accumulating different phase shifts and amplitude damping. However, only the wave(s) that accumulates the certain phase shift will be amplified by the electric part. The amplification comes first to the waves that possess the minimum propagation losses. It makes this type of device suitable for TSP solution, where waves are similar to the salesmen traveling in all possible routes at a time. We present the results of numerical modeling illustrating the TSP solutions for four and six cities. Also, we present experimental data for the TSP solution with four cities. The prototype device is built of commercially available components including magnetic phase shifters/filters, coaxial cables, splitters, attenuators, and a broadband amplifier. The device literally shows the shortest route between the four selected cities. There are three examples of finding the shortest route between the cities for three different sets of city-to-city distances. The ability to exploit classical wave superposition is the most appealing property of the demonstrated device. It allows us to check a number of possible routes in parallel without any time overhead. It provides a fundamental advantage over conventional digital computers in functional throughput. The proposed approach is scalable to TSP with a larger number of cities. The estimated functional throughput of the combinatorial device for TSP with 25 cities exceeds the limits of the existing supercomputers combined. Physical limits and challenges are also discussed [1].

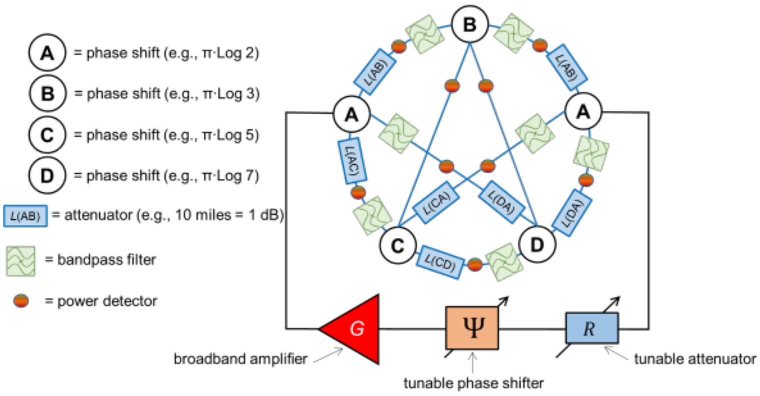

Figure 1: Magnetic vortex state.

REFERENCES

[1]A. Khitun and M. Balinskiy, “Combinatorial logic devices based on a multi-path active ring circuit”, Scientific Reports **12**, 9482 (2022).

Poster 2. PB06
Wednesday
16:30

Magnon suppression flowing $Y_3Fe_5O_{12}$ via inductive effect

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Magnon can potentially be a new information carrier because of its Joule-heating-less and long-distance propagation in ferromagnets [1]. Recently, Das *et. al.* demonstrated that magnon in $Y_3Fe_5O_{12}$ (yttrium-iron-garnet, YIG) is absorbed into an adjacent ferromagnet, NiFe alloy (Py), and the absorption can be modulated by the magnetization direction of the Py [2]. Although this study paves the way to realize the magnonic device, many magnons are unintentionally lost by only attaching Py to the YIG magnon waveguide. Here, we study magnon propagation with several middle strips (MSs), Py, SiO_2, and metals on SiO_2 to explore the mechanisms of magnon loss. Figure. 1 shows a schematic of the device. Two Ti/Au coplanar waveguides with a center-to-center distance of $300\ \mu\mathrm{m}$ and an MS with a width of $240\ \mu\mathrm{m}$ were fabricated on a YIG substrate ($5\ \mu\mathrm{m}$ in thickness). An external magnetic field (B) applied to the device was swept from $140\ \mathrm{mT}$ to $50\ \mathrm{mT}$. An input AC electric current with the power of $0\ \mathrm{dBm}$ and frequency of $5\mathrm{GHz}$ was injected into the antenna using a vector network analyzer. Magnons were excited by the induced AC magnetic field. Magnons propagating in the YIG were partially suppressed by the MS and detected by the other antenna as an induced AC magnetic field. We measured the S_{21} parameter and calculated $\Sigma|S_{21}|$ $(= \int |S_{21}| dB)$ to compare the amounts of the detected magnons. To clarify whether the magnon suppression is an interfacial effect between YIG and Py, we measured the samples with Py-MS and SiO_2/Py-MS. Figure. 2 shows the SiO_2 thickness dependence of magnon transmission. The Py thicknesses are $25\ \mathrm{nm}$. TheSiO_2 thickness is changed from 30 to $100\ \mathrm{nm}$ and data at $t_{\mathrm{SiO}_2} = 0\ nm$ is obtained from the sample whose Py-MS and YIG are directly connected. The normalized $\Sigma|S_{21}|$ of YIG/SiO_2/Py is almost constant for all thickness ranges. These results indicate that suppression does not originate simply from the interfacial effect between YIG and ferromagnet such as spin exchange interaction. We suggest the eddy current by magnon-induced magnetic field contributes to the magnon loss [3].

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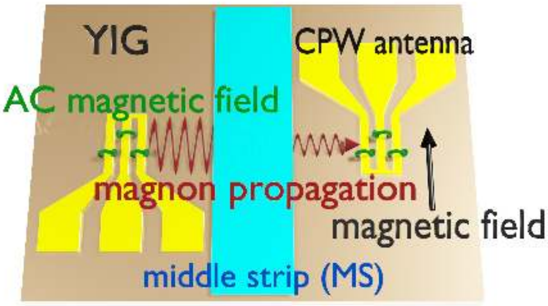

Figure 1: A schematic of the device structure.

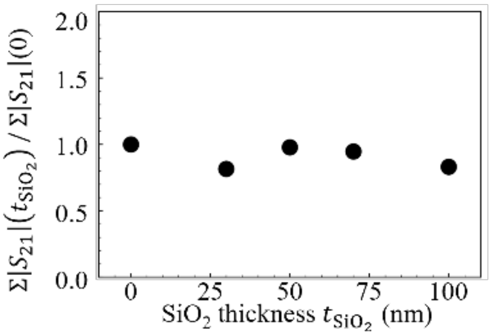

Figure 2: The SiO2 thickness dependence of magnon transmission

REFERENCES

[1] A. V. C. *et. al.*, “Magnon spintronics”, Nature Physics **11**, 453–461 (2015).
[2] K. S. D. *et. al.*, “Modulation of magnon spin transport in a magnetic gate transistor”, Physical Review B **101**, 054436 (2020).
[3] S. M. *et. al.*, “Influence of adjacent metal films on magnon propagation in $Y_3Fe_5O_{12}$”, Physical Review B **105**, 104415 (2022).

Poster 2. PB07
Wednesday
16:30

Numerical Investigations of the Linearity of Magnonic Devices for RF Signal Processing

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One of the most important application areas of magnonic devices is miniaturized, high-function radio-frequency (RF) signal processing, like filtering or phase shifting. Such applications require the transmission of high powers without nonlinear effects. Hence a precise characterization of the power transmission and signal distortion of magnonic conduits is essential - preferably using the same metrics that are used for their electronic counterparts. This work makes an attempt at the latter on simulation level. In electronic devices, intermodulation distortion products are of special interest in the RF area, and a major concern in the design of active devices. Rather than simply examining the harmonic distortion produced by a single tone sinewave input, it is often useful to look at the intermodulation products produced by two tones, an effect which can significantly impact modulated RF signals used for data transmission. The nth order intermodulation distortion is often specified by the nth order intercept point. Intercept points are suitable for the analysis of undesired responses generated by the non-linear properties of electronic devices. As the third order intermodulation usually shows the strongest impact compared to the higher order distortions, the third order intercept point (TOI) is primarily considered for the analysis [1, 2].

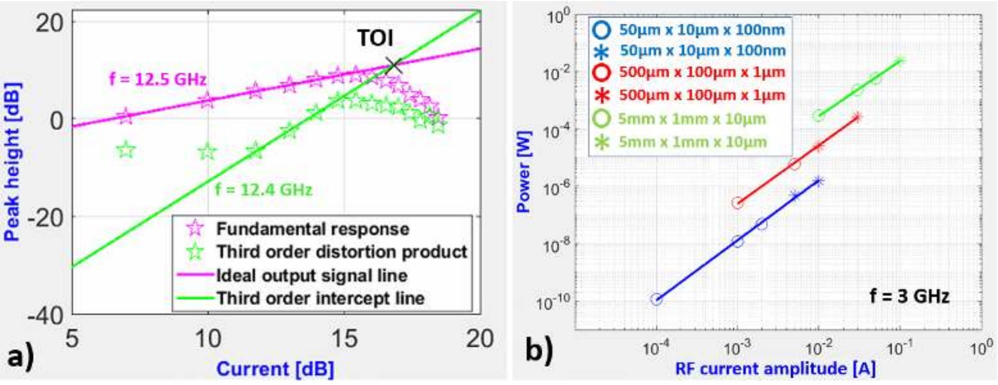

Figure 1: Third order intercept point of a CoFeB waveguide stripe (a), and transmission power of a YIG waveguide as a function of size (b) (cirlces: linear regime, stars: nonlinear regime)

In order to quantify the nonlinearity of magnonic devices we propose a simple method based on the determination of TOI (Figure. 1a). The examined systems are magnonic waveguide stripes, in that an inductive antenna excites spin waves, and the output of the devices is another antenna, that inductively converts spin waves to microwave signals. The approach is demonstrated on simulation level using the mumax^3 environment. The transmission power as a function of the dimensions (Figure. 1b) as well as the radiation resistance - i.e. the resistance due to the power carried away from the antenna as spin waves - are also addressed.

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REFERENCES

[1]W. Kester, "Communication amplifiers", in *Op amp applications handbook* (Elsevier, 2005), pp. 545–566.
[2]R. Sagers, "Intercept point and undesired responses", IEEE Transactions on Vehicular Technology **32**, 121–133 (1983).

Control of Bulk and Surface Magnon Modes in 3D Ferromagnetic Nanonetworks by Additive Manufacturing

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Three-dimensional (3D) ferromagnetic nanoarchitectures gain substantial interest in view of magnetochiral effects [1] and applications. However, the challenging 3D nanofabrication hinders thorough exploration of 3D spintronics and magnonics. Here, we combine two-photon lithography (TPL) which offers unprecedented possibilities to create complex 3D nanoscaffolds with atomic layer deposition (ALD) which supplies conformal ferromagnetic coatings without shadowing effect [2]. Through this additive manufacturing methodology, we have accomplished Ni nanotubes interconnected in a 3D woodpile structure (Fig. 1a) with different lattice constants.

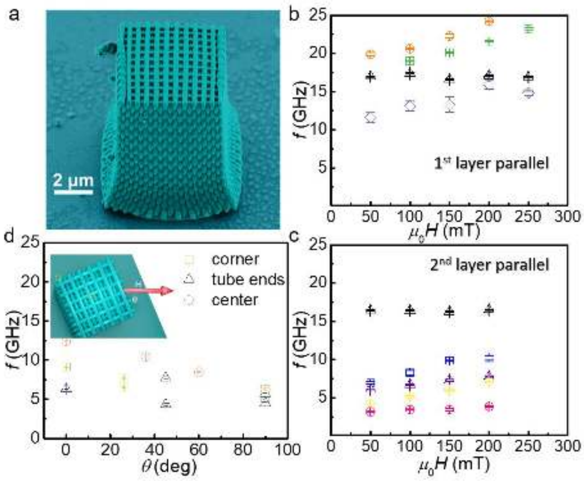

Figure 1: a) Colored SEM image of a 3D Ni nanonetwork. Resonance modes in dependence of a magnetic field applied parallel to the tubes of the b) 1^{st} and c) 2^{nd} layer. d) Modes detected at three different positions of the first layer when altering the angle θ between the magnetic field and 3D Ni nanonetwork.

We detected thermal magnon modes by micro-focus Brillouin Light Scattering (BLS) at room temperature in the first (Fig. 1b) and second layer (Fig. 1c) of such a 3D Ni nanotube network (Fig. 1a). The lattice constant was 1 μm. These data show a clear shift in frequency for surface and bulk magnon modes, respectively, of the 3D superstructure. Also, angle- and spatially-dependent resonance modes are observed (Fig. 1d). Overall, our work implies that additive manufacturing combined with BLS is a promising platform to investigate magnon states in 3D ferromagnetic superstructures. The TPL-based methodology promises complex nanoarchitectures with chiral unit cells which are a prerequisite towards the engineering of topological surface modes in 3D magnonic crystals and might allow for multi-frequency 3D information transmission. Financial support by SNSF via grant number 197360 is acknowledged.

REFERENCES

[1] M. C. Giordano, M. Hamdi, A. Mucchietto, and D. Grundler, “Confined spin waves in magnetochiral nanotubes with axial and circumferential magnetization”, Phys. Rev. Mater. **7**, 024405 (2023).

[2] M. C. Giordano, K. Baumgaertl, S. Escobar Steinvall, et al., “Plasma-enhanced atomic layer deposition of nickel nanotubes with low resistivity and coherent magnetization dynamics for 3d spintronics”, ACS Applied Materials & Interfaces **12**, 40443–40452 (2020).

Poster 2. PB09
Wednesday
16:30

Spin-Wave Dynamics in Co_2 MnSi Heusler Magnonic Crystals

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Thanks to their unique properties, Co-based Heusler alloys represent an interesting class of materials for application in the field of magnonics. For example, Co_2 MnSi is characterized by high Curie temperature (around 985 K), low damping and high saturation magnetization, which allows operating with frequencies above the GHz range at remanence. Neverthless, only a few investigations concerning Co-based Heusler alloy magnonic crystals are present in literature. In this work we have investigated spin wave (SW) dynamics in Co_2 MnSi magnonic crystals, consisting of square antidots (ADs) arrays, having a side of 200 nm and arranged into square matrix having a period of 0.8 μm and 1 μm. The samples have been fabricated from a 50 nm thick Co_2 MnSi film, by e-beam lithography followed by Ar^+ ion beam etching (IBE). The spatial profile of the spin-wave modes, supported by the ADs lattices, has been mapped by micro-focused Brillouin light Scattering (micro-BLS). All micro-BLS measurements have been carried out exciting SWs by means of an inductive antenna and applying an external magnetic field parallel to the side of the square matrix and to the antenna. The experimental data have been compared to micromagnetic simulations performed by using MuMax. For all the investigated samples we have experimentally observed an extended mode propagating in the channels of continuous Co_2 MnSi film comprised between the square holes and a localized mode located in the regions between adjacent holes (see Fig.1). A good agreement between the experimental results and the calculated frequencies and spatial profiles has been obtained for both the samples.

This work is performed using HPC resources from CALMIP (Grant No. 2022-p1554).

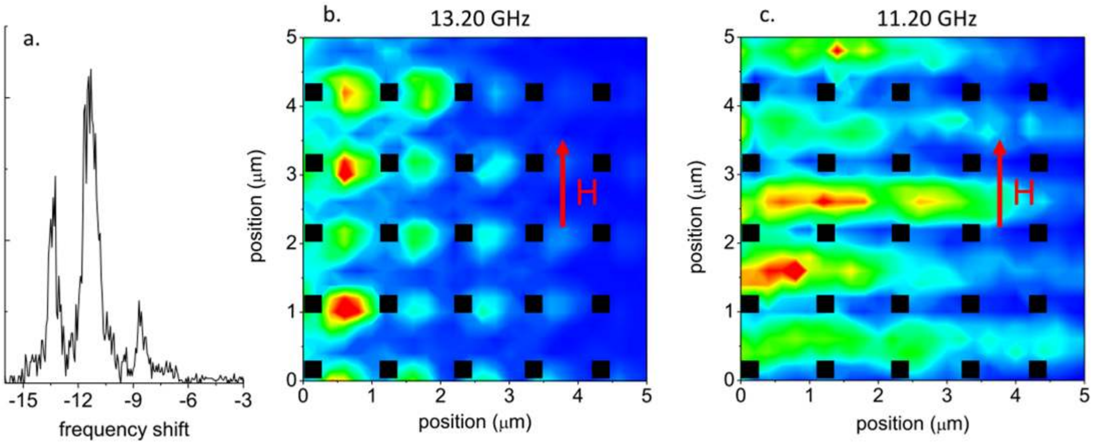

Figure 1: Micro-BLS measurements of the sample having a period of 1 μm performed applying a magnetic field of H=1 kOe. (a) Micro-BLS spectrum. (b) and (c) Areal maps of BLS intensity, recorded from the antenna edge (positioned on the left side of the graphs) at excitation frequencies of 13.20 GHz and 11.20 GHz, respectively.

Poster 2. PB10
Wednesday
16:30

Excitation of Propagating Spin Waves in Ga:YIG Thin Films

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Recently, the material parameters of an YIG thin film doped with gallium atoms (Ga:YIG) were characterized and an isotropic dispersion relation of thermal spin waves was reported [1, 2]. Here, we study the direct excitation of spin waves in Ga:YIG, yielding a direct proof of their exchange dominated nature. Furthermore, we study the nonlinear regime of excitation and demonstrate the control over the sign of the nonlinear coefficent by the external in-plane field. We coherently excited spin-wave packets by a microscopic coplanar waveguide. The subsequent detection was performed using time-resolved Brillouin-light-scattering microscopy. This allows for a direct measurement of the spin-wave group velocity, yielding values ranging from approximately $v_\mathrm{g} = 0.35\,\mu\mathrm{m\,ns}^{-1}$ to $v_\mathrm{g} = 1\,\mu\mathrm{m\,ns}^{-1}$. Due to the uniaxial out-of-plane anisotropy of the Ga:YIG film, the orientation of the static magnetization can be changed by an externally applied in-plane magnetic field, which enables control over the sign of the nonlinear frequency shift. The nonlinear shift is shown in Figure 1 b) for different in-plane fields as a function of the applied microwave power. In agreement with the negative effective magnetization M_eff, using high amplitude excitation, we find a positive nonlinear frequency shift for an in-plane magnetization ($\mu_0 H_\mathrm{ext} =$ 85.76 mT). Compared to undoped YIG, the sign of the nonlinear shift is inverted as expected. The positive nonlinear shift results in a significant power-dependent foldover effect, which provides nonlinear power dependencies for the excitation. Our experiments confirm the presence of exchange dominated spin waves, as well as an isotropic spin-wave dispersion relation and strong nonlinear effects. This study is of high interest for magnonic data processing and reveals novel possibilities for magnonic devices with a easily tunable nonlinearity.

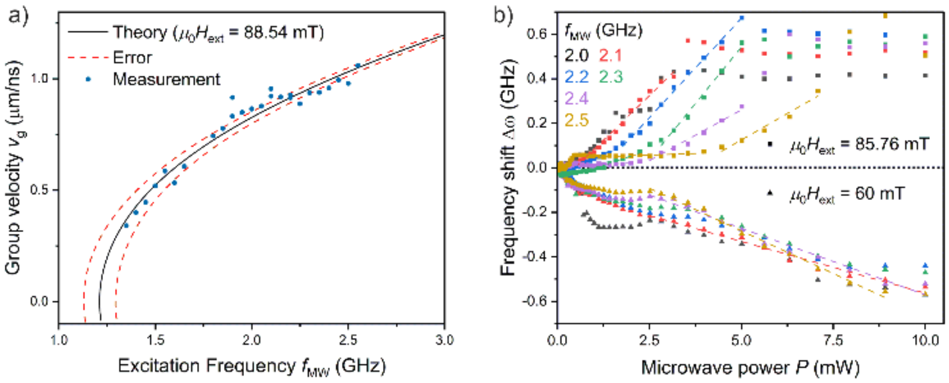

Figure 1: a) Group velocity v_g of excited spin waves as a function of excitation frequency f_MW in Damon-Eshbach configuration b) Nonlinear frequency shift $\Delta\omega$ as a function of the applied microwave power P for an in-plane and out-of-plane magnetization.

This research was funded by the European Research Council within the Starting Grant No. 101042439 ”CoSpiN” and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center—TRR 173–268565370 “Spin + X” (project B01) and the project 271741898.

REFERENCES

[1] J. J. Carmiggelt, O. C. Dreijer, C. Dubs, O. Surzhenko, and T. van der Sar, “Electrical spectroscopy of the spin-wave dispersion and bistability in gallium-doped yttrium iron garnet”, Applied Physics Letters **119**, 202403 (2021).

[2] T. Böttcher, M. Ruhwedel, K. O. Levchenko, et al., “Fast long-wavelength exchange spin waves in partially compensated Ga:YIG”, Applied Physics Letters **120**, 102401 (2022).

Poster 2. PB11
Wednesday
16:30

Dynamics and Reversible Control of the Vortex Bloch Point Domain Wall in Short Cylindrical Magnetic Nanowires

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Spin waves (SWs) in quasi one-dimensional structures have recently attracted much attention. For example, numerical and experimental studies allowed observation of spin waves channeling along domain walls in circular [1] and triangular [2, 3] dots (Winter magnons). In contrast to the two-dimensional textures in thin films and dots, three-dimensional (3D) magnetic textures could significantly enhance the diversity of the possible magnetic topologies, opening the door to a radically new applications. Fast and efficient switching of nanomagnets is one of the main challenges in the development of future 3D magnetic memories. Here we numerically investigate the evolution of the static and dynamic (SWs) magnetization in short (50-400 nm length and 120 nm diameter) cylindrical ferromagnetic nanowires, where competing single vortex (SV) and vortex domain wall with a Bloch point (BP-DW) magnetization configurations could be formed. For a limited nanowire length range (between 150 and 300 nm) we demonstrate a reversible microwave field induced (forward) and opposite spin currents (backwards) transitions between the topologically different SV and BP-DW states. By tuning the nanowire length, SW excitation frequency, microwave (MW) pulse duration and spin current values we show that the optimum (low power) manipulation of the BP-DW could be reached by a MW excitation tuned to the main SW mode and for nanowire lengths around 230-250 nm, where single vortex domain wall magnetization reversal via nucleation and propagation of SV-DW takes place. An analytical model for dynamics of the Bloch point provides an estimation of the gyrotropic mode frequency close to the one obtained via micromagnetic simulations. A practical implementation of the method on a device has been proposed involving MW excitation and the generation of the opposite spin currents via spin orbit torque.

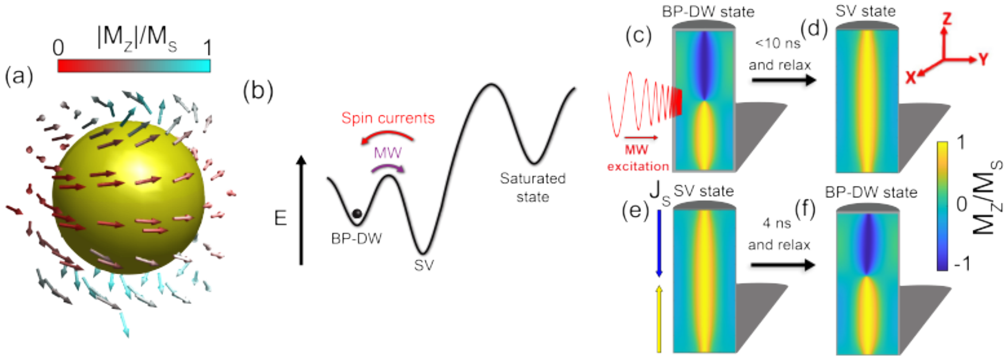

Figure 1: (a) 3D magnetization configuration surrounding the BP-DW centered in the middle of a 250 nm long nanowire. (b) Sketch of the two level (BP-DW and SV) system and transitions that exist in the NWs of the studied length range. Cross section sequence of magnetization of the NW, showing the used method to destroy the BP-DW state via a frequency-tuned MW field (c, d) and its posterior restoration using spin currents, (e, f).

REFERENCES

[1] F. G. Aliev, A. A. Awad, D. Dieleman, et al., "Localized domain-wall excitations in patterned magnetic dots probed by broadband ferromagnetic resonance", Physical Review B **84**, `10.1103/physrevb.84.144406` (2011).

[2] A. Lara, J. R. Moreno, K. Y. Guslienko, and F. G. Aliev, "Information processing in patterned magnetic nanostructures with edge spin waves", Scientific Reports **7**, `10.1038/s41598-017-05737-8` (2017).

[3] D. Caso and F. G. Aliev, "Edge spin wave transmission through a vertex domain wall in triangular dots", SN Applied Sciences **4**, `10.1007/s42452-022-05067-z` (2022).

Bistability Based Magnon Computing

David Breitbach[1,*], **Moritz Bechberger**[1], **Björn Heinz**[1], **Jan Maskill**[1], **Bert Lägel**[1], **Roman Verba**[2], **Qi Wang**[3], **Andrii Chumak**[3], **Carsten Dubs**[4], **Burkard Hillebrands**[1], **Philipp Pirro**[1]
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Bistabilities occur when a dynamic system exhibits two stable equilibrium states, which can be controlled by external stimuli. They can be utilized as a robust mechanism to realize a variety of information processing devices, such as switches, memories and amplifiers, and have been subject of interdisciplinary research, in fields such as photonics [1] and biology [2]. Here, we report on the realization of a nonlinear spin-wave device with bistable behavior and demonstrate its capabilities for computing applications. Our approach is based on one of the most robust nonlinear spin-wave effects, known as the nonlinear spin-wave frequency shift. We use a micro-sized coplanar waveguide (CPW) to coherently excite spin waves in an in-plane magnetized, gallium-substituted yttrium iron garnet film [3]. This system exhibits an exchange-dominated dispersion relation and perpendicular magnetic anisotropy, resulting in a positive nonlinear frequency shift. By applying time-resolved Brillouin-light-scattering microscopy, we investigate the excited spin dynamics. We observe a strongly power-dependent nonlinear excitation with a bistable excitation regime, i.e., two different states of excitation for the same input power, caused by the nonlinear frequency shift and the characteristics of the CPW antenna. We demonstrate that this effect can be used in a versatile way to realize nonlinear magnonic devices, such as magnonic (stochastic) switches, magnonic logic gates and neurons as well as amplifiers. Our work provides a foundation for future implementations of wave-based neuromorphic computing applications.

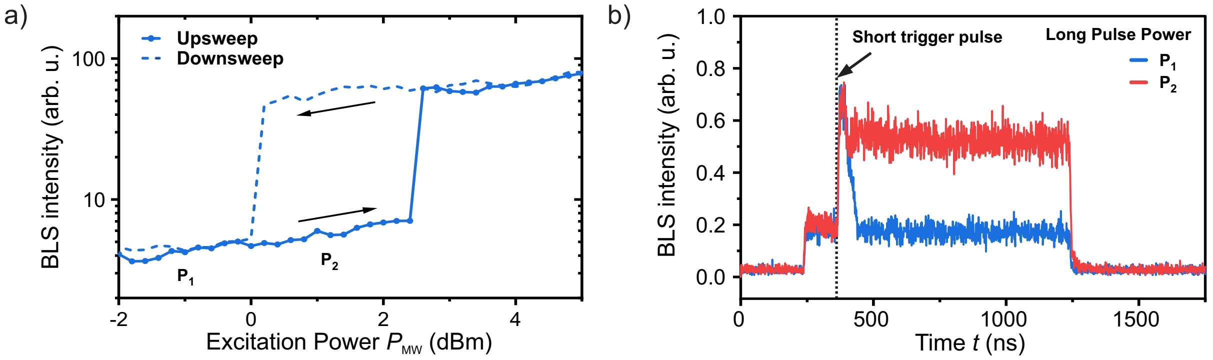

Figure 1: a) BLS intensity as a function of the applied microwave power. In an intermediate power regime P_2, a nonlinear transition into a different intensity state can be observed, which depends on the direction of the powersweep, indicating bistable behavior. b) In the bistable regime P_2, a 30 ns short trigger pulse can induce the nonlinear switching transition into the upper intensity branch, while in the regime P_1 the system is left unaffected.

This research was funded by the European Research Council within the Starting Grant No. 101042439 ”CoSpiN” and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the Transregional Collaborative Research Center—TRR 173–268565370 “Spin + X” (project B01) and the project 271741898.

REFERENCES

[1] S. D. Smith, “Optical bistability, photonic logic, and optical computation”, Appl. Opt. **25**, 1550–1564 (1986).
[2] A. Longtin, A. Bulsara, D. Pierson, and F. Moss, “Bistability and the dynamics of periodically forced sensory neurons”, Biological Cybernetics **70**, 569–578 (1994).
[3] T. Böttcher, M. Ruhwedel, K. O. Levchenko, et al., “Fast long-wavelength exchange spin waves in partially compensated Ga:YIG”, Applied Physics Letters **120**, 102401 (2022).

YIG Gratings for Interference-Based Spin-Wave Devices

Johannes Greil[1,*], **Martina Kiechle**[1], **Ádám Papp**[2], **Matthias Golibrzuch**[1], **György Csaba**[2], **Markus Becherer**[1]
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In this work, we demonstrate a practical approach to pattern nanometer-thin Yttrium Iron Garnet (YIG) films using maskless, resist-based optical lithography combined with a wet-chemical etching step. The resulting structures exhibit sharp edges and excellent structural quality. Due to the diffraction limit, this method is limited to micrometer resolution, but with orders of magnitude higher throughput while being easier to handle compared to E-beam lithography where high vacuum conditions and long writing times are needed [1]. Characterizations via time-resolved MOKE (trMOKE) imaging show that, in terms of spin-wave (SW) propagation, the YIG quality can be maintained in the same quality as on a plain film.

The YIG layer is deposited via RF magnetron sputtering and patterned with a maskless lithography system 365 nm optical wavelength. Pattern transfer into YIG is achieved with phosphoric acid (H_3PO_4: HNO_3:CH_3COOH). Etching the amorphous YIG, i.e. before annealing in an Oxygen atmosphere, is found to be much more efficient than with recrystallized YIG. Using small islands of YIG as alignment markers also allows for a precise re-alignment for e.g. inductive spin-wave transducers including electrical I/O circuitry on top and in close vinicity to the YIG structures.

With the developed fabrication method, we demonstrate a popular spin-wave device exploiting interference, namely a spin-wave spectrometer based on a curved grating. An interesting working principle of a Rowland grating has been presented by our group before [2], however, this device could not work as a full spectrometer due to the necessary nonlinear excitation mechanism. The new fabrication approach of physically structuring YIG in combination with a curved antenna close to a grating enables a full spin-wave spectrometer adapted from the initial design in [3].

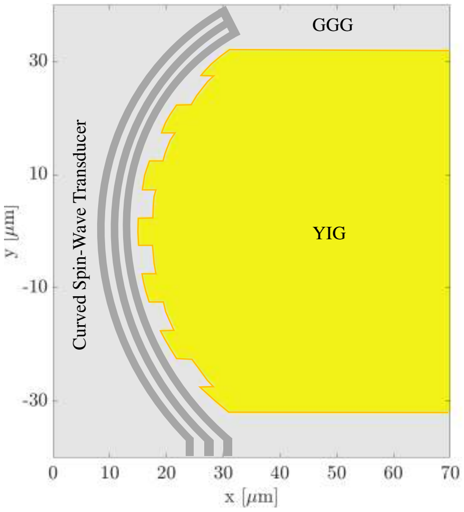

Figure 1: Principal drawing of a YIG grating for a spectrometer, adapted from the initial design in [3]. We are able to fabricate a freestanding YIG layer on the GGG substrate with a curved spin-wave transducer bent around the grating.

REFERENCES

[1] N. Zhu, H. Chang, A. Franson, et al., “Patterned growth of crystalline Y3Fe5O12 nanostructures with engineered magnetic shape anisotropy”, Applied Physics Letters **110**, 252401 (2017).
[2] Á. Papp, M. Kiechle, S. Mendisch, et al., “Experimental demonstration of a concave grating for spin waves in the Rowland arrangement”, Scientific Reports **11**, 1–8 (2021).
[3] Á. Papp, W. Porod, Á. I. Csurgay, and G. Csaba, “Nanoscale spectrum analyzer based on spin-wave interference”, Scientific reports **7**, 1–9 (2017).

Poster 2. PB14
Wednesday
16:30

Domain Wall Qubits on Magnetic Racetracks

Ji Zou[1,*], **Stefano Bosco**[1], **Banabir Pal**[2], **Stuart S. P. Parkin**[2], **Jelena Klinovaja**[1], **Daniel Loss**[1]

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Topological spin textures, such as chiral domain walls, are defined homotopically and are topologically protected in magnetic systems. They have been exploited for various spintronic-logic devices and proposed to be stable information carriers because of their robustness [1, 2]. A particularly appealing proposal is the (classical) magnetic memories, where the controllable domain wall motion is the key. However, its utility is largely unexplored in the fast-growing field of quantum spintronics.

Here, we take advantage of the topological nature of the domain wall and its high mobility to propose a scalable quantum computer [3]. In our theoretical proposal, the quantum information is encoded in the chirality of the spin structure of nanoscale domain walls on ferrimagnetic racetracks, as shown in Fig. 1. We estimate that these qubits are long-lived and could be operated at sweet spots reducing possible noise sources. Single-qubit gates are implemented by controlling the movement of the walls in magnetic nanowires, and two-qubit entangling gates take advantage of naturally emerging interactions between different walls. These gates are sufficient for universal quantum computing and are fully compatible with current state-of-the-art experiments on racetrack memories. Possible schemes for qubit readout and initialization are also discussed.

We also discuss two possible schemes for the domain wall qubit readout. The first approach relies on the recent advances in nanoscale imaging techniques with NV centers, which could serve as a non-invasive quantum sensor. Alternatively, we can measure the chirality of the qubit with well-developed readout techniques for spin qubits which can be coupled to DW magnetically.

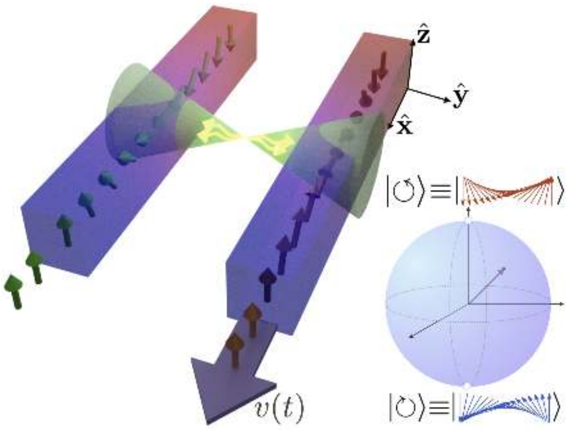

Figure 1: Sketch of two DW qubits on two parallel ferrimagnetic racetracks. The spin texture of the right racetrack has a well-definite positive chirality and is in state $|\uparrow\rangle$, whereas the texture within the left one has negative chirality and is in state $|\downarrow\rangle$. Single qubit gates are implemented by shuttling the domain wall and controlling its velocity $v(t)$. Two-qubit entangling gates between different racetracks take advantage of inter-track exchange and dipolar interactions.

REFERENCES

[1] J. Zou, S. Zhang, and Y. Tserkovnyak, “Topological transport of deconfined hedgehogs in magnets”, Phys. Rev. Lett. **125**, 267201 (2020).
[2] J. Zou, S. K. Kim, and Y. Tserkovnyak, “Topological transport of vorticity in heisenberg magnets”, Phys. Rev. B **99**, 180402 (2019).
[3] J. Zou, S. Bosco, B. Pal, et al., “Domain wall qubits on magnetic racetracks”, arXiv preprint arXiv:2212.12019 (2022).

Modulated Spin-Wave System for Neuromorphic Machine Learning

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In this work, a prototype physical reservoir based on spin-wave dynamics is developed and investigated numerically by micromagnetic simulations. The system under study is a nanometer-sized magnonic waveguide, on top of which a coplanar waveguide (CPW) antenna is placed for spin-wave excitation, as well as a localized region for spin current injection. The inputs of the reservoir are spin current pulses injected via the spin Hall effect, which modulates the amplitude of a carrier spin-wave created by the CPW. The carrier spin wave is reflected at the end of the waveguide, which allows for an interaction of the subsequent input signals. The resulting spin dynamics are shown to become highly nonlinear under the influence of the spin current. The output of the reservoir is its magnetic state as a function of time, which is calculated as part of numerical simulations. Based on an analysis using the kernel and generalization rank [1], the nonlinearity of the input-output relation of the reservoir is quantified. In the kernel rank analysis, the nonlinearity of the reservoir is extracted with spatial resolution, uncovering regions of interest for possible output definitions. This work contributes to the realization of neuromorphic applications based on spin waves and helps to improve benchmarks for physical reservoirs.

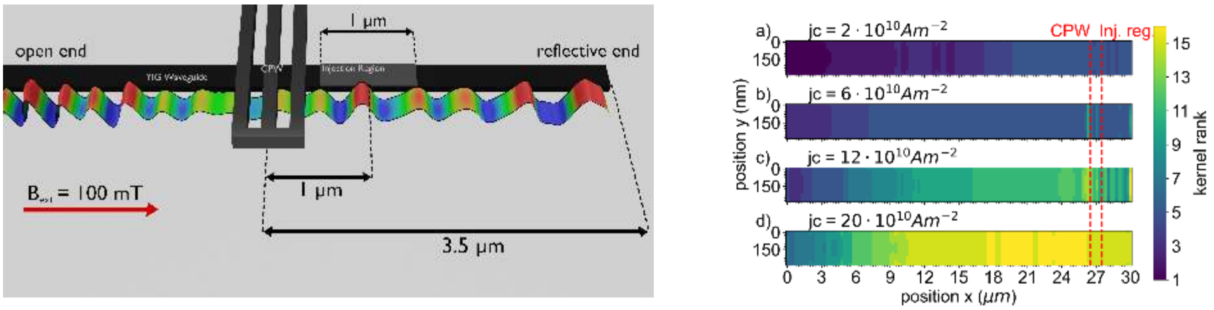

Figure 1: left: Schematic layout of the benchmarked reservoir. An exemplary magnetization profile of the z-component which is extracted from simulations is placed next to the waveguide (3D color-band). right: Spatially resolved kernel rank. The position of the CPW and the injection region are marked using dashed lines.

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REFERENCES

[1] A. Papp, G. Csaba, and W. Porod, “Characterization of nonlinear spin-wave interference by reservoir-computing metrics”, Applied Physics Letters **119**, 112403 (2021).

Enhancement of Microwave to Optical Spin-Based Quantum Transduction via a Magnon Mode

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The highly localized $4f$ electrons of rare-earth-doped materials provide a simple atom-like level structure with a spin-photon interface, telecom-wavelength optical transitions, potential for long spin and optical coherence times, and the ability to realize high-density doping. Proposals for microwave to optical quantum transduction using rare-earth ions [1] rely on spin-flip transitions from microwaves that couple to optical inter-4f transitions. An example is the Er^{3+} ion's $|J = 15/2\rangle \equiv |g\rangle_{Er}$ to $|J = 13/2\rangle \equiv |e\rangle_{Er}$ transition at telecom wavelength. The oscillator strengths (g_b) of the microwave excitations of the Er^{3+} are particularly weak leading to poor transduction efficiencies.

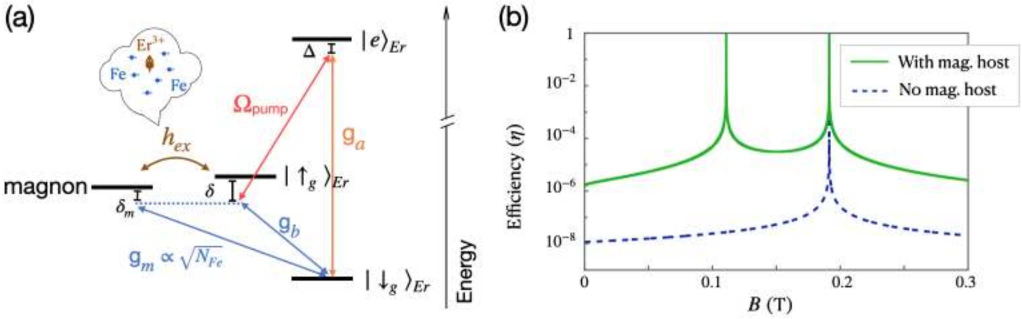

Figure 1: (a) Erbium level structure and its spin-spin exchange interaction with a magnon mode. Coupling *strengths* are indicated next to optical (g_a, Ω_{pump}) and microwave transitions (g_b, g_m) (b) Quantum transduction efficiency.

We describe an approach to dramatically enhance the microwave coupling without diminishing the optical oscillator strength (g_a) for Er^{3+} ions. The microwave excitation is coupled (g_m) to a magnon of a magnetic material in which the Er^{3+} ions are embedded, such as yttrium iron garnet (YIG). Recently synthesis of Er:YIG has been reported[2]. We predict [Eq. (1)] that the iron sublattices of the YIG host have a strong antiferromagnetic exchange coupling to the Er^{3+} ions that dramatically exceeds the dipolar coupling they would experience to direct microwave excitation. We analyze this situation using a formalism similar to Ref. [1] and show in Fig. 1(b) the magnon-enhanced conversion efficiency (η) is estimated to be several orders of magnitude larger than Ref. [1].

$$\eta = \left(\frac{4S\sqrt{\kappa_a \kappa_b}}{4S^2 + \kappa_a \kappa_b} \right)^2, \quad \text{where} \qquad S = \frac{N_{\mathrm{Er}}\, |\Omega_{\mathrm{pump}}|\, |\mathrm{g}_a|\, |\delta_m \mathrm{g}_b - h_{\mathrm{ex}} \mathrm{g}_m|}{\Delta\, |\delta_m \delta - h_{\mathrm{ex}}^2|} \tag{1}$$

This work is supported by the U. S. Department of Energy, Office of Science: theoretical analysis of magnon mode enhancement of microwave-to-optical transduction by BES Award Number DE-SC0023393, magnon-erbium spin coupling by BES Award Number DE-SC0019250, and material processing and spectroscopy work that supports efficiency estimates by the NQISRC Co-design Center for Quantum Advantage (C2QA) under contract number DE-SC0012704.

REFERENCES

[1] L. A. Williamson, Y.-H. Chen, and J. J. Longdell, “Magneto-optic modulator with unit quantum efficiency”, Phys. Rev. Lett. **113**, 203601 (2014).

[2] Y. Cho, S. Kang, Y. W. Nahm, et al., “Structural, optical, and magnetic properties of erbium-substituted yttrium iron garnets”, ACS Omega **7**, 25078–25086 (2022).

Poster 2. PB17
Wednesday
16:30

Electric Field Gated Magnon Transistor

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Magnons as the collective excitation of a magnetically ordered lattice possess both spin-angular momenta and phases but no charges, born an ideal information carrier for the Joule-heating-free electronics. Magnon transistors that can efficiently manipulate the magnon current are long desired . However, also due to their electric neutrality, magnons have no access to directly interact with an electric field and it is thus difficult to manipulate magnon transport by voltages straightforwardly. Recently, the prototypes of magnon transistors gated by magnetic field [1] or bias current [2] were proposed; however the difficulty in integration or energy inefficiency hindered their application.

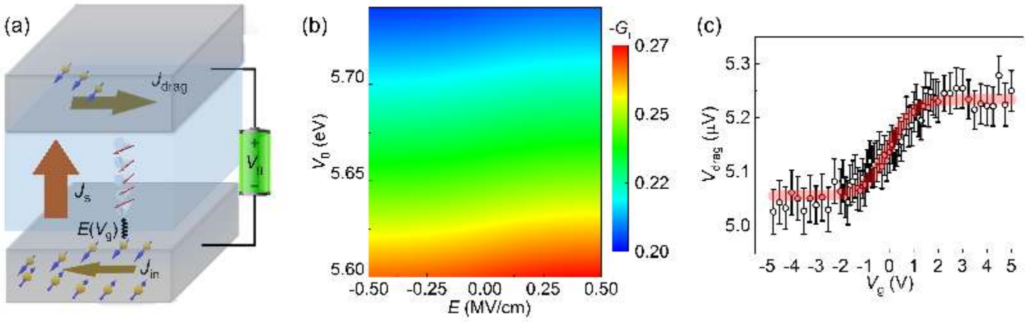

Figure 1: (a) Schematics of the voltage-gated magnon transistor. (b) The calculated inteficial potential step (V_0) and gating electric fied (E) dependence of real part of spin mixing conductance ($G_{\rm r}$) (the color scale bar in units of $e^2/\hbar a^2$). (c) Gate voltage ($V_{\rm g}$) dependence of magnon drag voltage signal ($V_{\rm drag}$) in the Pt(10)/YIG(80)/Pt(5 nm) sample.

Inspired by the theoretical model where the spin mixing conductance ($G_{\uparrow\downarrow}$) at a magnetic insulator/ normal metal interface relies sensitively on the interfacial s-d exchange coupling [3], we theoretically and experimentally demonstrated an electric field gated magnon transistor based on the magnon mediated electric current drag effect (MECD) [4] in an Pt/$Y_3Fe_5O_{12}$ (YIG)/Pt sandwich. The gating electric field applied across the Pt/YIG interface bended the energy band of YIG, then modulated the possibility of Pt conduction electron spin tunnelling into YIG and consequently affected the spin-magnon conversion efficiency of the interface. The obtained efficiency (the change ratio between the MECD voltage at $\pm V_{\rm g}$) reached 10%/(MV/cm) at 300 K. This prototype of magnon transistor offers an effective scheme to control magnon transport by a gate voltage.

REFERENCES

[1]C. Y. Guo, C. H. Wan, W. Q. He, et al., “A nonlocal spin hall magnetoresistance in a platinum layer deposited on a magnon junction.”, Nat. Electron. **3**, 304 (2020).
[2]L. J. Cornelissen, J. Liu, B. J. van Wees, and R. A. Duine, “Spin-current-controlled modulation of the magnon spin conductance in a three-terminal magnon transistor”, Phys. Rev. Lett. **120**, 097702 (2018).
[3]W. Chen, M. Sigrist, J. Sinova, and D. Manske, “Minimal model of spin-transfer torque and spin pumping caused by the spin hall effect”, Phys. Rev. Lett. **115**, 217203 (2015).
[4]S. S.-L. Zhang and S. Zhang, “Magnon mediated electric current drag across a ferromagnetic insulator layer”, Phys. Rev. Lett. **109**, 096603 (2012).

Poster 2. PB18
Wednesday
16:30

Magnon Junction Effect in $Y_3Fe_5O_{12}$/CoO/$Y_3Fe_5O_{12}$ Insulating Heterostructures

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Magnonics optimizing magnon excitation, transportation, and detection, hence, emerges as a frontier of spintronics recently[1]. The most attractive feature of magnonic devices is the Joule-heating-free transportation of spin information, which potentially reduces power dissipation dramatically.To fully avoid electronic contributions, insulating magnon junctions (MJs) with a key structure of magnetic insulator/antiferromagnetic insulator/magnetic insulator have also been proposed and experimentally demonstrated in the $Y_3Fe_5O1_2$(YIG)/antiferromagnetic insulator NiO/YIG sandwich. In such structures, a magnon-mediated nonlocal spin Hall magnetoresistance effect is also uncovered indicating feasibility of using magnetic states to control magnon transport and relaxation[2].In general, magnon currents can be excited both thermally and electrically in magnetic insulators, by applying a current in an adjacent heavy-metal layer. Here, we report another kind of magnon junctions (MJs) composed by YIG/CoO/YIG heterostructures in which YIG and CoO are respectively ferrimagnetic and antiferromagnetic insulators[3]. A temperature gradient can drive a high (low) magnon current via spin Seebeck effect when the YIG layers in an MJ are configurated at the parallel (antiparallel) state, showing a spin valve-like behavior. Electrically injected magnon current could also be controlled by the MJs, contributing to a magnon-mediated nonlocal spin-Hall magnetoresistance (SMR). Furthermore, compared with its NiO counterpart, both magnon junction and magnon-mediate SMR effects can be clearly observed at room temperature for the CoO-based magnon junctions which can possibly be applied as a building block for room-temperature magnon-based memory or logic devices.

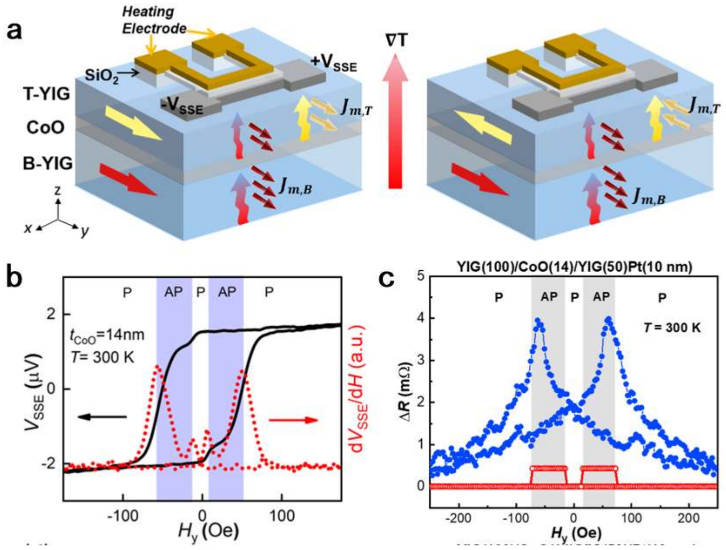

Figure 1: a,Schematics of the magnon junction effect and its measurement steup for MJs where a temperature gradient is applied to excite a magnon current by the spin Seebeck effect. b, Field dependence of V_{SSE} for the MJ with t_{CoO}=14 nm (black line) and field dependence of dV_{SSE}/dH (red line) at 300 K.c, Electrically injected magnon current could also be controlled by the MJs, contributing to a magnon-mediated nonlocal spin-Hall magnetoresistance (SMR).

REFERENCES

[1] X. Han, C. Wan, H. Wu, et al., “From microelectronics to spintronics and magnonics”, Chinese Physics B **31**, 117504 (2022).
[2] C. Guo, C. Wan, W. He, et al., Nature Electronics. **3**, 304–308 (2020).
[3] W. He, H. Wu, C. Guo, et al., “Magnon junction effect in y3fe5o12/coo/y3fe5o12 insulating heterostructures”, Applied Physics Letters **119**, 212410 (2021).

Observation of Dispersion Relation for Hybridized Magnons in Synthetic Antiferromagnets

Daiju Hayashi[1,*], **Yoichi Shiota**[1,2], **Mio Ishibashi**[1], **Ryusuke Hisatomi**[1,2], **Takahiro Moriyama**[1,2],
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Creating a new magnon state by coherent coupling of two magnon modes is expected to significantly contribute to the development of future magnonic devices [1]. In our recent study, it was found that the hybridization of two antiferromagnetic magnon modes, called magnon-magnon coupling, can be realized using synthetic antiferromagnets (SAFs) due to the dynamic dipolar interactions [2]. Those results were measured by the electrical spin wave spectroscopy technique with the microwave reflection occurring from the coplanar waveguide. In this study, we measured the hybridized magnon propagation in SAFs using a heterodyne-magneto-optical Kerr effect (MOKE) technique [3] and obtained magnon dispersion relation which is important to understand the properties of magnons.

The SAF structures of Ta(3)/Ru(3)/$\mathrm{Fe_{60}Co_{20}B_{20}}$(15)/Ru(0.6)/$\mathrm{Fe_{60}Co_{20}B_{20}}$(15)/Ru(3) (thicknesses in nm) were fabricated using dc magnetron sputtering on thermally oxidized Si substrates. The films were micro-fabricated to spin wave devices, as presented in Ref. [2]. Magnons were excited by applying microwave current to the antenna from the port 1 of a vector network analyzer (VNA). Then the magnetization precession dynamics were detected using a focused laser beam in the polar MOKE geometry, which enable to detect only acoustic magnons, and the optical heterodyne signal was send to the port 2 of the VNA. In this measurement, both the intensity and phase of the propagating magnon were obtained. Figure 1 shows the experimentally obtained dispersion relation of the magnons from the complex fast Fourier transformation of the obtained signals under the in-plane magnetic field of 38.1 mT to 45° away from the direction of the magnon propagation direction. A pronounced mode splitting was observed in negative wavenumber region, indicating the anticrossing of magnon dispersion relations between acoustic and optical magnons. Further investigation, such as the dependences on magnetic field strength and angle, will be discussed in the presentation.

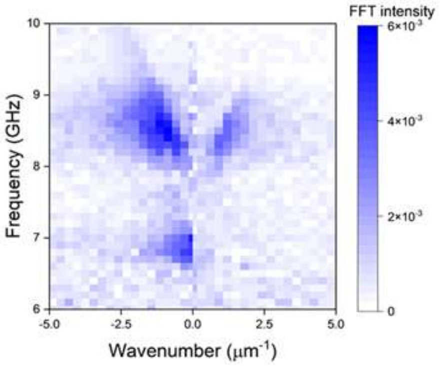

Figure 1: The magnon dispersion relation reconstracted from a fast Fourier transform of a complex magnon amplitude.

REFERENCES

[1] G. Kurizki, P. Bertet, Y. Kubo, et al., “Quantum technologies with hybrid systems”, Proceedings of the National Academy of Sciences **112**, 3866–3873 (2015).

[2] Y. Shiota, T. Taniguchi, M. Ishibashi, T. Moriyama, and T. Ono, “Tunable magnon-magnon coupling mediated by dynamic dipolar interaction in synthetic antiferromagnets”, Physical Review Letters **125**, 017203 (2020).

[3] Y. Shiota, S. Funada, R. Hisatomi, T. Moriyama, and T. Ono, “Imaging of caustic-like spin wave beams using optical heterodyne detection”, Applied Physics Letters **116**, 192411 (2020).

Binary Encoding of Spin-Wave Active Ring Oscillator Modes

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Spin-wave active ring oscillators (SWAROs) are a novel dynamical system, capable of supporting bright and dark solitons, chaos, fractal solitons etc. [1]. The SWARO enters a sustained oscillation state when the total ring gain is greater than zero, and the phase difference over a single round trip is an integer multiple of 2π. We use magnetostatic surface spin-waves (MSSWs) excitations in a Yttrium iron garnet (YIG) film within the ring, and suitably adjust the gain within the ring, to observe the modes of the oscillator. These modes are then manipulated and binary-encoded by injecting a GHz signal into the ring. A driven SWARO with such encoding can be used to solve multi-class classification and pattern recognition problems [2].

We have encoded the output power spectrum of a SWARO under the influence of an external GHz drive signal into a binary format to create multiple states. Figure 1(a) shows the SWARO circuit, where the YIG film is kept on a pair of microstrip line antennae. A distance of 9 mm separates the antennae. The in-plane saturation field of 19.7 kA/m is applied along the width of the film. The gain block amplifier provided a constant gain of 35 dB. The variable attenuator, α was set at 4 dB. The drive frequency (f_d) was swept from 2.052 to 2.112 GHz with a resolution of 300 kHz. The drive power was fixed at $P_\mathrm{d} = -4\,$dBm.

A spectrum analyzer records the frequency content of the signal that was coupled out of the ring. We set a threshold power value of 30 dB below the maximum power observed in the output spectrum of the driven SWARO. This allows us to code the output spectrum of the driven SWARO as binary values, i.e., power values below the threshold are ‘0’ and those above are ‘1’, as shown in Fig. 1(b). For a fixed P_d and f_d, we have observed power values at four frequency points, i.e. 2.0653, 2.075, 2.084, and 2.093 GHz, marked by the horizontal dashed blue lines in Fig. 1(b). The most significant bit (MSB) is situated at 2.0653 GHz, and f_d = 2.0615, 2.072, 2.082, 2.091, and 2.101 GHz are mapped onto the sequences 0111, 1011, 1101, 1110, 1111 respectively. By suitably tuning P_d and f_d, we expect to identify more such states and expand the coding scheme.

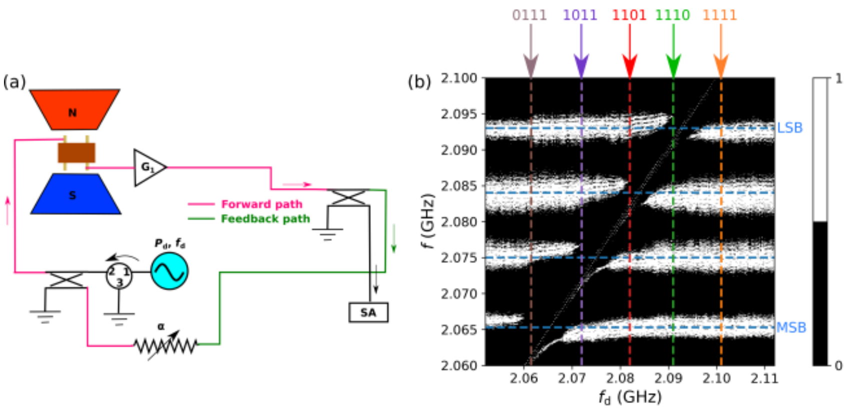

Figure 1: (a) Schematic of the SWARO setup. SA stands for the spectrum analyzer. (b) Binary output spectrum from SWARO with a drive power of -4 dBm. The blue dashed lines indicate the frequencies of observation.

REFERENCES

[1]M. Wu, “Nonlinear spin waves in magnetic film feedback rings”, in *Solid state physics*, Vol. 62 (Elsevier, 2010), pp. 163–224.

[2]M. Romera, P. Talatchian, S. Tsunegi, et al., “Vowel recognition with four coupled spin-torque nano-oscillators”, Nature **563**, 230–234 (2018).

Nanoscale YIG Gratings for Interference-Based Spin-Wave Devices in Thin YIG Layers

Johannes Greil[1,*], **Martina Kiechle**[1], **Ádám Papp**[2], **Matthias Golibrzuch**[1], **György Csaba**[2], **Markus Becherer**[1]
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In this work, we demonstrate a practical approach to pattern nanometer-thin Yttrium Iron Garnet (YIG) structures using optical lithography combined with an etching step. The resulting structures exhibit sharp edges and excellent structural quality. Due to the diffraction limit, this method is limited to micrometer precision, but much more practical compared to using electrons or ions for lithography due to the required high vacuum and long writing times [1]. Characterizations via time-resolved MOKE (trMOKE) imaging showed that in terms of spin-wave (SW) propagation the YIG quality can be maintained in the same quality as on a plain film.

The YIG layer is fabricated via RF magnetron sputtering and afterwards etched with phosphoric acid (H_3PO_4:HNO_3:CH_3COOH:H_2O) in combination with a lithography mask. Etching the amorphous YIG, i.e. before annealing in an Oxygen atmosphere, is found to be much more efficient than with recrystallized YIG. Using small islands of YIG as alignment markers also allows for a precise re-alignment for inductive spin-wave transducers including electrical I/O circuitry ontop and around the YIG structures. Alternatively, we also explore a lift-off instead of etching step before the annealing which, however, causes a high surface roughness and thus degrades the edge quality especially for trMOKE imaging significantly. With these developed technologies, we demonstrate a popular spin-wave device exploiting interference, a spin-wave spectrograph based on a curved grating. An interesting working principle of a Rowland grating has been presented by our group before [3], however, this device could not function as a full spectrometer due to the nonlinear excitation mechanism unveiled. The new fabrication approach of physically structuring YIG in combination with a curved antenna behind a grating enables a full spin-wave spectrograph emulated by the initial design in [2].

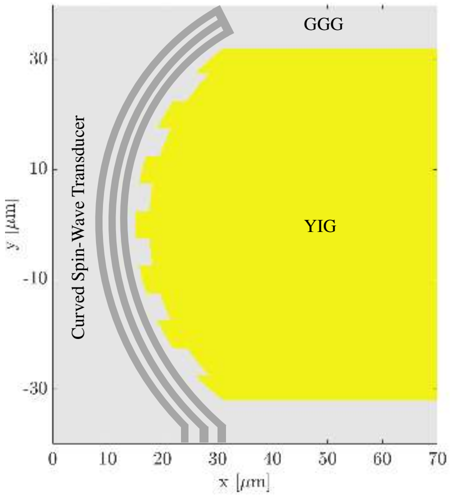

Figure 1: Principal drawing of a YIG grating for a spectrograph adapted from the initial design in [2]. We are able to fabricate a free-standing YIG layer on the GGG substrate with a curved spin-wave transdcuer bent around the grating.

REFERENCES

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[2] Á. Papp, W. Porod, Á. I. Csurgay, and G. Csaba, “Nanoscale spectrum analyzer based on spin-wave interference”, Scientific reports **7**, 1–9 (2017).
[3] Á. Papp, M. Kiechle, S. Mendisch, et al., “Experimental demonstration of a concave grating for spin waves in the rowland arrangement”, Scientific Reports **11**, 1–8 (2021).

Influence of Paramagnetic GGG Substrates on YIG Films at Millikelvin Temperatures

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The ferrimagnet yttrium iron garnet (YIG) $Y_3Fe_5O_{12}$ grown on gadolinium gallium garnet (GGG) $Gd_3Ga_5O_{12}$ substrates [1] has the lowest known magnetic damping and is therefore the material of choice for both room-temperature and quantum magnonics operating at millikelvin temperatures [2, 3]. However, it is well known that YIG gradually worsens its magnetic properties at low temperatures due to the paramagnetic GGG substrate. Here, we present experimental results, simulations, and an analytical theory to clarify the influence of the GGG substrate on a 97 nm-thick YIG film at temperatures down to 30 millikelvin. The magnetization of the GGG substrate was measured using vibrating-sample magnetometry, and the magnetic properties of the YIG film were characterized by ferromagnetic resonance (FMR) measurements. At low temperatures, the paramagnetic GGG substrate can be easily magnetized by an external magnetic field. The GGG magnetization results in the formation of a stray field in the YIG film that affects the magnetization dynamics within it [4] - see Fig. 1a. The highly inhomogeneous stray field is oriented in the opposite direction to the external field in the case of in-plane magnetization of YIG/GGG and shifts the FMR frequency to lower values. Moreover, the magnetization of GGG increases the magnetic damping of YIG by more than eight times compared to measurements at room temperature - see Fig. 1b. The mechanisms responsible for this behaviour are under investigations.

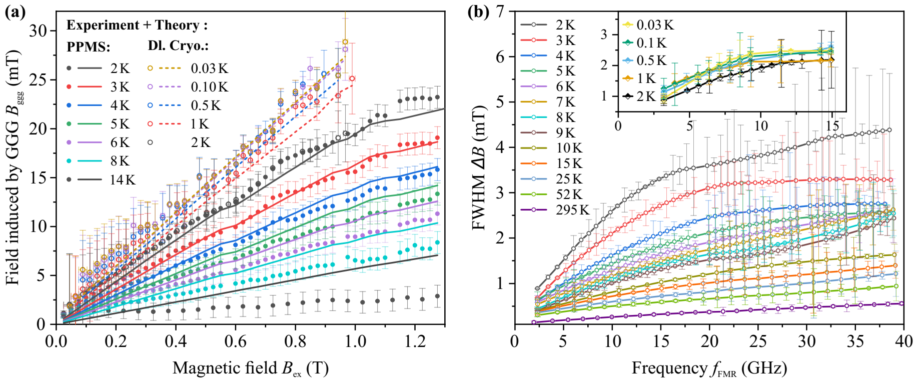

Figure 1: (a) Field induced by GGG B_{ggg} in YIG, extracted from the temperature dependent FMR measurements. (b) Temperature dependent FMR linewidth ΔB of the YIG film vs. the resonance frequency f_{FMR}.

REFERENCES

[1] C. Dubs et al., “Low damping and microstructural perfection of sub-40nm-thin yttrium iron garnet films grown by liquid phase epitaxy”, Phys. Rev. Materials **4**, 024416 (2020).
[2] A. V. Chumak, P. Kabos, M. Wu, et al., “Advances in magnetics roadmap on spin-wave computing”, IEEE Transactions on Magnetics **58**, 1–72 (2022).
[3] D. Lachance-Quirion, S. P. Wolski, Y. Tabuchi, et al., “Entanglement-based single-shot detection of a single magnon with a superconducting qubit”, Science **367**, 425–428 (2020).
[4] V. V. Danilov, D. L. Lyfar’, Y. V. Lyubon’ko, A. Y. Nechiporuk, and S. M. Ryabchenko, “Low-temperature ferromagnetic resonance in epitaxial garnet films on paramagnetic substrates”, Sov. Phys. J. **32**, 276–280 (1989).

Understanding the Magnetic Properties of Ultrathin BiYIG Grown by Sputtering

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Ferrimagnetic insulator thin film garnets with perpendicular magnetic anisotropy have recently expanded the realm of experimental possibilities in magnonics (e.g., [1]). Even though several rare-earth doped and substituted garnet compositions (from Ce to Tm) have been investigated for their perpendicular magnetization, thin films of LuIG [2], YIG [3] and Bi-doped YIG (BiYIG) [4] remain the only compositions enabling a damping in the 10^{-4} range, required for many types of experiments. Among these low-damping garnets, perpendicular magnetic anisotropy has been more practically achieved with BiYIG.

We cover in this contribution our recent progress in the growth by magnetron sputtering of ultrathin BiYIG films with tunable magnetic anisotropy and low damping. The thickness of BiYIG ranges within 3–30 nm. We study the degree of crystalline perfection, the strain, the elemental composition and its thickness dependence, as well as the dynamic magnetic properties of BiYIG, by X-ray characterization, TEM imaging, analytical techniques in SEM and TEM, ferromagnetic resonance measurements and non-local magnon transport experiments. We relate the evolution of these properties to deposition parameters, such as sputtering gas mixture and deposition power, in order to provide guidelines for future work with this system.

As expected from strain-related magnetocrystalline anisotropy and growth-induced anisotropy under epitaxial conditions, the choice of the substrate [4] and deposition conditions [5] allows us to tune the magnetic anisotropy with precision across the magnetic reorientation transition. We find that the sputter-grown films differ from films grown by pulsed laser deposition in several aspects. This establishes BiYIG as an ideal platform to combine studies relating to spin-pumping, incoherent spin-waves diffusion and coherent spin-waves propagation, while almost continuously tuning the magnetic parameters, and with the possibility of going towards low temperatures without significant damping increase, which we demonstrate by a few examples.

REFERENCES

[1] Y. Fan, M. J. Gross, T. Fakhrul, et al., “Coherent magnon-induced domain wall motion in a magnetic insulator channel”, arXiv **2212.01408**, v1 (2022).
[2] C. L. Jermain, H. Paik, S. V. Aradhya, et al., “Low-damping sub-10-nm thin films of lutetium iron garnet grown by molecular-beam epitaxy”, Appl. Phys. Lett. **109**, 192408 (2016).
[3] J. Ding, C. Liu, Y. Zhang, et al., “Nanometer-Thick Yttrium Iron Garnet Films with Perpendicular Anisotropy and Low Damping”, Phys. Rev. Appl. **14**, 014017 (2020).
[4] L. Soumah, N. Beaulieu, L. Qassym, et al., “Ultra-low damping insulating magnetic thin films get perpendicular”, Nat. Commun. **9**, 3355 (2018).
[5] D. Gouéré, H. Merbouche, A. El Kanj, et al., “Temperature-independent ferromagnetic resonance shift in Bi-doped YIG garnets through magnetic anisotropy tuning”, Phys. Rev. Mater. **6**, 114402 (2022).

Characterising Noncollinear Exchange Coupled trilayers of Epitaxial Co_2oMnSi / Cr / Co_2MnSi for Magnonic Applications

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Magnonic computing is a novel computing paradigm that exploits the unusual behaviour of magnons to develop faster, more efficient devices, that have the potential to rival existing CMOS technologies. To date, most Magnonics research has been carried out in yttrium iron garnet (YIG), since it has low magnetic damping and hence long spin-wave propagation distances [1]. However, currently, epitaxial YIG cannot be integrated into existing CMOS circuits [2] and hence further research into CMOS compatible magnonic media is required. Heusler alloys are a potential candidate for such applications. In particular, epitaxial thin films of Co_2MnSi, where the Gilbert damping parameter has been reported in the 10^{-4} range [3].

Exchange coupled trilayers of Co_2MnSi are also of great interest for Magnonic applications. The exchange coupled magnon modes provide a richer range of potential information-carrying degrees of freedom. Moreover, unlike conventional antiferromagnets, the frequencies of these coupled magnon modes are in the easily accessible GHz frequency range and hence can be studied using conventional microwave techniques [4].

In this contribution, we report on exchange coupled epitaxial trilayers consisting of two Co_2MnSi layers separated by a Cr spacer layer. The lattice mismatch between Cr and Co_2MnSi is small and hence Cr is chosen to minimise any strain induced during growth. A series of Co_2MnSi (20nm) / Cr (t_{Cr} = 0.292nm - 4.38nm) / Co_2MnSi (8nm) samples were fabricated via Molecular Beam Expitaxy and their epitaxial quality was then verified using Transmission Electron Microscopy. The exchange coupling was expected to show both collinear and noncollinear contributions, in part due to the antiferromagnetic order of Cr [5]. However, the magnetometry results indicate the exchange coupling is solely noncollinear and varies as a function of Cr thickness. A peak in the exchange coupling strength is observed in samples with t_{Cr} = 0.584nm.

REFERENCES

[1]A. A. Serga, A. V. Chumak, and B. Hillebrands, "YIG magnonics", Journal of Physics D: Applied Physics **43**, 264002 (2010).
[2]A. Mahmoud, F. Ciubotaru, F. Vanderveken, et al., "Introduction to spin wave computing", Journal of Applied Physics **128**, 161101 (2020).
[3]C. Guillemard, S. Petit-Watelot, J.-C. Rojas-Sánchez, et al., "Polycrystalline co_2mn-based heusler thin films with high spin polarization and low magnetic damping", Applied Physics Letters **115**, 172401 (2019).
[4]R. A. Duine, K.-J. Lee, S. S. P. Parkin, and M. D. Stiles, "Synthetic antiferromagnetic spintronics", Nature Physics **14**, 217–219 (2018).
[5]D. Pierce, J. Unguris, R. Celotta, and M. Stiles, "Effect of roughness, frustration, and antiferromagnetic order on magnetic coupling of fe/cr multilayers", Journal of Magnetism and Magnetic Materials **200**, 290–321 (1999).

Poster 2. PB25
Wednesday
16:30

Nonreciprocal Magnetoacoustic Excitation of Magnons in Yttrium Iron Garnet

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Magnonic computing promises lower energy consumption, reduced footprints and easily accessible non-linearity [1], moving away from bottlenecked CMOS architecture. Such computing requires efficient excitation of magnons if practical devices are to be realised. Excitation via conventional techniques, namely microwave antennae, is inherently inefficient owing to Joule heating, thus an alternative is required [2].

Surface Acoustic Waves (SAWs) are used in a multitude of everyday devices, most notably filters for mobile communications. The magnetoacoustic coupling between SAWs and spin waves offers an energy-efficient mechanism for magnon excitation. Furthermore, the nonreciprocal nature of this coupling gives additional functionality [3].

In this contribution, magnetoacoustic excitation of magnons is examined in yttrium iron garnet (YIG) thin films. Ti/Au interdigital transducers are patterned on GGG/YIG structures, as seen in Figure 1. These are subsequently covered by a layer of piezoelectric zinc oxide. This zinc oxide layer enables the excitation of GHz frequency SAWs, which couple to spin waves in the YIG layer. The SAWs and spin waves are then characterised using a vector network analyser and micro-focused Brillouin light scattering spectroscopy. The observed magnetoacoustic excitation is distinctly nonreciprocal.

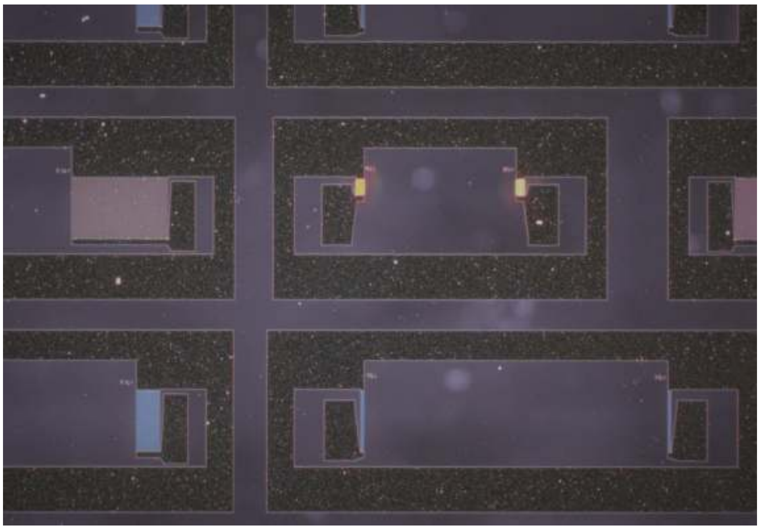

Figure 1: Dark-field microscopy image of a yttrium iron garnet sample with patterned interdigital transducers.

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REFERENCES

[1]A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, "Magnon spintronics", Nature Physics **11**, 453–461 (2015).
[2]A. Barman, G. Gubbiotti, S. Ladak, et al., "The 2021 magnonics roadmap", Journal of Physics: Condensed Matter **33**, 413001 (2021).
[3]M. Küß, M. Heigl, L. Flacke, et al., "Nonreciprocal dzyaloshinskii–moriya magnetoacoustic waves", Phys. Rev. Lett. **125**, 217203 (2020).

Poster 2. PB26
Wednesday
16:30

Topological Magnons for Hybrid Magnonic Systems

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Magnonics has been an emerging field with great applications, including novel quantum functionalities [1–3]. Most recently, magnonic quantum hybrid systems have been proposed as a scheme to couple and entangle solid-state spin centers (e.g., Nitrogen-Vacancy centers) over micrometer lengths [4, 5]. This leverage the potential use of spin centers in quantum information science. However, the required operating temperature for those hybrid schemes is $\sim$100 mK, mainly due to the noise susceptibility of these magnetic excitations at high temperatures. This makes these systems less practical, thus stopping their widespread use. Accordingly, to use the whole capability of the room-temperature spin center qubits and push forward more practical quantum technologies, further alternative proposals for hybrid systems are needed.

Here we study the use and implementation of topological magnon modes for solid-state hybrid quantum technologies. We start by deriving topological magnons in layered honeycomb ferromagnetics in the presence of both inter and intra layer exchange, Dzyaloshinskii–Moriya interaction and anisotropy. Secondly, we develop a formalism for how topological magnons interact with solid-state spin centers. Interestingly, this formalism allows us to predict the fingerprint of topological magnons via quantum sensors. Finally, we discuss entangling protocols using topological magnons, and compare with their trivial counterpart.

REFERENCES

[1] D. D. Awschalom, C. R. Du, R. He, et al., “Quantum engineering with hybrid magnonic systems and materials”, IEEE Transactions on Quantum Engineering **2**, 1–36 (2021).

[2] A. Barman, G. Gubbiotti, S. Ladak, et al., “The 2021 magnonics roadmap”, Journal of Physics: Condensed Matter **33**, 413001 (2021).

[3] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, “Advances in coherent magnonics”, Nature Reviews Materials **6**, 1114–1135 (2021).

[4] D. R. Candido, G. D. Fuchs, E. Johnston-Halperin, and M. E. Flatté, “Predicted strong coupling of solid-state spins via a single magnon mode”, Materials for Quantum Technology **1**, 011001 (2020).

[5] M. Fukami, D. R. Candido, D. D. Awschalom, and M. E. Flatté, “Opportunities for long-range magnon-mediated entanglement of spin qubits via on- and off-resonant coupling”, PRX Quantum **2**, 040314 (2021).

Poster 2. PB27
Wednesday
16:30

Magnonic Band Structures of CoFeB and CoFeB/Ta/NiFe Meander-Shaped Films

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In magnonic crystals, a nanoscale periodic modulation of the magnetic properties allows for tuning the magnon band structure with permitted and prohibited frequency regions, as well as controlling related properties such as the group velocity or magnon interactions. The current state-of-the-art is focused on the understanding of magnonic band formation in planar 1D and 2D MCs which can be fabricated by standard nano-lithographic techniques. The recent interest in 3D MCs is driven by the potential for vertically integrated magnonic devices that may ultimately mimic the current development of 3D integrated microelectronic circuits.[1] Meander-type ferromagnetic films and multilayers, grown on the top of periodically structured substrates, are candidates of such 3D MCs and represent a wide playground to study the emergent properties of spin waves in 3D systems. In this work, we present an experimental and micromagnetic study of the magnonic band structure in CoFeB and CoFeB/Ta/NiFe meander-shaped films.[2, 3] We reveal the dispersion relations and the periodic character of several dispersive branches as well as alternating frequency bands, where spin waves are allowed or forbidden to propagate. For both structures, the mode crossing and the absence of a bandgap were observed at $k = n\pi/a$ (n is an odd number). We found a narrower width of the magnonic band for the CoFeB/Ta/NiFe structure as compared to the CoFeB sample. An additional feature of the CoFeB/Ta/NiFe system is the presence of the three lowest frequency modes that exhibit a nondispersive character. The properties of the individual modes have been further characterized by the phase relation (in-phase or out-of-phase) between the magnetization oscillations in the two layers and their localization in the horizontal and vertical segments. The results show that the investigated structures behave as three-dimensional spin-wave waveguides enabling thus the vertical spin-wave transport.

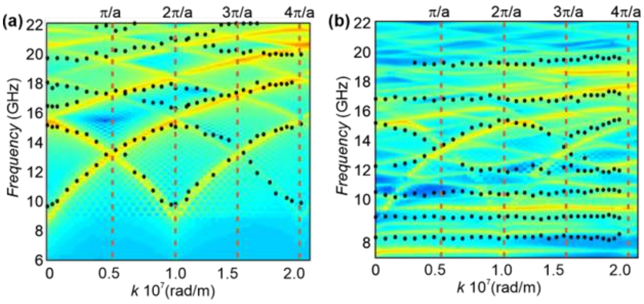

Figure 1: Comparison between measured (points) and simulated (color map) dispersion relations for (a) CoFeB and (b) CoFeB/Ta/NiFe meander structures.

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REFERENCES

[1] A. Barman and et al, “The 2021 magnonics roadmap”, Journal of Physics: Condensed Matter **33**, 413001 (2021).
[2] G. Gubbiotti and et al, “Magnonic band structure in vertical meander-shaped cofeb thin films”, Phys. Rev. Applied **15**, 014061 (2021).
[3] G. Gubbiotti and et al, “Magnonic band structure in cofeb/ta/nife meander-shaped magnetic bilayers”, Appl. Phys. Lett **118**, 162405 (2021).

Poster 2. PB28
Wednesday
16:30

Spatial Control of Hybridization Induced Spin Wave Transmission Stop Band

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For certain material parameters the Damon-Eshbach dispersion relation in soft thin magnetic films displays a hybridization between the n=0 and n=1 modes. As was previously shown, this results in an anticrossing between those two modes and a strong attenuation of spin wave propagation [1]. Furthermore, it is well known that at the edges of thin magnetic films the effective field is locally reduced, in order to avoid the generation of magnetic surface charges.

Here, we aim to harness those two effects by means of film geometry and applied external field. A gradual local reduction of the effective field is achieved by fabrication of a wedge-like structure. This allows the dispersion to access the hybridization at a fixed position in the wedge where the spin wave propagation vanishes. Now, by slightly tuning the external field, this position in space may be controlled.

In the experiments, spin waves are excited reasonably close to the hybridization field in 200 nm thick Yttrium Iron Garnet by a shorted coplanar waveguide. Time Resolved Kerr Microscopy is used to investigate the dynamic magnetization both, spatially, as well as time resolved. In the measurements (see Figure. 1), we indeed observe a field dependent stopping of propagation, which makes this approach interesting for magnonic devices.

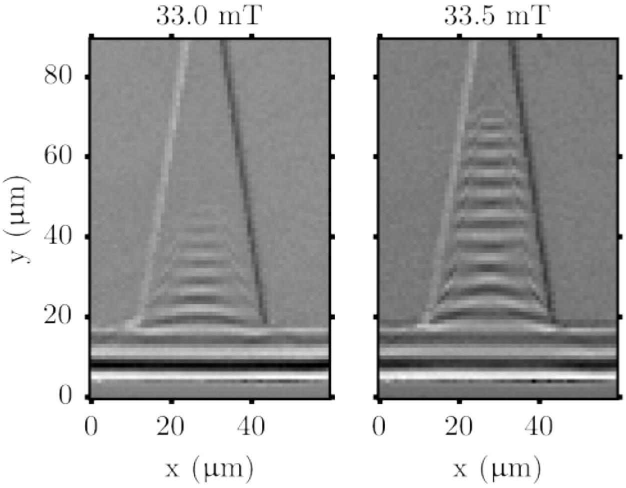

Figure 1: Experimental data 2.8 GHz for two different external fields.

REFERENCES

[1]C. Riedel et al. accepted for publication in Adv. Phys. Research.

Poster 2. PB29
Wednesday
16:30

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.

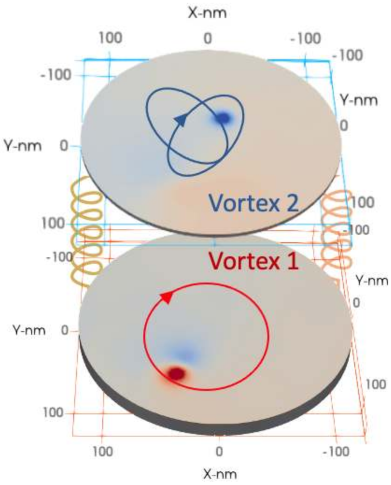

Figure 1: Simplified schematic illustration of the coupled system. The coupled vortex cores' trajectories are traced via red/blue lines.

Hybrid Magnonic-Oscillator System: towards the Development of Hybrid Artificial Network Structures

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Due to the tremendous increase in available data from various sources, new methods of data processing and analysis are required. Nano-spintronics devices, which use 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 spintronics, namely spin torque oscillators and magnonic waveguides, to enable new possibilities for spin-wave-based circuits. The device comprises a spin transfer oscillator that is dipolarly coupled to a nanoscale spin-wave waveguide with longitudinal magnetization. In the auto-oscillating 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 the uniform to vortex state and controlling the chirality and polarity of the magnetic vortex, the system can be reconfigured, and spin waves can be emitted with high non-reciprocity, with the preferred direction depending on the core polarity of the vortex. Varying vortex chiralities leads to different amplitudes of the emitted waves [1].

We have also studied a pair of oscillators in the uniform state, each with individual electrical contacts, coupled to a spin-wave waveguide. Using micromagnetic simulations, we achieved synchronization even for large separations of at least 10 μm, with a significant difference in the uncoupled, free-running frequency of the synchronized auto-oscillators. 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 of these features will pave the way for the development of new and efficient signal-processing devices for unconventional computing.

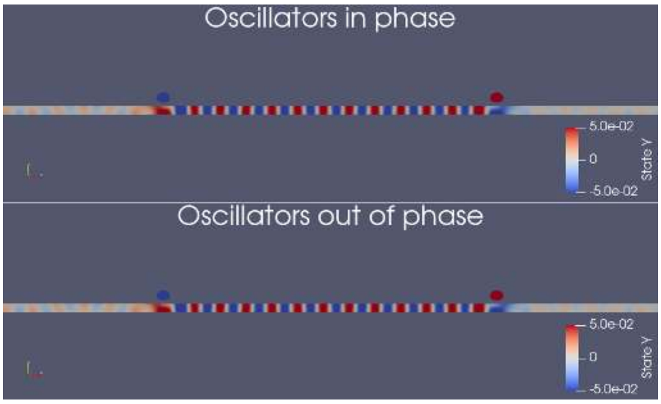

Figure 1: Synchronization of two oscillators via spin waves . Depending on the phase difference of the oscillators and the SW wavelength, different SW intensity patterns are realized which change the coupling to further oscillators.

REFERENCES

[1] A. Hamadeh, D. Breitbach, M. Ender, et al., “Hybrid magnonic-oscillator system”, Journal of Applied Physics **132**, 183904 (2022).

Poster 2. PB31
Wednesday
16:30

Machine-Learned Gradient Patterns in YIG via Focused-Ion-Beam Irradiation

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We are demonstrating the experimental realization of machine learned patterns for spin waves via focused-ion-beam (FIB) irradiation of YIG. We are using our recently developed SpinTorch [1] micromagnetic simulator with built-in gradient-based optimization to create gradient patterns with pre-defined tasks – in this example focusing a straight spin-wave wavefront to a point, as shown in Fig. 1b). The training parameter in the simulation is the pointwise saturation magnetization (Ms) of YIG, which influences the local spin-wave wavelength, thus steering the waves. We show that these patterns can be experimentally realized via FIB irradiation of YIG.

The effect of FIB on the spin-wave wavelength was recorded using a time-resolved MOKE microscope at various dose levels, as shown in Fig. 1a). It can be observed that the wavelength decreases with dose up to about $8 \cdot 10^{12}$ ions/cm^2, corresponding to a relative refraction index $n_{\mathrm{rel}} = 0.69$. At higher doses this trend reverses and the wavelength increases to infinity at a dose of $28 \cdot 10^{12}$ ions/cm^2, which corresponds to ferromagnetic resonance (FMR). Further increasing the dose, the cutoff frequency becomes higher than the excitation frequency, but as expected by also increasing the excitation frequency spin-waves reappear.

In this work we used the dose levels above $8 \cdot 10^{12}$ ions/cm^2, which provides practically unlimited range of refractive indices. Previously [2] it was assumed that damages to YIG increase damping to unacceptable levels at these dose levels, however, upon closer investigation we found that this is not the case and large propagation distances are still possible at such high doses. This provides much higher flexibility in the design and enables more compact devices.

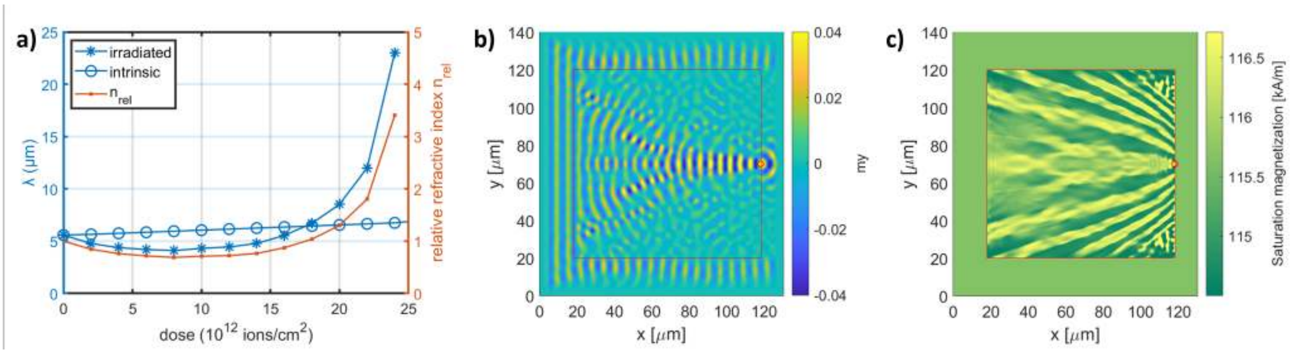

Figure 1: Demonstration of a spin-wave focusing pattern. a) The spin-wave wavelength as a function of ion dose was experimentally recorded and plotted (using 100 nm YIG thickness and 30 kV FIB acceleration voltage). b) Snapshot of the spin-wave interference pattern after training in SpinTorch (plane waves generated on the left, focusing on the red circle on the right). c) The Ms pattern as a result of the training, to be translated into FIB doses via a) and the dispersion relation. Only the center 100 μm by 100 μm area is trained, outside of that region the intrinsic YIG Ms is assumed.

We believe that this work serves as a proof-of-principle demonstration for inverse-design magnonic devices. SpinTorch (and other machine-learning approaches [3]) can be used to complex linear and nonlinear spin-wave devices in a small footprint, and FIB irradiation is a high-resolution method to realize the designed patterns.

REFERENCES

[1] Adam Papp, “SpinTorch”, https://github.com/a-papp/SpinTorch.
[2] M. Kiechle, L. Maucha, V. Ahrens, et al., “Experimental demonstration of a spin-wave lens designed with machine learning”, IEEE Magnetics Letters **13**, 1–5 (2022).
[3] Q. Wang, A. V. Chumak, and P. Pirro, “Inverse-design magnonic devices”, Nat. Commun. **12**, 1–9 (2021).

Poster 2. PB32
Wednesday
16:30

Degenerate and Non-Degenerate Parametric Excitation in YIG Nanostructures

Hugo Merbouche[1,*], **P. Che**[2], **N. Beaulieu**[3], **J. Ben Youssef**[3], **M. Muñoz**[4], **P. Bortolotti**[2], **A. Anane**[2], **S.O. Demokritov**[1], **V.E. Demidov**[1]
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Spin-waves represent a promising alternative to charge carriers for new information technology due to their low energy, small wavelength, large degree of freedom (frequency and phase), and their easily attainable non-linear dynamics. These characteristics make them particularly suited for neuromorphic computing schemes that take advantage of the massive parallelization of operations in the frequency space and of the non-linear properties of spin-waves. Such schemes require the excitation 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 (Fig. 1a). However, when the rf field is applied transversely, it non-resonantly excites a magnon which splits into a magnon-pair that is typically non-degenerate (Fig. 1b). This non-resonant transverse parametric pumping 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.

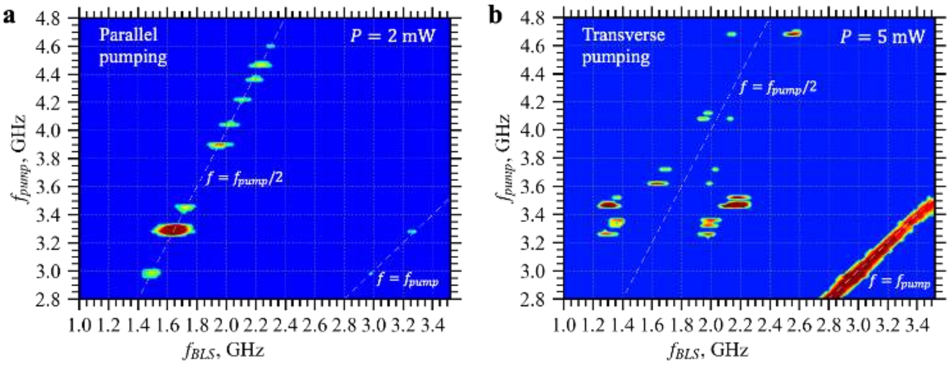

Figure 1: µ-BLS spectra as a function of the pump frequency for a pumping field parallel (a) and transverse (b) to the static magnetic field. In the parallel case, there is no excitation at $f = f_{pump}$ and a degenerate magnon-pair can be excited at $f_{pump}/2$ when it coincides with a mode frequency.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

REFERENCES

[1]G. A. Melkov and A. Gurevich, *Magnetization Oscillations and Waves*, en, CRC Press (New York, 1996).
[2]L. Körber et al., *Pattern recognition with a magnon-scattering reservoir*, en, arXiv:2211.02328, Nov. 2022.
[3]A. Melkov and S. V. Sholom, “Parametric excitation of spin waves by a surface magnetostatic wave”, Journal of Experimental and Theoretical Physics **96**, 712–719 (1989).

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Emission of Coherent THz Magnons in an Antiferromagnetic Insulator Triggered by Ultrafast Spin-Phonon Interactions

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Antiferromagnets have a strong potential for future spintronic devices due to their insensitivity to perturbative external magnetic fields, absence of stray fields, and for accessing to frequencies from GHz to the terahertz (THz) regime[1–3]. However, their functionalization in thin films remains a challenging task. In this work [4], we achieve a coherent emission of THz magnons in NiO(001)(10nm)/Pt(2nm) bilayer triggered by 100 fs pulses and using THz time-domain emission spectroscopy (Fig. 1a). The generated THz signal has two main components as shown in Fig. 1b: i) a broadband contribution (up to 3 THz) alongside ii) a narrowband contribution centered at 1.1 THz. The latter can be associated with the THz radiation of high-frequency AFM mode of NiO.

We demonstrate by experiment and modelling that the THz magnon excitation arises from spin-phonon interactions and detect it via THz inverse spin Hall effect. Using ultrafast X-ray diffraction, we show the presence of a strain wave that can effectively trigger an out-of-plane precession of the Néel vector in NiO via dynamical magneto-striction. These results highlight promising perspectives for the development of AFM THz devices.

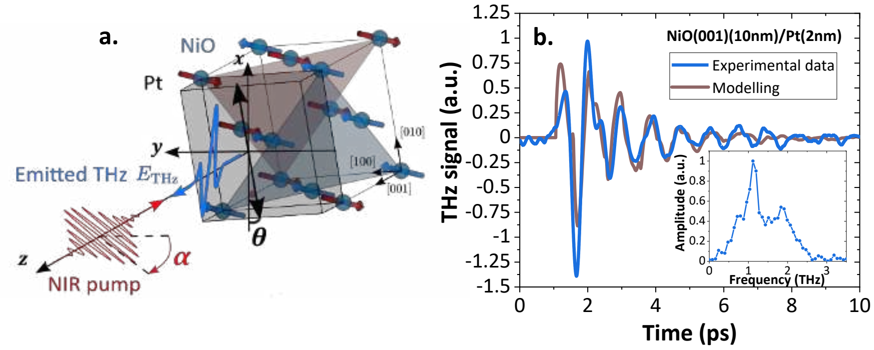

Figure 1: Laser induced coherent and incoherent THz emission from NiO/Pt bilayer. (a) Schematic of the setup. (b) THz emission from a low damping NiO(001)(10nm)/Pt(2nm) bilayer showing 1 ps oscillations (experiment:blue, model: brown).

REFERENCES

[1] R. Cheng and al., Phys. Rev. Lett. **116**, 207603 (2016).
[2] J. Li and al., Nature **578**, 70–74 (2020).
[3] I. Boventer, H. Simensen, A. Anane, et al., Phys. Rev. Lett. **126**, 187201 (2021).
[4] E. Rongione and al., arXiv, in press in Nat. Comm., `10.48550/ARXIV.2205.11965` (2023).

Magnetisation Dynamics of Epitaxial $Co_2MnSi/X/Co_2MnAl$ Heusler Bilayers with Metallic and Non-Metallic Interlayers

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Magnetic materials with low Gilbert damping are indispensable for future spintronic and magnonic applications. Half-metallic Co_2Mn-Heusler compounds are promising candidates for such applications mainly due to their 100% spin polarisation at the Fermi level and the associated ultralow Gilbert damping in the 10^{-4} range [1].

However, the various chemical (dis)order types in Co_2Mn-based Heusler compounds are known to influence the material properties and particularly the Gilbert damping parameter significantly. Domains of different chemical (dis)order can coexist in single films if epitaxial growth conditions are not set properly [2]. As a result, multiple peaks are observed in ferromagnetic resonance (FMR) spectroscopy which can be ascribed to a difference in the exchange coupling in small domains of the various chemical (dis)ordering types and consequently an influence on the magnetisation dynamics in neighbouring domains of a different (dis)ordering types. To investigate these effects in a controlled model environment, we study the coupling of $L2_1$-ordered Co_2MnSi and B2-ordered Co_2MnAl Heusler thin films mediated by metallic and non-metallic interlayers.

For the purpose of this study, $Co_2MnSi/X/Co_2MnAl$ multilayers with X={Mn (t=1 atomic plane), MgO (t=1 nm)} were grown by molecular beam epitaxy and the crystalline quality and chemical ordering were confirmed by transmission electron microscopy techniques as shown in figure 1 (A). To study the resulting magnetisation dynamics, we performed FMR measurements on the thin film samples. These revealed significant differences in the FMR spectra of the sample with the MgO interlayer compared to the sample with the Mn interlayer as shown in figure 1 (B), the results of which we compare with numerical calculations. Equally, magnon dispersion relations measured by Brillouin light scattering (BLS) spectroscopy show similar differences for the two interlayers. We ascribe the observed behaviour to differences in the coupling mediated by the interlayers, the understandig of which is critical for the design of future hybrid devices for magnonic / spintronic applications.

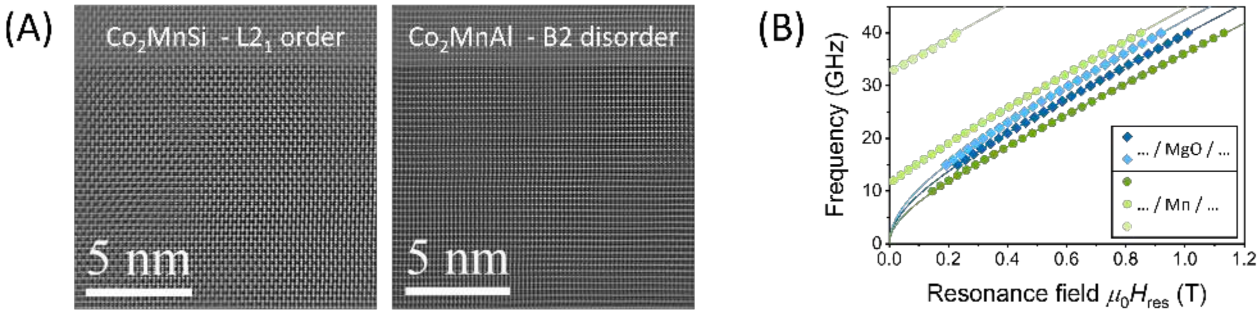

Figure 1: (A) HAADF-STEM micrograph showing the (dis)ordering types in the two Heusler compounds in the study.
(B) In-plane FMR measurements showing different behaviour for the $Co_2MnSi/X/Co_2MnAl$ with interlayers X={Mn, MgO} .

REFERENCES

[1] C. Guillemard, S. Petit-Watelot, L. Pasquier, et al., “Ultralow magnetic damping in $\mathrm{Co_2Mn}$-based heusler compounds: promising materials for spintronics”, Phys. Rev. Appl. **11**, 064009 (2019).

[2] C. Guillemard, S. Petit-Watelot, T. Devolder, et al., “Issues in growing heusler compounds in thin films for spintronic applications”, Journal of Applied Physics **128**, 241102 (2020).

Modelling a 3-Port Network in Cavity Magnonics for Nonreciprocal RF Devices

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Over the last decade, cavity magnonics has attracted a lot of attention. The study of the associated quasiparticle of cavity magnonics, cavity magnon polaritons which refer to strongly coupled magnon-photon system offers new possibilities of sensing and quantum information processing [1, 2] as well as a new interesting platform for disruptive RF applications. In the realm of signal transmission, nonreciprocity allows the enhancement of the communication channels capacities as well as the protection of the transmission quality. Our goal is to build new types of magnon based microwave non-reciprocal device. For this purpose, we use the possibility to tune and combine the regimes of dissipative and coherent coupling control leading to PT symmetry breaking [3] in cavity magnonics devices. We develop a non-reciprocal device consisting of a three ports 3D re-entrant cavity coupled with a ferromagnetic sample (see sketch in Figure. 1 (a)). The cavity is equipped with two cavity ports and an additional third port used as a direct drive for the magnons [4].

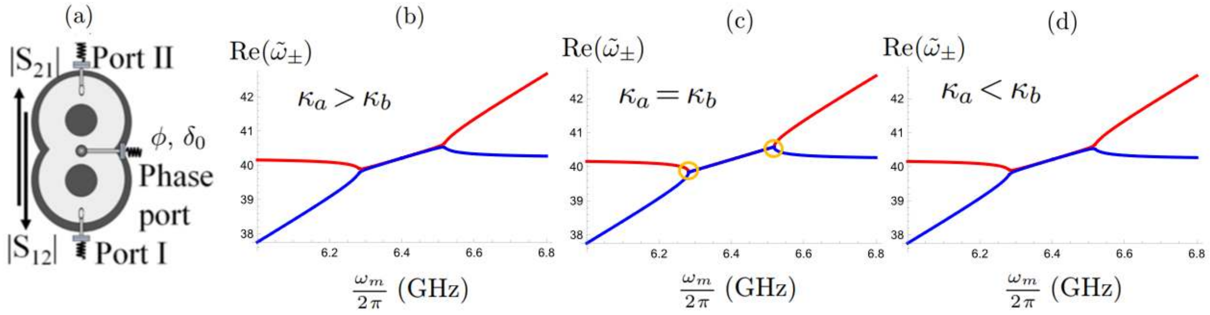

Figure 1: (a) sketch of the 3-port re-entrant cavity setup. (b), (c) and (d) calculated real part of the eigenfrequency of the system showing level attraction and exceptional points (encircled in orange in (c)) for matched damping condition where κ_a and κ_b stand for the damping ratios of the cavity and the magnon respectively.

By adjusting the amplitude ratio δ_0 and phase shift ϕ between the cavity input port and the magnon port, the coupling strength can be either purely real, complex or purely imaginary, allowing us to tune the regime of the system from coherent to dissipative at will (see Figure. 1. (b) and (d)). As displayed in Figure. 1 (c), our modelled system exhibits exceptional points for matched damping condition [3] which is a signature of PT symmetry breaking. Following the approach described in [5] we then expect both theoretically and experimentally to achieve controlled and compact non-reciprocal behaviour by controlling the two tuning parameters δ_0 and ϕ in our system.

REFERENCES

[1] D. Lachance-Quirion, Y. Tabuchi, A. Gloppe, K. Usami, and Y. Nakamura, “Hybrid quantum systems based on magnonics”, Applied Physics Express **12**, 070101 (2019).
[2] B. Z. Rameshti, S. V. Kusminskiy, J. A. Haigh, et al., “Cavity magnonics”, Physics Reports **979**, 1–61 (2022).
[3] Y.-P. Wang, J. Rao, Y. Yang, et al., “Nonreciprocity and unidirectional invisibility in cavity magnonics”, Physical Review Letters **123**, `10.1103/physrevlett.123.127202` (2019).
[4] I. Boventer, C. Dörflinger, T. Wolz, et al., “Control of the coupling strength and linewidth of a cavity magnon-polariton”, Physical Review Research **2**, `10.1103/physrevresearch.2.013154` (2020).
[5] L. Zhong, C. Zhang, and B. M. Yao, “Controlling the dynamics of cavity magnon polariton via microwave polarization”, AIP Advances **12**, 085323 (2022).

Magneto-Optical Investigation of Magnetoacoustic Waves in Yttrium Iron Garnet / Zinc Oxide Heterostructures

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Surface Acoustic Waves (SAWs) that operate in the Gigahertz regime with wavelengths on the micrometer scale enable the miniaturization of telecommunication microwave devices. In recent years, the coupling of SAWs with spin waves (SWs) in ferromagnetic metals has proven to be a viable option for the realization of applications like acoustic diodes, as the interaction is intrinsically nonreciprocal [1].

However, the coupling of SAWs with SWs in ferrimagnetic insulators is much less explored. We investigated SAWs excited by interdigital transducers made of Ti/Au, which were deposited on a YIG/GGG thin film bilayer and covered by a piezoelectric ZnO layer. The ferrimagnetic YIG layer serves as a source for SWs to which the SAWs can couple. We used micro-focused Brillouin light scattering (BLS) spectroscopy to identify the SAW characteristics in the YIG-based heterostructure. From our time-resolved BLS data we extract the SAW group velocity, shown in Fig.1 a), and reconstruct the non-linear SAW dispersion in the ZnO/YIG/GGG heterostructure. The dispersion is in agreement with expectations from a Rayleigh mode in such a multilayer, as demonstrated by our analytical model calculations. We furthermore study the magnetic-field dependent interaction of the SAWs with SWs in YIG. As shown in Fig.1 b), we observe a linewidth of about 1 mT in agreement with magnetoacoustic excitation of low-damping magnons in YIG.

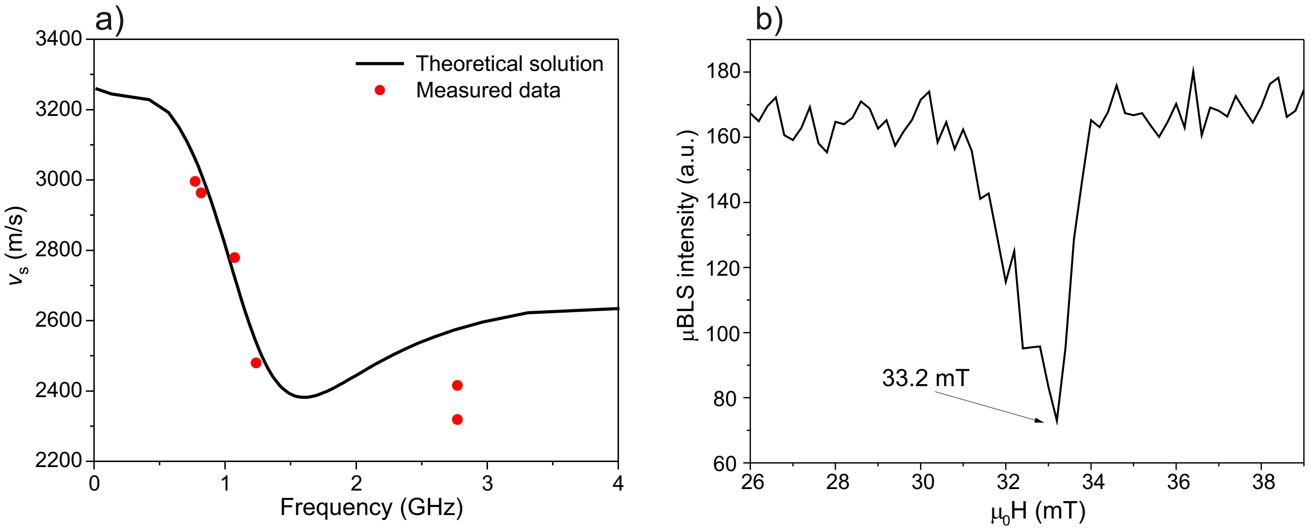

Figure 1: a) SAW group velocity obtained from BLS measurements (red dots) and theoretically calculated for a ZnO/YIG/GGG multilayer (black line). b) Magnetic field sweep with fixed SAW excitation frequency of 2.772 GHz.

REFERENCES

[1] M. Küß, M. Hassan, Y. Kunz, et al., “Nonreciprocal magnetoacoustic waves in synthetic antiferromagnets with Dzyaloshinskii-Moriya interaction”, Phys. Rev. B **107**, 024424 (2023).

Poster 2. PB37
Wednesday
16:30

Leveraging Spin-Torque Oscillator's Phase Dynamics for Unconventional Computing

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As computing tasks become increasingly complex and energy-intensive, there is a growing need for hardware-level innovations that can address crucial issues such as energy consumption, speed, compactness, and integrability. In this context, spin-torque oscillators (STOs) have been explored recently to develop innovative cognitive computing schemes, demonstrating vowel recognition via the synchronization of an array of STOs [1]. STOs thus provide an important avenue to develop novel computing approaches, making detailed analyses of their amplitude, frequency, and phase dynamics essential, particularly for coupled STO arrays. In this contribution, the stochastic phase dynamics is studied for vortex-based STOs, for which a magnetic vortex is stabilized in the free layer and whose dynamics is excited by spin-transfer torque using an applied electrical DC current. While the free-running STO suffers from large phase fluctuations, it takes discrete values when the STO is synchronized to an external RF signal [2, 3]. Nevertheless, thermal fluctuations induce stochastic jumps between discrete values at room temperature, as demonstrated in Fig. 1. Results will be presented to illustrate how these stochastic phase jumps can be controlled by the operating point (DC current, applied magnetic field), the ratio and mismatch between the STO and external RF source frequencies, the RF excitation type (via current or field), and an additional weak RF signal provided by a signal generator or the coupling to one or more STOs. We illustrate how this phase dynamics can be exploited to develop an oscillator-based Ising machine [4] and Hopfied networks [5].

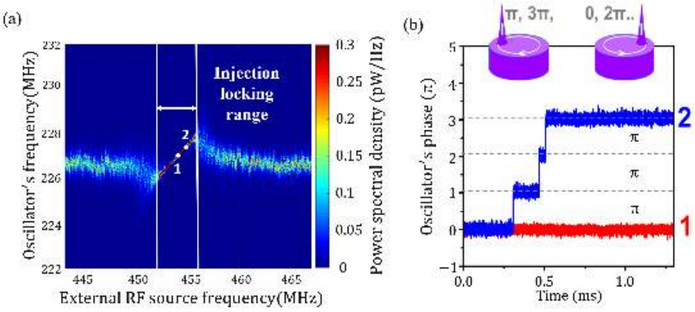

Figure 1: (a) Power spectral density color map of a vortex STO under second harmonic injection locking. (b) The STO phase for two values (red and blue curves) of the locking signal frequency extracted by applying the Hilbert transform on the time trace of the STO's voltage.

This research was funded in part by l'Agence Nationale de la Recherche (ANR), projects SpinIM ANR-22-CE24-0004 and StochNET ANR-21-CE94-0002 as well as by the CEA projects PTC-MINOS and Carnot AE SIGMA.

REFERENCES

[1]M. Romera, P. Talatchian, and et al, "Vowel recognition with four coupled spin-torque nano-oscillators", Nature **563**, 230–234 (2018).
[2]R. Lebrun, A. Jenkins, and et al, "Understanding of phase noise squeezing under fractional synchronization of a nonlinear spin transfer vortex oscillator", Physical Review Letters **115**, 017201 (2015).
[3]A. Litvinenko and et al, "Analog and digital phase modulation and signal transmission with spin-torque nano-oscillators", Physical Review Applied **16**, 024048 (2021).
[4]T. Wang and J. Roychowdhury, "OIM: oscillator-based ising machines for solving combinatorial optimisation problems", Unconventional Computation and Natural Computation, 232–256 (2019).
[5]N. Prasad, P. Mukim, A. Madhavan, and M. D. Stiles, "Associative memories using complex-valued hopfield networks based on spin-torque oscillator arrays", Neuromorphic Computing and Engineering **2**, 034003 (2022).

Poster 2. PB38
Wednesday
16:30

Nonlinear Interactions between Spin-Wave Modes in YIG Microdisks

Amel Kolli[1,*], Gabriel Soares[1], Rafael L. Seeger[1], Igor Ngouagnia[1], Titiksha Srivastava[1,2], Maryam Massouras[2], Joo-Von Kim[2], Hugo Merbouche[3], Sergej Demokritov[3], Vladislav Demidov[3], Nathan Beaulieu[4], Jamal Ben Youssef[4], Manuel Muñoz[5], Salvatore Perna[6], Massimiliano D'Aquino[6], Claudio Serpico[6], Abdelmadjid Anane[7], Grégoire De Loubens[1]
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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 train 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, with enhanced or suppressed peaks, and the appearance of additional peaks in the spectrum (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 Programme of the European Commission under FET-Open grant agreement no. 899646 (k-NET).

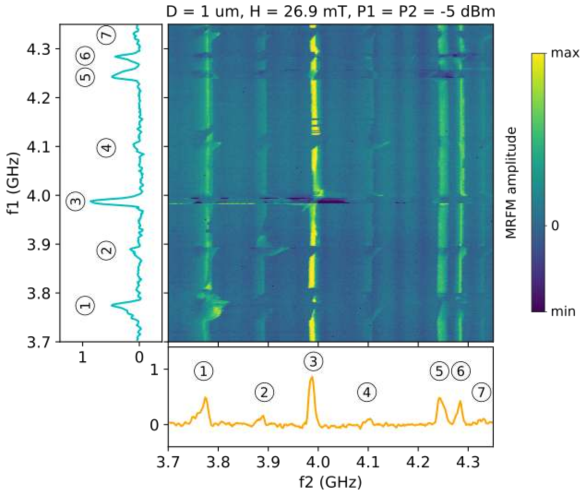

Figure 1: Two-tone parametric spectroscopy in a 1 μm diameter YIG disk.

REFERENCES

[1] Á. Papp, W. Porod, and G. Csaba, "Nanoscale neural network using non-linear spin-wave interference", Nature Commun. **12**, 1–8 (2021).
[2] L. Körber, et al., "Pattern recognition with a magnon-scattering reservoir", `10.48550/arXiv.2211.02328`.
[3] T. Srivastava, et al., "Complete identification of spin-wave eigenmodes excited by parametric pumping in YIG microdisks", `10.48550/arXiv.2301.13468`.
[4] S. Perna et al., "Computational micromagnetics based on normal modes: bridging the gap between macrospin and full spatial discretization", J. Magn. Magn. Mater. **546**, 168683 (2022).

Poster 2. PB39
Wednesday
16:30

Spin-Wave Quantization and Nonlinear Scattering in Non-Reciprocal Materials

Christopher Heins[1,2,*], **Katrin Schultheiss**[1], **Olga Gladii** [1], **Vadym Iurchuk**[1], **Jürgen Fassbender**[1,2], **Jürgen Lindner**[1], **Helmut Schultheiss**[1,2]
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Spin waves in magnetic thin films exhibit a strong anisotropy, with their amplitude and frequency depending on the propagation direction relative to the external magnetic field. This anisotropy is reflected in the difference in amplitude across the film thickness for spin waves in the Damon-Eshbach geometry. The asymmetric mode profile can be utilized to generate a large nonreciprocity of the wave vector at the same frequency by introducing a magnetisation gradient across the film depth [1]. The nonreciprocity has potential application in magnonic logic devices, such as spin wave diodes [2], and offers a pathway to gain a better understanding of magnon scattering processes in lateral confined structures.

Here, we show results on varying degrees of nonreciprocity in magnetic bilayers, which are composed of two ferromagnets with different saturation magnetisation and are investigated by Brillouin light scattering spectroscopy (BLS). As shown in Figure 1, we observe a strong nonreciprocity in the thermal magnon spectra, resulting in a negative group velocity in the thick bilayer system. Furthermore, we outline how we utilize such bilayer systems to gain a better understanding of magnon scattering processes. In particular, we tackle the separation of different contributions from spatial and temporal modulation to the stimulation of four-magnon scattering, which can be used to generate spin wave frequency combs [3].

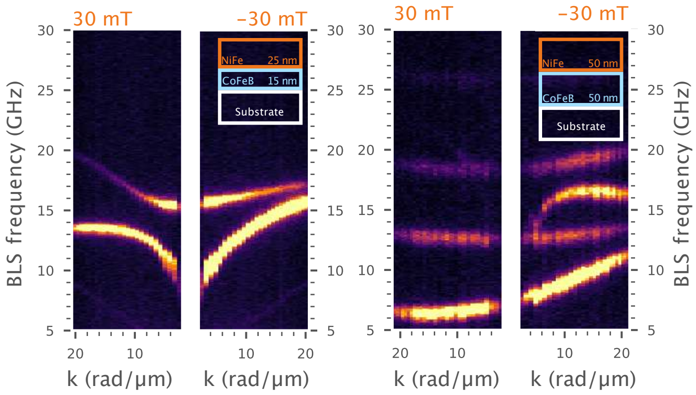

Figure 1: Spin-wave dispersion relation of CoFeB/NiFe bilayers with different thickness, measured using conventional BLS for two directions of the external magnetic field in the Damon-Eshbach geometry.

REFERENCES

[1] R. Gallardo, P. Alvarado-Seguel, T. Schneider, et al., “Spin-wave non-reciprocity in magnetization-graded ferromagnetic films”, New Journal of Physics **21**, 033026 (2019).

[2] M. Grassi, M. Geilen, D. Louis, et al., “Slow-wave-based nanomagnonic diode”, Physical Review Applied **14**, 024047 (2020).

[3] T. Hula, K. Schultheiss, F. J. T. Goncalves, et al., “Spin-wave frequency combs”, Applied Physics Letters **121**, 112404 (2022).

A Non-Volatile Binary Synapse Based on a Vortex Nano-Oscillator

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In recent years, spin torque nano-oscillators (STNOs) have been intensively studied as spintronic devices for use in artificial neural networks (ANNs) [1]. Non-trivial tasks such as vowel recognition were achieved in a computing system, where four STNOs represent a chain of four artificial neurons [2]. More recently, STNOs have also been proposed to work as synapses in ANNs where, based on the spin diode effect [3], the synaptic weight depends on the frequency difference between the input RF signal and the resonator [4].

In this work, a new mechanism to combine a non-volatile behaviour with the spin diode detection of a vortex-based spin torque nano-oscillator is presented [5]. Experimentally, it is observed that the spin diode response (i.e. synaptic weight) of the oscillator depends on the vortex chirality. Consequently, as shown in Fig. 1, fixing the frequency of the incoming signal and switching the vortex chirality results in a different rectified voltage (V^+ and V^-) and, consequently, different synaptic weights (slopes W^+ and W^-). The chirality is stable at remanence, leading to a non-volatile control of the output voltage for a given input frequency. Micromagnetic simulations corroborate the experimental results and show the main contribution of the Oersted field created by the input RF current density in defining two distinct spin diode detections for different chiralities. This work opens new perspectives for the integration of spintronic devices in neuromorphic hardware.

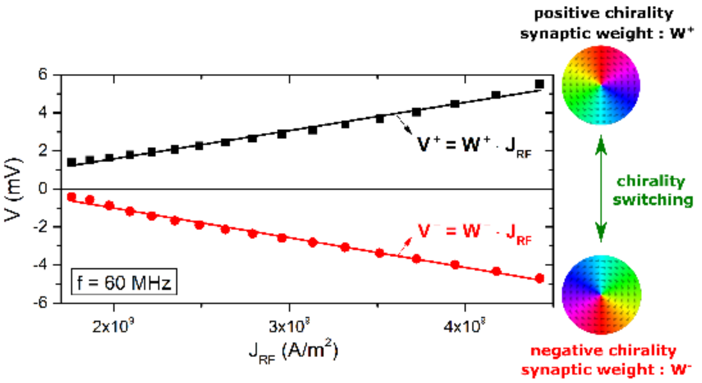

Figure 1: Rectified voltage measured at a fixed frequency of 60 MHz and presented as a function of the input RF current density. A linear fit is also calculated for each set of experimental data. Different chiralities lead to different slopes, corresponding to two distinct synaptic weights, W^+ and W^-.

REFERENCES

[1] J. Grollier, D. Querlioz, K. Y. Camsari, et al., “Neuromorphic spintronics”, Nature Electronics **3**, 360–370 (2020).
[2] M. Romera, P. Talatchian, S. Tsunegi, et al., “Vowel recognition with four coupled spin-torque nano-oscillators”, Nature **563**, 230–234 (2018).
[3] A. A. Tulapurkar, Y. Suzuki, A. Fukushima, et al., “Spin-torque diode effect in magnetic tunnel junctions”, Nature **438**, 339–342 (2005).
[4] N. Leroux, A. Mizrahi, D. Marković, et al., “Hardware realization of the multiply and accumulate operation on radio-frequency signals with magnetic tunnel junctions”, Neuromorphic Computing and Engineering **1**, 011001 (2021).
[5] L. Martins, A. S. Jenkins, L. S. E. Alvarez, et al., “Non-volatile artificial synapse based on a vortex nano-oscillator”, Scientific Reports **11**, 16094 (2021).

A Numerical Study of Spin Torque Nano-Oscillators Based Ising Machines

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Spin torque nano-oscillators (STNO) are nanoscale magnetic tunnel junction devices that generate microwave output voltage signals upon injection of a DC current. Coupled arrays of such STNOs and/or injection locking of STNOs to an external RF signal, can be harnessed to develop novel hardware approaches for unconventional computing [1]. One particular approach is the Oscillator based Ising Machine (OIM) [2]. In this approach, the binary phase states of second-harmonic-injection-locked oscillators are exploited to represent the binary spins of an Ising Hamiltonian. The inherent convergence of the coupled Ising-spin configuration towards its global energy minimum is used as an algorithm to determine the solution of a given combinatorial optimization problem. This hardware implementation of OIM is more efficient in terms of time and energy than conventional solutions. Here we address in a numerical study the implementation of an OIM using STNOs that brings the advantage of a small footprint and operation at room temperature [3]. The system considered is an in-plane magnetized STNO, see Fig.1. To extract the dynamic properties, we resort to solving numerically the Landau-Lifshitz-Gilbert-Slonczewski equation in the presence of thermal fluctuations, in combination with the non-linear auto-oscillator model [4]. When second harmonic injection locked to an external microwave signal, the STNO phase is binarized with respect to the phase of the source, taking values of 0 and π. Due to thermal fluctuations, stochastic transitions occur between these two states. This stochastic phase dynamics, the correlation of the phase states under coupling and the corresponding phase state probabilities are investigated for a single STNO and for N=2,3.. electrically weakly-coupled STNOs (see Fig. 1). This is done as a function of the operating point, the temperature, the strength and sign of the coupling between the STNOs as well as the frequency mismatch to the external locking signal. The results provide the route for the experimental realization of an STNO-based IM and more specifically, how the solution state can be reached and/or influenced by the different parameters.

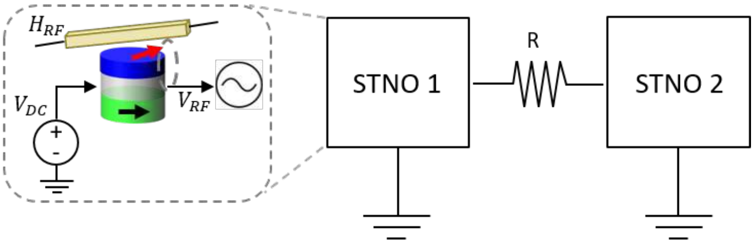

Figure 1: Schematics showing the STNO operation and the electrical coupling of two STNOs via a resistance R. H_{RF} is the RF field that injection locks the STNOs and V_{DC} is the DC voltage applied to the STNO device.

This research was funded in part by l'Agence Nationale de la Recherche (ANR), project SpinIM ANR-22-CE24-0004 and the CEA projects PTC-MINOS and Carnot AE SIGMA. MIG acknowledges financial support from the French Space Agency (CNES) and the European Union's Horizon 2020 research and innovation programme under grant agreement No 800945 — NUMERICS — H2020-MSCA-COFUND-2017.

REFERENCES

[1] J. Grollier, D. Querlioz, K. Y. Camsari, et al., "Neuromorphic spintronics", Nature Electronics **3**, 360–370 (2020).

[2] T. Wang and J. Roychowdhury, "OIM: oscillator-based ising machines for solving combinatorial optimisation problems", Unconventional Computation and Natural Computation, 232–256 (2019).

[3] B. C. McGoldrick, J. Z. Sun, and L. Liu, "Ising machine based on electrically coupled spin hall nano-oscillators", Physical Review Applied **17**, 014006 (2022).

[4] A. Slavin and V. Tiberkevich, "Nonlinear auto-oscillator theory of microwave generation by spin-polarized current", IEEE Transactions on Magnetics **45**, 1875–1918 (2009).

The Influence of the Field Direction on the Symmetries of Angle Dependent FMR Studies of YIG Films

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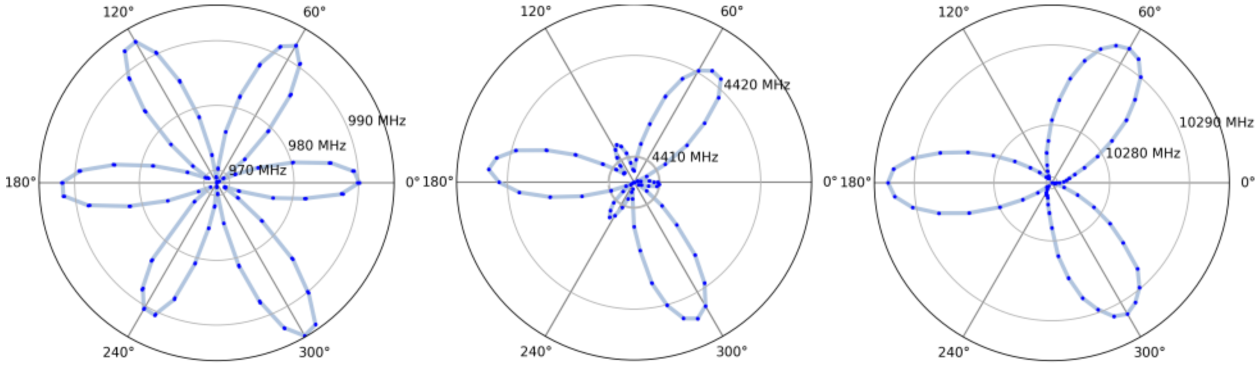
Yttrium iron garnet (YIG) is a commonly used material in magnonics due to its low spin-wave damping. Previous ferromagnetic resonance spectroscopy (FMR) studies on (111) grown YIG thin films showed a deviation from the expected sixfold symmetry of the FMR frequencies as a function of the external field angle [1]. For more in-depth investigations, we developed a fully automized setup for angle dependent vector network-analyzer-FMR studies of YIG films. We apply this setup to investigate a (111) grown, d=55nm thick LPE YIG film. For a perfect alignment of the external field along the in-plane direction, our results confirm the expected sixfold symmetry even for high external field values. However, if we break the rotational symmetry by tilting the film and coplanar waveguide by a small angle relative to the external field, this leads to a change in the measured symmetry of the FMR frequencies from a sixfold symmetry to a threefold symmetry. Further, we apply the setup to quantify the magnitude of the present anisotropy field and compare it to previous studies [2]. This study contributes to the understanding of YIG thin films and the impact of the magnetocrystalline anisotropy for magnonic applications.



a) low external field
B ≈ 7.4 mT

b) intermediate external field
B ≈ 87.8 mT

c) high external field
B ≈ 278.2 mT

Figure 1: FMR resonance frequency as a function of the rotation angle around the normal axis of the sample for different applied field values. a) For low applied field values, a sixfold anisotropy in the resonance frequency is found. With increasing field values, this transitions into a threefold symmetry, as shown in b) and c).

REFERENCES

[1] B. Heinz, “Herstellung und Untersuchung der Magnetisierungsdynamik in einzelnen Yttrium-Eisen-Granat Mikrostrukturen”, Diploma thesis (Nov. 2016), pp. 70–73.

[2] L. Seongjae, S. Grudichak, J. Sklenar, and C. C. Tsai, “Ferromagnetic resonance of a yig film in the low frequency regime”, Journal of Applied Physics **120**, 033905 (2015).

Optimizing Acoustic Wave - Spin Wave Resonant Coupling in the Magnetoelastic Systems

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Magnonics, alongside spintronics, opens the possibility to design devices even smaller, faster, and more energetically efficient than electronic ones. Magnetostrictive systems are used for switching of the magnetic configuration, spin-wave generation, spin-wave steering, appearance of nonreciprocity for acoustic waves and acoustic pumping of spin currents. Thus, magnetoelastic coupling is promising candidate for the realization of logic gates, magnetic recording, or signal processing devices based on spin waves.

We investigate numerically the dynamics of magnetoelastic excitations in a one-dimensional magnonic-phononic crystal consisting of alternating layers of permalloy and cobalt [1]. The studied structure is optimized for hybridization of specific spin-wave and acoustic dispersion branches in the entire Brillouin zone in a broad frequency range. We show that this type of periodic structure can be used for efficient generation of high-frequency spin waves.

Besides phase and frequency matching, there are another key challenges for the efficient conversion between surface acoustic waves and spin waves. In particular, one should obtain a proper overlapping of the acoustic wave and spin wave amplitudes. We obtained the proper overlapping of spin wave and acoustic wave amplitude for the 50 nm CoFeB/Au multilayer on Si substrate [2]. Here, the hybridization of Love wave with backward volume magnetostatic wave have been shown experimentally by Brillouin Light Scattering. Interestingly, the well-known fingerprint of the magnetoelastic resonance – the fourfold angular symmetry of the coupling – is suppressed for the Rayleigh wave because of the nodal line wchich fits within this layer. Consequently, the effective magnetic fields generated by the Rayleigh wave are opposite at the top and the bottom of the CoFeB/Au multilayer, thus suppressing the interaction between spin wave and acoustic wave.

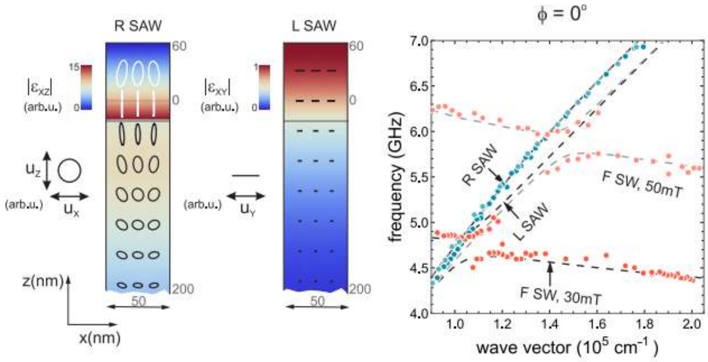

Figure 1: The profile of Rayleigh and Love waves obtained in simulations and the spin wave - Love wave anticrossing measured by Brillouin Light Spectroscopy.

This work was conducted under grant no. 2018/28/C/ST3/00052 from National Science Centre in Poland.

REFERENCES

[1] P. Graczyk, J. Kłos, and M. Krawczyk, "Broadband magnetoelastic coupling in magnonic-phononic crystals for high-frequency nanoscale spin-wave generation", Phys. Rev. B **95**, 104425 (2017).
[2] Nandan K. P. Babu et. al, "The Interaction between Surface Acoustic Waves and Spin Waves: The Role of Anisotropy and Spatial Profiles of the Modes — Nano Letters", Nano Letters **21**, 946–951 (2021).

Poster 2. PB44
Wednesday
16:30

Brillouin Light Scattering Characterization of Voltage-Controlled Magnonic Crystals and Waveguides via Magnetoelectric Coupling

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Magnonics is receiving considerable attention as it promises miniaturized low-power-consuming information technologies thanks to the spin wave precession with only momentum transmission without moving charges and the nanoscale wavelength of spin waves at giga-hertz frequencies. Magnetoelectric coupling offers the possibility to control the spin degree of freedom via charge degree freedom in oxide interfaces for novel all-magnonic devices[1, 2]. Here, we realize a reprogrammable magnonic crystal and magnonic waveguides by using ferromagnetsic-multiferroic heterostructures where the latter is capable of implementing voltage-control on the spin waves in the ferromagnetic layer[3]. The magnonic waveguides constructed in a thin-film multiferroic bismuth ferrite $BiFeO_3$ (BFO)- lanthanum strontium manganite $La_{2/3}Sr_{1/3}MnO_3$ (LSMO) heterostructure by imprinting an electrical polarization in the multiferroic BFO layer which modulates the effective magnetic field seen by the magnons in the LSMO layer (Fig. 1). We characterize the spin waves spectra using the Brillouin light scattering technique. The imprinted ferroelectric domains can be reconfigured repeatedly and are robust and long-lived. Our results open a new path for the function of magnonics-based logic devices by CMOS compatible voltage control. In general, by bridging between the scientific fields of functional oxides and magnonics, we propose new perspectives for the development of beyond CMOS based technologies.

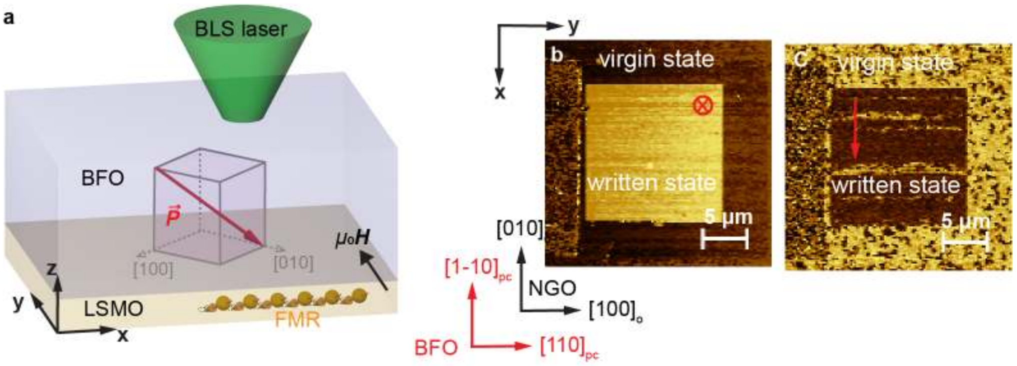

Figure 1: Fig. 1. a. Schematic diagram of the BLS measurement configuration in BFO/LSMO bilayer after PFM writing. Here red arrow indicate the polarization axis of the ferroelectric domain in BFO in the PFM written area. BLS green laser is focused on the top surface of the bilayer film. The laser diameter at the focus spot is about 400 nm. Yellow arrows indicate the motion of the FMR mode in LSMO. b. and c. Out-of-plane and in-plane components of the PFM phase imaging of the ferroelectric domain implemented by voltage-control in BFO layer.

REFERENCES

[1] C.-G. Duan, J. P. Velev, R. F. Sabirianov, et al., “Tailoring magnetic anisotropy at the ferromagnetic/ferroelectric interface”, Applied Physics Letters **92**, 122905 (2008).

[2] Q. Wang, A. V. Chumak, L. Jin, et al., “Voltage-controlled nanoscale reconfigurable magnonic crystal”, Physical Review B **95**, 134433 (2017).

[3] H. Merbouche, I. Boventer, V. Haspot, et al., “Voltage-controlled reconfigurable magnonic crystal at the sub-micrometer scale”, ACS Nano **15**, 9775–9781 (2021).

Magnetic Nanopatterning of YIG Films via Direct Laser Writing for Magnonics

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Among the systems which are currently under study in magnonics, Yttrium Iron Garnet (YIG) certainly plays a major role, mainly because of its peculiar optical and magnetic properties, such as the lowest Gilbert damping ever measured. That allows spin-waves (SWs) to propagate in YIG crystals up to few millimetres preserving their coherence, which is essential for unconventional computing in interference-based devices [1]. Notwithstanding, an actual exploitation of YIG-based technology is still prevented by the failure of standard lithographic processes in patterning YIG films, primarily due to the uncontrolled deterioration of its unrivalled magnetic properties.

In this work, we make use of direct laser writing (DLW) to achieve effective grayscale patterning of 1 μm-thick YIG crystals via local tunable modifications, according to a new paradigm in nanofabrication called phase nanoengineering [2]. By varying the exposure parameters, patterns having different structural, optical and magnetic properties have been obtained. Figure 1a shows an optical image of squares written by DLW with increasing laser power. The change in the static magnetic properties of such patterns has been studied by means of Kerr and Magnetic Force Microscopy (Figure 1b), revealing a tunable change in the magnetic configuration at remancence, which is compatible with a variation of the effective field inside the patterned areas. Raman spectroscopy has then been employed to correlate the change in the magnetic properties with a modification in the composition and structure of the film. The graph in Figure 1c presents the spectra recorded on the corresponding squares in Figure 1a; the degree of structural modification increases consistently as the laser power increases as shown by the emergence of new peaks at 49 mW irradiation. Finally, micro-Brillouin Light Scattering (μ-BLS) measurements on arrays of patterned nanodots have revealed a tunable change in the spatial distribution of spin waves.

These results prove how phase nanoengineering holds promise for the design and implementation of novel magnonic devices based on the crafting of the magnetic and structural properties of YIG films.

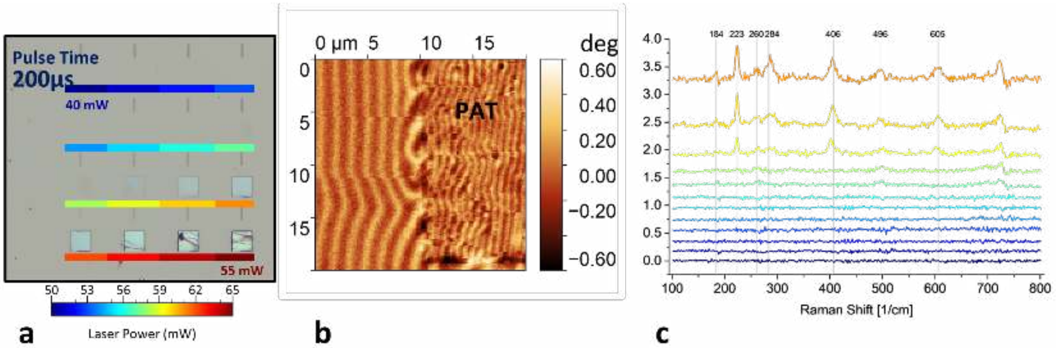

Figure 1: Phase nanoengineering of YIG films. a) Optical image of $30 \times 30 \mu m^2$ squares obtained via DLW with different patterning parameters. b) MFM image of a patterned area showing narrower stripe domains with respect to the pristine sample. c) Raman spectra recorded inside the squares highlight the tunable chemical-structural changes following DLW. The color code is the same of panel a.

REFERENCES

[1] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, “Advances in coherent magnonics”, Nature Reviews Materials **6**, 1114–1135 (2021).
[2] V. L. et al., in preparation.

Poster 2. PB46
Wednesday
16:30

Direct Observation of Propagating Spin Waves with Large Non-Reciprocity

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Non-reciprocal wave propagation occurs in systems with broken time-reversal symmetry, and is essential to the functionality of devices, such as circulators, in microwave, photonic and acoustic applications. In magnetic systems, spin waves were found to yield only moderate dispersion non-reciprocities so far, e.g. [1–3].

Here, we demonstrate the direct observation of propagating coherent spin waves with large non-reciprocity in a patterned element of an antiparallel ferromagnetic bilayer stack [4, 5]. We use time-resolved scanning transmission x-ray microscopy (TR-STXM) to image the collective spin-wave dynamics at wavelengths (λ) ranging from 5 μm down to 100 nm, corresponding to frequencies between 500 MHz and 5 GHz (see Figure 1). The non-reciprocity factor of these counter-propagating waves is found to be larger than 10 with respect to both wavelengths and group velocities. Our experimental results are supported by numeric calculations solving an analytic theory that is also predicting caustic spin-wave focusing effects to emerge in the system.

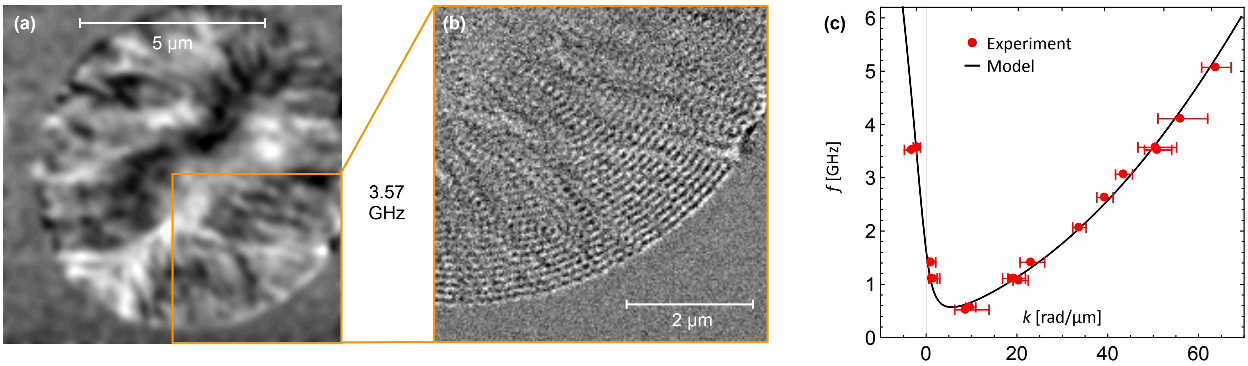

Figure 1: Non-reciprocal spin-wave propagation, adapted from [5]. (a,b) TR-STXM micrographs (snapshots) showing the normalized dynamic perpendicular magnetic deflection at an excitation frequency of 3.57 GHz. (a) Long-λ branch with outward phase propagation (blurred to mask short-λ waves), (b) zoom-in of short-λ branch with inward propagating phase. (c) Non-reciprocal spin-wave dispersion relation, experimental data points (red dots) and modeled curve (black line).

REFERENCES

[1] P. Grünberg, “Magnetostatic spin-wave modes of a heterogeneous ferromagnetic double layer”, Journal of Applied Physics **52**, 6824–6829 (1981).
[2] K. Mika and P. Grünberg, “Dipolar spin-wave modes of a ferromagnetic multilayer with alternating directions of magnetization”, Physical Review B **31**, 4465–4471 (1985).
[3] R. Gallardo et al., “Reconfigurable spin-wave nonreciprocity induced by dipolar interaction in a coupled ferromagnetic bilayer”, Physical Review Applied **12** (2019).
[4] S. Wintz, V. Tiberkevich, M. Weigand, et al., “Magnetic vortex cores as tunable spin-wave emitters”, Nature Nanotechnology **11**, 948–953 (2016).
[5] R. A. Gallardo, M. Weigand, K. Schultheiss, et al., “Coherent magnons with giant non-reciprocity”, (under review) (2023).

Poster 2. PB47
Wednesday
16:30

Multi-Port Sample Carrier System for All-Electrical Characterisation of Thin-Film Magnonic Devices

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Implementing a sample carrier system to characterize spin waves on thin films put demands on signal integrity, wide bandwidth, optimized interface connections and multiple layouts per sample. We will present detailed results from our design of an improved device carrier for wideband electrical interfacing ($<$17 GHz) of mixed signal magnonic devices. The device is designed for all electrical measurements of mixed surface acoustic waves and spin waves.

The focus will be the verification of a compact, 16-port chip carrier and enclosure compatible with material requirements for measurement setups that include an applied magnetic field and variable temperature. The design premise accommodates commercially available direct cable interface contacts and a mechanical enclosure for both shielding and thermal control. The contacts are connected to a reusable chip carrier printed-circuit-board (PCB), designed to provide a controlled, repeatable sample chip environment. For signal integrity and broad band impedance, CST software simulations are used and compared to control measurements. The chip carrier PCB is designed for commercial reproduction. The sample chips are produced in-house, utilizing a thin film growth and lithography techniques.

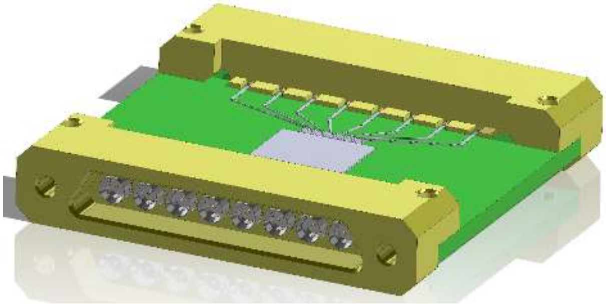

Figure 1: Sample (gray) connected to the PCB (green) via ribbon bonding, and then connected to two compact 8-port Mini-D RF Edge Launch Connectors (gold)

From this design we will present simulations and experimental results. We will address effects of different bonding methods (wire/ribbon) and circuit layout designs of the chip carrier and the sample lithography. We will exemplify the design through presenting results from studies of all-electrical measurements of coupling between spin-waves generated by wide-band antennas [1] and surface acoustic waves on LiNbO$_0$ [2]. We will present results on signal integrity, correlation with simulation, as well as preliminary results of intermixing of signals. Results will be presented from thin film magnetic materials in surface acoustic wave substrates. Prototypical materials such as Fe and Ni films will provide baseline measurements, leading toward measurement of La$_{0.7}$Sr$_{0.3}$MnO$_3$/SrTiO$_3$ (LSMO) thin films deposited on the surface acoustic wave material LiNbO$_3$.

REFERENCES

[1] S. Singh, N. K. Gupta, S. Hait, et al., “Propagation properties of spin wave in Co$_2$FeAl Heusler alloy ultrathin films”, Materials Research Express **8**, 086101 (2021).

[2] B. Casals, N. Statuto, M. Foerster, et al., “Generation and imaging of magnetoacoustic waves over millimeter distances”, Phys. Rev. Lett. **124**, 137202 (2020).

Poster 2. PB48
Wednesday
16:30

Acoustic Driven Ferromagnetic Resonance in Iron Thin Film: Impact of Spin Wave Dispersion

Louis Christienne[1,*], **Pauline Rovillain**[1], **Jean-Yves Duquesne**[1], **Mahmoud Eddrief**[1], **Maria Gloria Pini**[2], **Angelo Rettori**[3,4], **Silvia Tacchi**[5], **Massimiliano Marangolo**[1]
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Surface Acoustic Waves (SAW) have been proposed to dynamically control Spin Waves (SW) propagation and even to generate SWs, in order to implement reconfigurable and energy efficient magnonic devices. Indeed, SAW technology is mature and widely used in today's sensors, filters, and microwave circuitry, notwithstanding the lack of tunability of SAW transducers. For this reason a multitude of them are currently integrated in modern devices (e.g. mobile phones).

Recently, the so-called SAW induced Ferromagnetic Resonance (SAW-FMR) has been observed by Weiler et al. [1], Thevenard et al. [2], and Duquesne et al. [3] in Ni, GaMnAs, and Fe thin film respectively, by exciting SAWs in the GHz and sub-GHz regime in piezoelectric media. The SAW-FMR interaction is often described by taking into account only the uniform FMR mode. However this approximation is rather crude, and it misses out the wealth of modes that can be excited in a ferromagnetic (FM) material.

Here, we study SAW propagation in a Fe thin film epitaxially grown on a piezoelectric GaAs substrate. The SAW velocity and absorption show a dependance on the external magnetic field in amplitude and direction. The observed angle dependence can be described only by taking into account the spin wave dispersion. In our frequency range (below GHz) the resonant magnetoelastic coupling is effective only in the backward configuration. To interpret this dependence on the magnetic field angle, a phenomenological approach to the relative change in SAW velocity is implemented with the calculated spin wave dispersion curves.

Our study permits to envisage SAW-based magnonic devices where a single IDT provides the energy needed to activate magnetization dynamucs and SW propagation in hundreds if not thousands of magnonic waveguides, in a Joule heat free manner.

REFERENCES

[1]M. Weiler, L. Dreher, C. Heeg, et al., "Elastically driven ferromagnetic resonance in nickel thin films", Physical Review Letters **106**, `10.1103/physrevlett.106.117601` (2011).
[2]P. Kuszewski, I. S. Camara, N. Biarrotte, et al., "Resonant magneto-acoustic switching: influence of rayleigh wave frequency and wavevector", Journal of Physics: Condensed Matter **30**, 244003 (2018).
[3]J.-Y. Duquesne, P. Rovillain, C. Hepburn, et al., "Surface-acoustic-wave induced ferromagnetic resonance in fe thin films and magnetic field sensing", Physical Review Applied **12**, `10.1103/physrevapplied.12.024042` (2019).

Coupled Parametric Excitations in Neighboring Nanomagnets

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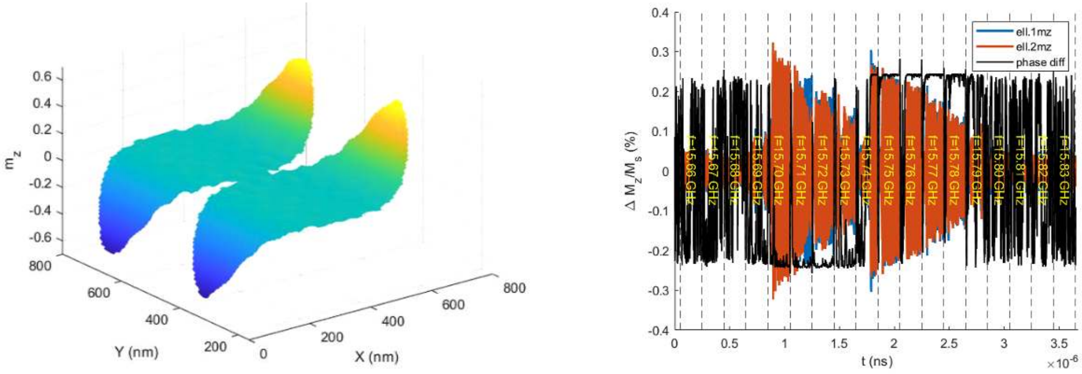
Computing by parametric excitations is an old and well-established concept in computing: in the so-called parametron [1] the phase of sub-harmonically excited oscillations carries the binary information. It has also been extensively studied, how parametric excitations can be created in nanomagnets [2] [3]. In order to construct a computing device, one should interconnect the parametrons - for close-by magnets this can be done by their oscillatory stray field. This motivates our study of such field-coupled magnetic excitations in coupled nanoscale magnets.

We use Mumax simulations to demonstrate that parametrically excited eigenmodes in nearby nanomagnets can be coupled to each other in such a way that the oscillation phases go into either a stable positive (in-phase) or negative (anti-phase) configuration, and the couplings from neighboring magnets uniquely determine the phase. The sign of the coupling and the amplitude of the steady-state oscillation depends on the geometry and the pumping frequency. The couplings are sufficiently stable against thermal fluctuations. We also observe that the mode-coupling shows a hysteretic behavior, and once the phase is stabilized, it remains fixed over a wider range of frequencies.



a) *b)*

Figure 1: a) is an illustration of coupled eigenmodes in two ellipsoidal magnets - oscillations are in phase in this case. b) is a frequency sweep, showing also the dot product (black line) of the average magnetization besides the oscillating magnetization. A constant negative or positive dot product indicates a stable phase configuration

It is envisioned that such dynamic coupling allows the construction of logic or neuromorphic computing devices or possibly phase-based Ising machines.

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REFERENCES

[1] Goto, Eiichi. "The parametron, a digital computing element which utilizes parametric oscillation." Proceedings of the IRE 47, no. 8 (1959): 1304-1316.

[2] Makiuchi, Takahiko, Tomosato Hioki, Yoshiki Shimazu, Yasuyuki Oikawa, Naoto Yokoi, Shunsuke Daimon, and Eiji Saitoh. "Parametron on magnetic dot: Stable and stochastic operation." Applied Physics Letters 118, no. 2 (2021): 022402.

[3] Srivastava, Tiet al. "Complete identification of spin-wave eigenmodes excited by parametric pumping in YIG microdisks." arXiv preprint arXiv:2301.13468 (2023).

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Universal Set of Magnon-Mediated Quantum Gates

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Quantum magnonics explores using spin excitations, magnons, within quantum technologies [1–3]. Explorations focusing on systems of coupled magnons and qubits show their potential as bases of hybrid quantum computing architectures [1–3]. Magnons are favored for their strong interaction with both bosonic and fermionic excitations; however, this leaves them unsuitable for use as quantum memories or qubits. Consequently, this means that magnons can act between disparate subsystems as mediators of quantum interactions. In this work, we study the limits of quantum information manipulation and processing using dynamic magnon-mediated interactions.

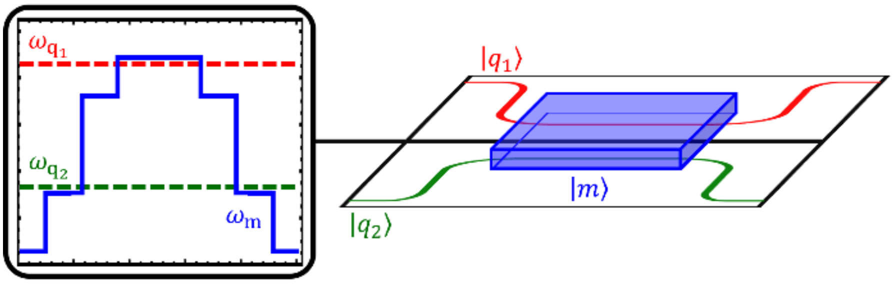

Figure 1: Schematic geometry of the hybrid quantum system described by the Hamiltonian $\hat{\mathcal{H}}(t)/\hbar = \omega_m(t)\hat{m}^\dagger\hat{m} + \omega_{q_1}\hat{q}_1^\dagger\hat{q}_1 + \omega_{q_2}\hat{q}_2^\dagger\hat{q}_2 + g_1\hat{q}_1^\dagger\hat{m} + g_1^*\hat{m}^\dagger\hat{q}_1 + g_2\hat{q}_2^\dagger\hat{m} + g_2^*\hat{m}^\dagger\hat{q}_2$, where $\hat{m}^\dagger$ $(\hat{m})$ and $\hat{q}_{1,2}^\dagger$ $(\hat{q}_{1,2})$ are the creation (annihilation) operators for the magnon and qubit modes, respectively. The window shows an example protocol of $\omega_m(t)$ being applied to the system.

Here, we propose a universal set of magnon-mediated quantum gates that are realized using an ancilla magnon mode coupled to a hybrid system of mutually noninteracting qubits. These gates are realized without directly changing any qubit parameters, by exploiting dynamic manipulation of the magnon mode frequency $\omega_m(t)$, and control of the initial magnon state. In particular, we consider the hybrid quantum system shown schematically in Fig. 1. This system consists of two noninteracting qubit modes $|q_{1,2}\rangle$ and one magnon mode $|m\rangle$. Protocols of $\omega_m(t)$ such as the one shown in Fig. 1 can be applied by a control line to manipulate the frequency gap $\Delta\omega_{1,2} = \omega_m(t) - \omega_{q_{1,2}}$, where $\omega_{q_{1,2}}$ is the resonant qubit frequency. This induces resonant coupling, and, thus, interaction, between the magnon and qubit states when $\Delta\omega_{1,2}$ becomes comparable to the magnon-qubit coupling rate $g_{1,2}$. A large qubit frequency mismatch $|\omega_{q_1} - \omega_{q_2}| \gg |g_{1,2}|$ means that the magnon mode can interact with only one qubit mode at each moment of time. Different initial magnon states and different frequency control protocols of $\omega_m(t)$ lead to different qubit dynamics.

We show that by invoking different protocols of dynamic magnon-mediated interactions, arbitrary single-qubit gates and two-qubit controlled-phase gates can be realized. Together, these form a universal set of quantum gates that are mediated by magnons. This means that by using only interactions with magnons, any unitary transformation on the qubit subsystem can be performed. Our results demonstrate the plausibility of using the manipulation of dynamic magnon-mediated interactions as the sole control mechanism of a universal magnonic-based quantum computer.

REFERENCES

[1] Y. Li, W. Zhang, V. Tyberkevych, et al., “Hybrid magnonics: physics, circuits, and applications for coherent information processing”, Journal of Applied Physics **128**, 130902 (2020).
[2] D. D. Awschalom, C. R. Du, R. He, et al., “Quantum engineering with hybrid magnonic systems and materials (invited paper)”, IEEE Transactions on Quantum Engineering **2**, 1–36 (2021).
[3] J. Xu, C. Zhong, X. Han, et al., “Coherent gate operations in hybrid magnonics”, Phys. Rev. Lett. **126**, 207202 (2021).

Low Damping of Submicronic Thin Films of YIG Grown by RF Sputtering

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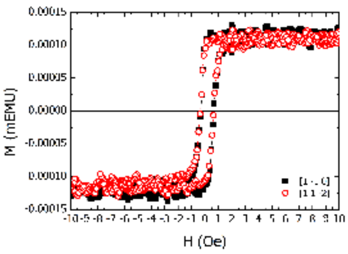
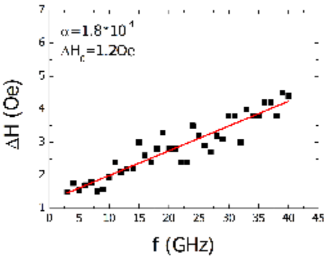
Magnonics requires materials with a very low damping parameter to ensure long propagation distances. Yttrium Iron Garnets (YIG) are well known to be the best material for these applications because of their very low damping (5.10^{-5} for bulk YIG). Furthermore, the electrical modulation of the magnon and spin-related phenomena can be performed by interfacial effects[1], which requires to work with thin films, in order to enhance these effects. An additional argument about the need to grow very thin garnet films for these applications is the resiliency of the YIG to usual lithography techniques.

As sputtering is far more used in industrial processes, we grew 70 nm thick YIG thin films on GGG with this technique. In this study, we varied the growth conditions (power, Argon pressure), as well as the annealing parameters (Temperature, Oxygen flux, Duration of annealing). The best samples produced were isotropic in plane, magnetically soft, with a coercive field smaller than 1 Oe, as shown in fig. 1. The samples we have grown present good dynamical quality: regarding the growth and annealing parameters we grew samples with a low damping parameter around 10^{-4}, a low extrinsic contribution to the linewidth ($\Delta H_0 < 2$ Oe) and very low roughness ($<$0.3 nm RMS). As we can observe in the fig. 2 and 3, we did not observe the same behaviour depending on the growth and annealing temperature: a linear evolution as a function of the frequency as observed in fig.2, or an evolution with a significant curvature at low frequencies as shown in fig.3, indicative of a two magnons scattering or maybe a spread of the effective magnetization[2] This behaviour regarding the growth and annealing parameters will be discussed during this presentation.





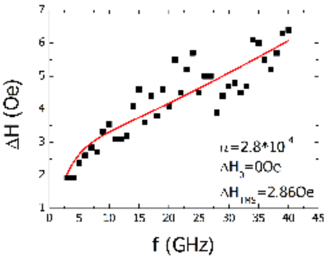


Figure 1: In-plane magnetic static characterization of a YIG sample annealed at 750C along $[1\bar{1}0]$ (black) and $[11\bar{2}]$ (red)

Figure 2: Linewidth frequency dependence measured with an in-plane applied magnetic field for low Ar pressure grown YIG

Figure 3: Linewidth frequency dependence measured with an in-plane applied magnetic field for high Ar pressure grown YIG

In this work, we demonstrate that the sputtering technique well suited for industrial processes permits the growth of submicronic YIG samples exhibiting dynamical properties near the LPE grown ones, and very low surface roughness.

This work has received financial support from the French ANR Framework Programme MAESTRO (ANR-18-CE24-0021) and k-NET (H2020-FETOPEN-2018-2019-2020-01, grant No. 899646).

REFERENCES

[1] X.-Y. Wei, O. A. Santos, C. H. S. Lusero, et al., “Giant magnon spin conductivity in ultrathin yttrium iron garnet films”, Nature Materials **21**, 1352–1356 (2022).

[2] R. Arias and D. L. Mills, “Extrinsic contributions to the ferromagnetic resonance response of ultrathin films”, Physical Review B **60**, 7395–7409 (1999).

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