The 2024 magnonics roadmap

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Roadmap

The 2024 magnonics roadmap

Benedetta Flebus[1,*], Dirk Grundler[2,3,*], Bivas Rana[4], YoshiChika Otani[5,6], Igor Barsukov[7], Anjan Barman[8], Gianluca Gubbiotti[9], Pedro Landeros[10], Johan Akerman[11], Ursula Ebels[12], Philipp Pirro[13], Vladislav E Demidov[14], Katrin Schultheiss[15], Gyorgy Csaba[16], Qi Wang[17], Florin Ciubotaru[18], Dmitri E Nikonov[19], Ping Che[20], Riccardo Hertel[21], Teruo Ono[22], Dmytro Afanasiev[23], Johan Mentink[23], Theo Rasing[23], Burkard Hillebrands[13], Silvia Viola Kusminskiy[24], Wei Zhang[25], Chunhui Rita Du[26], Aurore Finco[27], Toeno van der Sar[28], Yunqiu Kelly Luo[29,30], Yoichi Shiota[31], Joseph Sklenar[32], Tao Yu[17] and Jinwei Rao[33]

[1] Department of Physics, Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA 02467, United States of America
[2] Laboratory of Nanoscale Magnetic Materials and Magnonics, Institute of Materials (IMX), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015, Switzerland
[3] Institute of Electrical and Micro Engineering (IEM), EPFL, Lausanne 1015, Switzerland
[4] Institute of Spintronics and Quantum Information (ISQI), Faculty of Physics, Adam Mickiewicz University, Poznań, Poland
[5] Center for Emergent Matter Science, RIKEN, Wako, Japan
[6] Institute for Solid State Physics (ISSP), University of Tokyo, Kashiwa, Japan
[7] Department of Physics and Astronomy, University of California, Riverside, United States of America
[8] S N Bose National Centre for Basic Sciences, Salt Lake, Sector III, Kolkata, India
[9] Cnr-Istituto Officina dei Materiali, Perugia, Italy
[10] Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile
[11] Department of Physics, University of Gothenburg, Gothenburg, Sweden
[12] Univ. Grenoble Alpes, CEA, CNRS, Grenoble-INP, SPINTEC, Grenoble 38000, France
[13] Fachbereich Physik and Landesforschungszentrum OPTIMAS, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany
[14] Institute of Applied Physics, University of Münster, Münster 48149, Germany
[15] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[16] Pázmány Péter Catholic University, Budapest, Hungary
[17] School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
[18] Imec, Leuven 3001, Belgium
[19] Components Research, Intel Corp., Hillsboro, OR 97124, United States of America
[20] Laboratoire Albert Fert, CNRS, Thales, Université Paris-Saclay, Palaiseau 91767, France
[21] Université de Strasbourg, CNRS, Institut de Physique et Chimie des Matériaux de Strasbourg, Strasbourg 67000, France
[22] Institute for Chemical Research, Kyoto University, Center for Spintronics Research Network, Kyoto University, Uji, Japan
[23] Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands

[*] Authors to whom any correspondence should be addressed.

[24] RWTH Aachen University, Aachen and Max Planck Institute for the Physics of Light, Erlangen, Germany
[25] University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, United States of America
[26] School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, United States of America
[27] Laboratoire Charles Coulomb, Université de Montpellier, CNRS, Montpellier 34095, France
[28] Department of Quantum Nanoscience, Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, Delft 2628 CJ, The Netherlands
[29] Department of Physics and Astronomy, University of Southern California, Los Angeles, CA, 90089, United States of America
[30] Kavli Institute at Cornell, Ithaca, NY 14853, United States of America
[31] Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[32] Wayne State University, Detroit, MI, United States of America
[33] ShanghaiTech University, Shanghai, People's Republic of China

E-mail: flebus@bc.edu and dirk.grundler@epfl.ch

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Abstract

Magnonics is a research field that has gained an increasing interest in both the fundamental and applied sciences in recent years. This field aims to explore and functionalize collective spin excitations in magnetically ordered materials for modern information technologies, sensing applications and advanced computational schemes. Spin waves, also known as magnons, carry spin angular momenta that allow for the transmission, storage and processing of information without moving charges. In integrated circuits, magnons enable on-chip data processing at ultrahigh frequencies without the Joule heating, which currently limits clock frequencies in conventional data processors to a few GHz. Recent developments in the field indicate that functional magnonic building blocks for in-memory computation, neural networks and Ising machines are within reach. At the same time, the miniaturization of magnonic circuits advances continuously as the synergy of materials science, electrical engineering and nanotechnology allows for novel on-chip excitation and detection schemes. Such circuits can already enable magnon wavelengths of 50 nm at microwave frequencies in a 5G frequency band. Research into non-charge-based technologies is urgently needed in view of the rapid growth of machine learning and artificial intelligence applications, which consume substantial energy when implemented on conventional data processing units. In its first part, the 2024 Magnonics Roadmap provides an update on the recent developments and achievements in the field of nano-magnonics while defining its future avenues and challenges. In its second part, the Roadmap addresses the rapidly growing research endeavors on hybrid structures and magnonics-enabled quantum engineering. We anticipate that these directions will continue to attract researchers to the field and, in addition to showcasing intriguing science, will enable unprecedented functionalities that enhance the efficiency of alternative information technologies and computational schemes.

Keywords: magnonics, road map, spin wave, microwave, neuromorphic, ferromagnet, antiferromagnet

1. Introduction

Benedetta Flebus and Dirk Grundler

The research field of magnonics has witnessed rapid development in recent years (figure 1(a)). In this field, scientists and engineers explore the fundamentals of collective spin excitations (spin waves (SWs)) in magnetically ordered materials (which we summarize as 'magnetic materials' in the following) from the microscopic to the macroscopic length scales. Understanding the coherent and incoherent SWs (magnons) represents a multiscale problem. It ranges from the quantum-mechanical exchange interaction acting on the Angstrom length scale via magnetic domain formation on the (sub)micron length scale to classical electromagnetism with its far-reaching magnetic stray fields that act up to the mm scale and beyond. Relevant intrinsic timescales range from roughly fs (ultrafast demagnetization of materials) to several msec (decay times of long-wavelength SWs in a low-damping magnetic insulator). Providing charge-less angular momentum

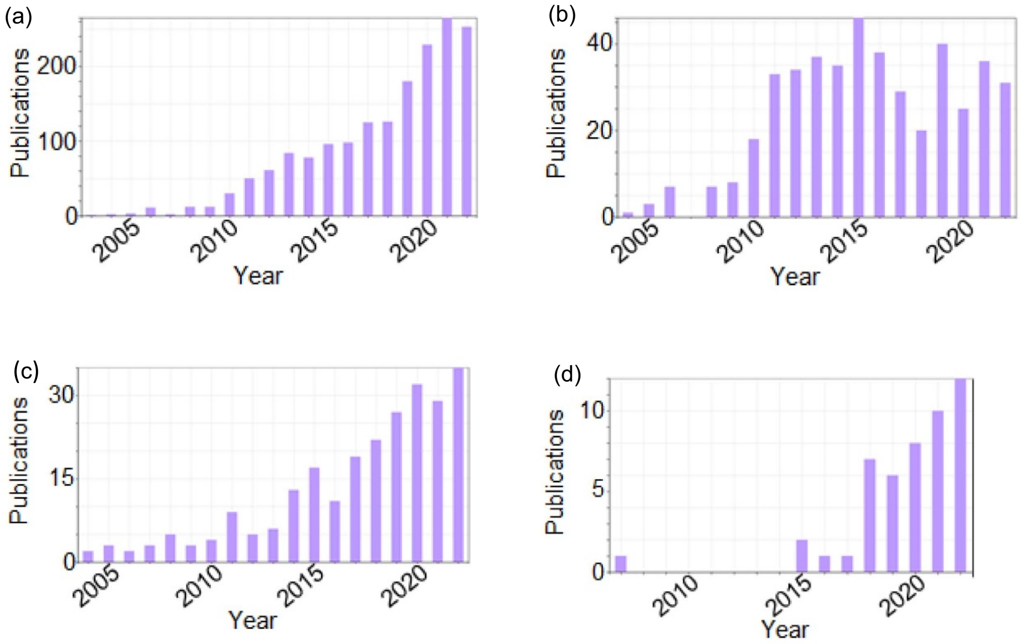

Figure 1. (a) Number of publications which contain the term '(nano)magnonic' or '(nano)magnonics' in the abstract. (b) Number of publications containing 'magnonic crystal' in the abstract. (c) Number of publications containing the terms ('spin wave' or 'magnon') and 'circuit' in the abstract. (d) Number of publications containing ('magnon' or 'spin wave') and ('neuromorphic' or 'neural') in the abstract. (a)–(d) Data from Web of Science, provided by Clarivate. Web of Science and Clarivate are trademarks of their respective owners and used herein with permission.

flow as an information carrier in thin-film materials and corresponding nanostructures, propagating magnons have been steered, gated, directionally coupled and amplified in the linear and nonlinear regime via different external control parameters and spintronics concepts [1–3]. Encoding signals and data in their amplitudes or phases, one can thereby functionalize magnons on the nanoscale for applications in information technology (IT) and computation that avoid charge flow and Joule heating. At the same time, clock frequencies can go far beyond the currently established few GHz as magnons with wavelengths down to the atomic scale offer the THz frequency regime concomitant with unprecedented miniaturization of circuits. Recently, propagating magnons moved domain walls (DWs) and changed the magnetic states of bistable nanomagnets enabling a non-volatile magnetic storage of magnonic signals.

In 2021 the first Magnonics Roadmap was published in the IOP's *Journal of Physics: Condensed Matter* [4]. The authors addressed the multiple directions pursued in magnonics. The Roadmap presented the advancements in the fundamental science and engineering of magnons in individual functional elements, such as logic gates for Boolean computing architectures and magnonic crystals for data processing. The latter devices have been the focus of research endeavors for many years (figure 1(b)). Recently, more complex magnonic circuits gained great interest (figure 1(c)) and their relevance continues growing. An emergent objective is now hardware implementations for unconventional computing schemes (figure 1(d)), which had yet to start off prominently in 2021. However, since then, the rapidly growing demands in artificial intelligence (AI) applications and machine learning have shown that conventional digital data processing and their charge-based circuits are particularly energy hungry and need to be optimized for future challenges in computation. To enhance the sustainability of modern information technologies, alternative solutions exploiting charge-less information carriers and, for instance, wave-based computation require accelerated and targeted exploration. Figure 2 demonstrates that magnonic crystal structures based on yttrium iron garnet $Y_3Fe_5O_{12}$ (YIG) films have pushed the field of magnonics in terms of miniaturization, led to numerous functional devices and paved the way towards nanostructured neural networks operating with magnons at deep-sub-100 nm wavelength. It is timely to create an updated magnonics roadmap that reviews the recent scientific and technical developments in the field, highlights the emergent topics and identifies white spots regarding the technological exploitation of magnonics (part I). To encode data in either amplitudes or phases and process them over macroscopic distances in magnetic circuits, coherently excited magnons are particularly interesting as they can propagate up to mm in e.g. a low-damping ferrimagnetic thin film grown at the wafer scale [5]. Their coherency and decay lengths have reached values at room temperature that are much larger than corresponding lengths of electrons used in conventional semiconductor technology, but also of incoherently excited magnons addressed in magnon spintronics [6]. Based on coherent magnons one can realize multifrequency circuits and computational devices that allow for parallel processing of

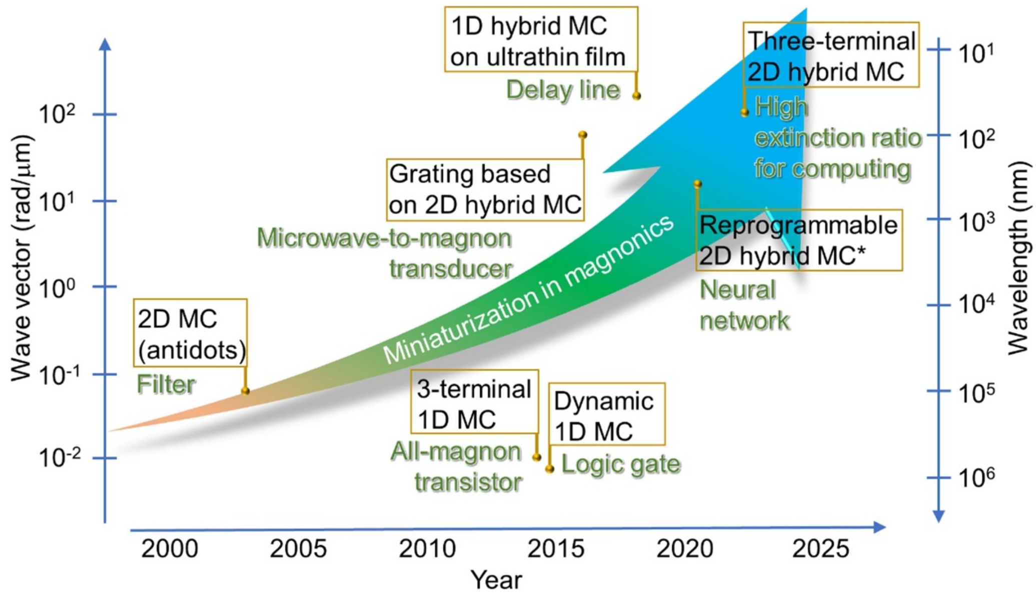

Figure 2. Functional devices and circuits (green labels) which make use of a magnonic crystal (MC) structure (black labels) based on yttrium iron garnet (YIG) subjected to periodic patterning or periodic ferromagnetic nanoelements (hybrid). Miniaturization during the last few years has led to one- (1D) and two-dimensional (2D) MCs that exploit and control magnons of wavelengths (wave vectors) down to 50 nm (up to 126 rad μm^{-1}) in YIG. Wave vectors are indicated by yellow circles. These exchange-dominated magnons enable large signal speeds in ultrathin films (beyond 2 μm ns^{-1}).
*The neural network circuit considered in the graph was explored by micromagnetic simulations.

data over a large array of memory cells. These aspects motivate the focus of part 1 on coherent magnons. At the same time, it is essential that the Magnonics Roadmap 2024 offers a broader perspective (part II) and reflects on the novel research endeavors in the fundamental and applied sciences. In the following, we motivate the different sections of the two parts of the Roadmap in detail. In each part, the sections are structured as follows: status, current and future challenges, advances in science and technology to meet challenges and concluding remarks.

Part I of this Roadmap addresses experimental and theoretical concepts and findings that define the state-of-the-art concerning functional elements and magnonic circuits. Magnetic materials such as insulating ferrimagnets support collective spin excitations in the technologically relevant GHz frequency regime. Embedded as macroscopic bulk elements in conventional microwave circuits and IT equipment, they are commercialized as power limiters, oscillators, bandpass filters and nonreciprocal circulators. On the macroscopic length scale, inductive coupling is adequate for signal transduction. For future on-chip applications and miniaturized circuitry, the same coupling mechanism is expected, however, to compromise the low-power consumption offered by the chargeless information processing. Section 2 discusses the current status and prospects of alternative transduction schemes based on electrical field effects and appropriate materials selection. To enable directional signal transmission with high power efficiency, avoid unwanted signal reflections and control the crosstalk in densely integrated magnonic channels, the nonreciprocal characteristics of magnons need special attention and optimization. However, the conventional approach based on interfacial Dzyaloshinskii–Moriya interaction and spin–orbit coupling is known to induce dissipation in metallic magnetic materials. Section 3 discusses recent findings that circumvent such a detrimental effect. A further way out is presented in section 4, which highlights advances in absolute spin-wave amplification, which is of significant importance for the whole field of applications in magnonics. The following sections 5 and 6 address recent developments that support the envisioned potential of magnonics for unconventional computing. The sections first revisit non-linear effects, which form the basis for computation and second present currently explored computing schemes. The remaining sections of part 1 outline strategies for realizing 3D magnonic device architectures (section 7) and explore operational frequencies up to the THz regime (section 8). These two last sections of part 1 outline the long-term vision of on-chip magnonics by which data processing capacity and speed, respectively, will be pushed to ultimate limits.

Part II of this roadmap delves into exciting new frontiers within the field of magnonics. Here, one aims at harnessing the quantum properties of magnons into novel and enhanced functionalities [7, 8]. By leveraging the interactions between diverse quantum degrees of freedom, quantum hybrid systems are paving the way for significant advancements in fundamental physics and cutting-edge device applications, particularly with their potential for coherent information processing. Due to their long coherence times, low dissipation rates and capability of reaching strong coupling with different excitations, magnons are promising candidates for novel hybrid technologies based on integrating complimentary quantum systems [8]. Section 9 guides the reader through three directions in hybrid quantum magnonics and their corresponding challenges, i.e. true magnonic quantum systems operated at very low temperatures, quantized SWs mimicking quantum functionalities and magnon Bose–Einstein condensation.

Quantum systems whose interactions with magnons are consistently and successfully leveraged are solid-state spin defects. Nitrogen vacancies in diamond, in particular, have emerged as a leading quantum sensor of static and dynamical magnetic properties owing to their exceptional sensitivity and coherence properties [9]. Section 10 discusses recent developments in this field and outlines new quantum sensing opportunities based on different solid-state defects. While vastly unexplored, particularly promising are the spin defects in layered van der Waals (vdW) crystals, which could enable nanoscale proximity to the quantum material under investigation, presenting a unique advantage for magnetic studies of vdW heterostructures. In recent years, vdW magnets have garnered intense attention as an ideal platform for exploring magnetism in the two-dimensional limit and magnon-magnon interactions in their layered form [10]. Synthetic antiferromagnets (SAFs) have already been essential and technologically relevant in spintronics for e.g. the sensors based on the giant magnetoresistance effect and the exploration of the racetrack memory concept. More recently, SAFs generated interest in skyrmionics for engineering topologically protected spin structures. Section 11 discusses how these material systems can play a key role in shaping the next generation of magnonic devices. SAFs allow for engineering novel spin dynamics properties via magnon-magnon interactions, as they offer a far more significant degree of tunability—via layer thickness and material composition—than bulk crystals and homogeneous thin films [11]. The tunability of these systems represents a critical asset not only for device optimization but also for engineering fundamentally novel physical phenomena. The recent application of non-Hermitian frameworks to open systems, e.g. photonic systems and metamaterials, has led to the observation of several new phenomena ranging from lasing topological edge states to the breakdown of the conventional bulk-edge correspondence. The key ingredient to engineering nontrivial non-Hermitian phases is the tunability of the parameters controlling the non-Hermiticity of an open system, i.e. gain and loss. While the feasibility with which the balance between gain and loss can be tuned suggests that magnetic systems might be promising solid-state platforms for harnessing non-Hermitian phenomena, their experimental investigation is still in its infancy [12]. Section 12 discusses the current status of this field and explores pathways to overcome its experimental challenges. It addresses as well topological magnonics [13] by considering the finite lifetimes of quasiparticles.

The different parts of the 2024 Roadmap allow us to define particular technological advantages of the magnonics platform over other platforms, such as electronics, plasmonics and phononics and identify white spots (challenges). The key advantages discussed in part I of the Roadmap are the availability of (i) an extremely broad microwave frequency regime for multi-frequency operation of, e.g. IT devices, (ii) ultrashort magnon wavelengths potentially reaching the soft x-ray wavelength regime at sub-THz frequencies, (iii) long decay lengths for parallel processing across an array of memory cells or nodes, (iv) the avoidance of Joule heating, (v) the inherent nonlinearity needed for (neuromorphic) computing and (vi) the nonvolatile data storage in the same materials system allowing for low energy consumption and instant-on computation. Magnonics enables in-memory computation schemes and avoidance of the von Neumann bottleneck currently threatening the sustainability of electronics-based digital computation in an era of ever-growing machine learning and AI applications. To harvest and functionalize the advantageous features in disruptive technologies that go beyond the planar circuit design, we see challenges in magnonics concerning materials science, 3D circuit design and modeling. Considering the existing blueprint of 3D IT devices, such as the multi-level NAND flash memory, experimental and theoretical research on 3D magnonic device architectures should be strengthened.

From part II, it becomes clear that the technological development of truly quantum magnonic platforms is still in its infancy. New powerful computation methods and fabrication techniques, together with high-quality, low-damping materials, are needed to unlock the set of unique features that quantum magnonics is shown to offer compared to the more mature field of quantum optics, such as scalability down to the atomic lattice scale, broad frequency range, straightforward control of spin dynamics by electric currents and fields and a manifold of nonreciprocal phenomena and nonlinearities. Central to the development of novel quantum hybrid platforms is the interaction between magnons and solid-state defects. While the latter has already been successfully leveraged to probe fundamental magnonic properties, new sensing methods with nanoscale proximity operating at cryogenic temperatures are required. By such methods one can access a strong-coupling quantum regime that will allow for single-spin-state-to-single-magnon-occupancy transduction and the implementation of quantum interconnects. A potential candidate in this sense is offered by vdW magnets, which host defects embedded in lower dimensional crystalline structures. The tunability and functionality of these materials, together with SAFs, make them also a leading platform for future fundamental and technological advances in the field of magnonics, including concrete realizations of non-Hermitian topological phases.

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2. Low-energy excitation and manipulation of SWs

Bivas Rana, YoshiChika Otani and Igor Barsukov

Status

For efficient excitation and manipulation of SWs, various electric-field-induced methods, i.e. magnetoelectric effects, were proposed. One of the most promising methods is voltage-controlled magnetic anisotropy (VCMA). The applied electric field relatively modifies electronic occupation in 3*d* orbitals of ferromagnetic materials at the ferromagnet/oxide interface. Since VCMA does not rely on chemical reactions and ionic movements, it is suitable for microwave applications. Because of its interfacial nature, the device dimension can be reduced dramatically and the VCMA coefficient can be increased significantly by interface engineering. VCMA has been widely adopted for the excitation of linear [14] and nonlinear parametric (figures 3(a) and (b)) [15–17] SWs and manipulation of SW frequency (figure 4(a)) [18]. Remarkably, parametric excitation becomes possible for perfectly in-plane and out-of-plane [15] magnetization orientation, where linear excitation is prohibited due to vanishing VCMA torque. Parametric excitations through VCMA has been proposed for antiferromagnets (figure 3(a)) [16] and shown in ferromagnets through electric field induced modulation of interfacial in-plane magnetic anisotropy (figure 3(b)) [17]. Reconfigurable magnonic crystals and magnonic nanochannels were proposed to operate by periodically arranging metal gate electrodes with specific shapes on waveguides and applying a gate voltage to the electrodes [4, 19]. The magnonic band structures and band gaps in these magnonic crystals and nanochannels (figure 4(b)) can be tuned on-demand through VCMA [4, 19]. Notably, the damping parameter of an ultrathin ferromagnetic film can also be modulated by an electric-field in a linear and nonlinear (figure 4(c)) fashion, depending on the ferromagnetic layer thickness, type of buffer layer and oxide materials [20].

In multiferroic materials, an external electric field can directly control the magnetization and magnetic anisotropy (figure 4(d)). In contrast, an electric-field-induced strain in piezoelectric/ferromagnetic and multiferroic/ferromagnetic bilayers is transferred to the adjacent ferromagnetic layer, resulting in the deformation of lattice in a ferromagnet and modulation of magnetic parameters through spin-lattice coupling. Likewise, an electric-field-induced electrical polarity in ferroelectric or multiferroic layers in ferroelectric/ferromagnetic and multiferroic/ferromagnetic bilayers affects the magnetic properties in ferromagnetic layers [24]. These magnetoelectric effects in multiferroic heterostructures have been used for SW excitation [25]; tuning of the amplitude, phase, resonance frequencies/fields [21] of SWs; and magnonic band structures. Interestingly, the SW routing between two waveguides placed parallel to each other on top of a piezoelectric layer (figure 4(e)) can be controlled by electric-field-induced strain in the piezoelectric layer [22]. When an external electric field is applied along a direction perpendicular to SW propagating direction and magnetization, it can induce a Dzyaloshinskii–Moriya-like interaction, known as the Aharanov–Casher effect. This method was found to be very efficient for tuning phases of exchange-dominated SWs (figure 4(g)) [23] and also able to impose nonreciprocity in SW-dispersion (section 3), which could be very promising for creating caustic-like SW beam excited from a point source in a ferromagnetic thin film. Among all these magneto-electric effects the VCMA has proven its potential due to its interfacial origin, ultrafast response time, linear response to electric field in most cases, possibility to customize VCMA coefficient through interface and material engineering.

Current and future challenges

The electric-field-induced excitation and manipulation of SWs are in the infant stage and associated with many challenges. The first challenge would be the experimental realization of various ideas, such as VCMA-induced two-dimensional magnonic crystals, magnonic logic gates, unidirectional SW flow (section 3) from phased-array antenna, etc. The next challenge would be to increase the VCMA coefficient in ferromagnet/oxide heterostructures beyond $\sim$pJ V^{-1} m^{-1}, which currently shows a value up to a few hundred fJ V^{-1} m^{-1}. Apart from interfacial magnetic anisotropy, the SWs are also affected by other interfacial properties, which originate from spin–orbit coupling (SOC). Although electric-field-induced modulation of other interfacial properties such as interfacial damping [20], interfacial Dzyaloshinskii–Moriya interaction (DMI), interfacial SOC and exchange interaction have been reported, substantial effort is still required to enhance its efficacy. Choosing appropriate materials seems to be the key to developing energy-efficient devices (section 11). In ultrathin ferromagnetic films, easily functionalized by interfacial phenomena, low SW group velocity may limit the performance of SW circuits. On the one hand, antiferromagnetic thin films, which generate short wavelength coherent SWs with THz frequency, begin to show their potential [26]. Magnetic insulators, Heusler alloys and band-engineered materials can ensure ultralow damping. On the other hand, magnetic 2D materials and their heterostructures show fascinating interfacial properties. However, experimental studies on the modulation and optimization of various interfacial properties are required. Consequently, SW manipulation via electric field in those materials are still lacking and would be one of the most challenging tasks.

In most proof-of-principle experiments, thick individual layers are used in multiferroics heterostructures. Therefore, a relatively large voltage is required to observe a substantial change in magnetic and SW properties. Reducing applied voltage by orders of magnitude and miniaturizing multiferroic heterostructures down to the nanoscale is urgently needed for practical applications. Growing epitaxial multiferroic films with nanometer thickness is another open challenge. The SWs should be coupled to other degrees of freedom such as spin current, phonons and skyrmions, for novel device

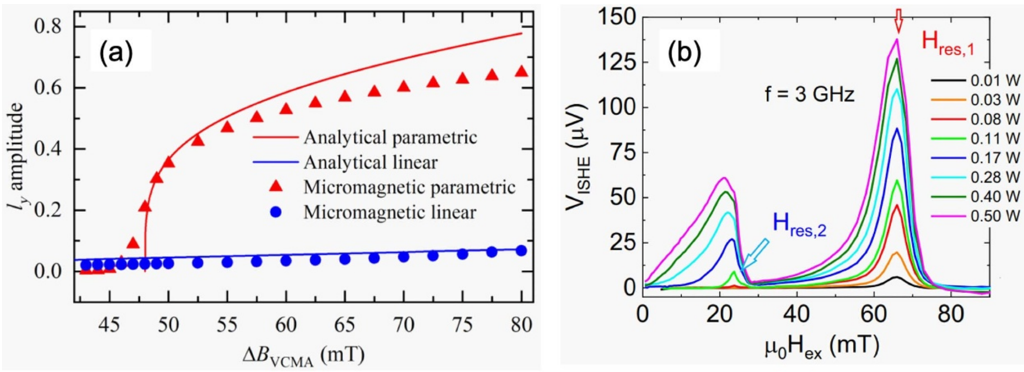

Figure 3. (a) Amplitude of the linear (blue circles and curve) and parametric (red triangles and curve) antiferromagnetic resonance (AFMR) as a function of driving VCMA amplitude. The frequencies of linear and parametric VCMA drivers were set as 33 GHz and 65 GHz, respectively. Note, parametric AFMR is excited only above the threshold VCMA amplitude. Adapted figure with permission from [16], Copyright (2022) by the American Physical Society. (b) The inverse spin Hall effect signal shows linear ($H_{\mathrm{res,\,1}}$) and parametric ($H_{\mathrm{res,\,2}}$) ferromagnetic resonance excited by electric field-induced modulation of interfacial in-plane magnetic anisotropy in Ta/Ru/Ta/CoFeB/MgO/Al_2O_3 heterostructure under parallel pumping condition. The bias magnetic field is applied in-plane of the magnetic film parallel to the in-plane magnetic anisotropy axis. The parametric resonance peak appears only above the threshold microwave power. Adapted from [17]. CC BY 4.0.

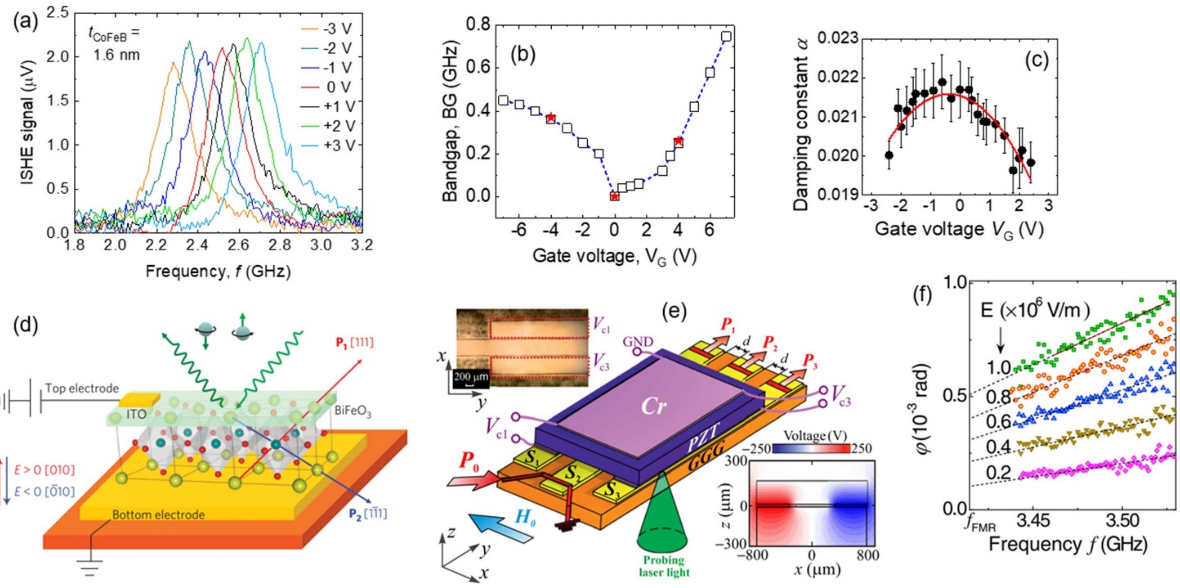

Figure 4. (a) The SW signals for various gate voltages show the modulation of SW frequency by VCMA. The SWs are excited by microwave antenna-induced Oersted field and detected by spin pumping and inverse spin Hall effect. Adapted figure with permission from [18], Copyright (2019) by the American Physical Society. (b) The evolution of magnonic band gap with gate voltage in a VCMA-induced configurable magnonic nanochannel. The stripe-like metal gate electrodes are fabricated on a ferromagnet/oxide waveguide and the gate voltage is applied across the electrodes to form virtual nanochannels through the VCMA effect. Red stars and square symbols represent the experimental and numerical simulation results. The figure is adapted from [19]. (c) Nonlinear variation of the damping parameter in the ultrathin ferromagnetic film with the gate voltage applied across the top metal gate electrode and metal waveguide. Adapted figure with permission from [20], Copyright (2020) by the American Physical Society. (d) Schematic of the experimental set-up for studying electric-field-induced modulation of SWs in single crystal multiferroic material. An external electric field E is applied to the multiferroic material through a transparent ITO top electrode and the SWs are probed by Raman spectroscopy. Adapted from [21], with permission from Springer Nature. (e) Schematic of bilateral magnonic stripes deposited on GGG substrate. The SWs are excited and detected in the middle strip. The piezoelectric layer (PZT) is deposited on the magnonic strips for applying strain. The strain is created in PZT using an applied electric potential across the top (Cr) and bottom electrodes. The top inset shows the microphotograph of the fabricated magnonic stripes, whereas the bottom inset shows the voltage distribution for $V_{c1} = 250$ V and $V_{c3} = -250$ V. Adapted figure with permission from [22], Copyright (2018) by the American Physical Society. (f) Experimental results show the electric-field-induced (i.e. Aharanov–Casher effect-induced) phase (symbols) of SW at various applied electric fields. Dashed lines indicate linear fittings. Adapted figure with permission from [23], Copyright (2014) by the American Physical Society.

functionalities. Although some efforts have been made to investigate the coupling of SWs with other quasiparticles, the coupling efficiency has always been very low. Increasing the coupling strength and control, preferably by the electric field and exploration of the quantum regime (sections 9 and 10) should be the priority.

Advances in science and technology to meet challenges

Significant advances in current technology are needed to combat current challenges. One of the essential tasks for studying and optimizing various interfacial properties would be to prepare magnetic thin film-based heterostructures with smooth and defect-free interfaces. The thin film deposition techniques should be cost-effective and suitable for large-scale production. The preference should be given to optimizing the properties of magnetic films deposited by sputtering techniques, generally used for commercial purposes. With the reduction of film thickness and device dimension, sensitive detection techniques are getting more critical. Although optical techniques (e.g. magneto-optical Kerr effects, inelastic scattering of lights) and various x-ray microscopy techniques have been widely used in laboratories, sensitive electrical methods should be developed for practical device applications. The magnetic tunnel junctions and generally electrical detection methods, nitrogen-vacancy (NV) centers and inverse VCMA effects can be considered as alternative approaches. However, improving their detection sensitivity, especially in the nanoscale dimension without complex device fabrication, is an open challenge. VCMA could be one of the most promising electric-field-induced methods for SW excitation because of its fast response time. However, the impedance mismatch between the microwave source and the junction for SW excitation should be sorted out by adequately optimizing the layer thicknesses, junction dimension, microwave signal frequency and power. Many strategies have been proposed and demonstrated to increase the VCMA coefficient beyond pJ V^{-1} m^{-1}, such as voltage-controlled redox reactions, charge trapping and electromigration. They could be beneficial for SW manipulation but less advantageous for developing faster and miniaturized magnonic devices. Alternatively, interfacial engineering, such as inserting ultrathin heavy metal layers or doping heavy metals at ferromagnet/oxide interfaces, has increased the VCMA coefficient to a few hundred fJ V^{-1} m^{-1}. Further studies are required to improve this coefficient.

Consequently, it would be interesting to investigate how interfacial engineering affects other interfacial properties. The damping parameter is one of the most critical parameters determining the SW decay rate [27]. Efforts have been made to reduce the damping parameter of ferromagnetic thin films by electronic band structure engineering. It would be instructive to study whether electric-field-induced charge accumulation or strain at interfaces can reduce the damping parameter. Understanding the underlying mechanism of this effect is equally important to improve damping modulation efficiency. Another novel approach to minimize power consumption would be to combine magnonics with fluxoids observed in superconductors. The superconductor can hold a lattice of quantized magnetic flux under a moderate magnetic field. This fluxoid lattice can interact with magnons to form magnonic band gaps. However, the realization of complex superconductor/ferromagnet hybrid nanostructures and stabilizing fluxoids during current-induced motion is crucial and requires low temperatures.

Concluding remarks

The electric-field-induced methods have emerged as one of the most potential approaches for the excitation and manipulation of SWs in ultrathin ferromagnetic films to develop energy-efficient magnonic devices. However, the research field is in the early stage of development and is naturally associated with many open challenges. Improving the VCMA coefficient, reduction of layer thickness down to nanometer in hybrid multiferroic structures and experimental demonstration of various ideas are some of the major challenges in this field. In addition to the outlined mitigation approaches, many new concepts have emerged, such as coupling or hybridizing magnons with other quasiparticles like microwave photons, surface acoustic wave phonons, superconducting fluxoids and spin-polarized electrons, which not only offers to increase the device functionality significantly but also brings opportunities to reduce the power consumption or enter quantum engineering (sections 9 and 10). Some efforts have also been made to reduce the power consumption in magnonic devices by eliminating or reducing power consumption from other sources, such as engineering magnetic damping [28], developing bias magnetic field-free magnonic devices, etc. Discovering new materials, including magnetic 2D heterostructures with gate-tuneable emerging interfacial properties, is also getting equal importance.

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3. Non-reciprocal magnonics

Anjan Barman, Gianluca Gubbiotti and Pedro Landeros

Status

The non-reciprocity of wave phenomena describes the situation in which inversion symmetry is broken and the wave dispersion depends on the propagation direction, i.e. waves propagating in opposite directions can exhibit different amplitudes and wavelengths for the same frequency. Such asymmetry appears in different kinds of waves and has been of great recent interest in magnonics. The non-reciprocal feature allows for additional functionalities. Traditional non-reciprocal components have relied on magnetic materials such as ferrites, which are incompatible with low-cost semiconductor integrated-circuit fabrication processes and are challenging to miniaturize to chip scales, rendering them bulky and expensive and ultimately preventing their widespread use [29]. Favorably for on-chip magnonics, in magnetic systems, which naturally break time-reversal symmetry, non-reciprocity emerges in the presence of any chiral magnetic interaction that breaks inversion symmetry [30], such as:

(i) Asymmetric exchange interactions (Dzyaloshinskii–Moriya) from the relativistic spin–orbit interaction, present in non-centrosymmetric crystals and ultrathin films in contact with a heavy-metal layer with strong SOC [31].
(ii) Dipolar interactions: present in films hosting topological Damon–Eshbach surface spin-waves (SWs) [30], coupled magnetic bilayers [32, 33], systems with graded magnetization [34], or in curvilinear architectures such as magnetic nanotubes [33, 35].
(iii) Symmetric anisotropic exchange interactions, which depend on the bond direction in honeycomb antiferromagnets [36].
(iv) Magnetic anisotropy, in the case where a thickness-dependent, graded anisotropy, or one-sided surface anisotropy is present, where the size of the avoided crossing among different SWs is also asymmetric [37].

In the DMI and dipolar cases, the non-reciprocity in frequency scales linearly with layer thickness for small wavenumbers. For the dipolar systems, however, the non-reciprocity in frequency (Δf) shows a maximum value and then decreases for larger wave vectors [32]. It is also found that Δf increases markedly in an antiparallel equilibrium state [32]. The frequency shift is usually larger for interfacial DMI rather than for bulk DMI.

A cylindrical SAF was recently proposed as an alternative to host non-reciprocal SWs (see figure 5(d)). Here, two concentric magnetic nanotubes with opposing vortex states are coupled by the interlayer and intralayer dipolar interaction [33]. A key advantage of the cylindrical bilayer over the planar one is that lateral reflections are avoided. Also, the advantage of the cylindrical bilayer over the isolated nanotube is that the latter requires large curvatures (a small radius), which may be challenging to fabricate.

The SW non-reciprocity is measured by various experimental techniques [31]. In particular, DMI has been reported by current and field-driven DW motion, Brillouin light scattering (BLS) spectroscopy, time-resolved magneto-optical Kerr effect (TRMOKE), propagating SW spectroscopy (PSWS), as well as spin–orbit torque (SOT) method based on a shift in anomalous Hall effect (AHE) [31]. Methods based on DWs are restricted by pinning and strain in the thin films. DMI measured in the creep regime is suited for low DMI constant, whereas those measured in the flow regime show better agreement with BLS. Besides, the requirement of knowledge of exchange stiffness constant poses additional restrictions on this method. BLS spectroscopy is an elegant and simple method for extracting the DMI constant in thin film heterostructures. Using this technique one can not only measure the non-reciprocity in amplitude, frequency and linewidth but also the attenuation length of the SW. Very few comparative studies of the application of various methods on the same samples have been performed. However, the available literature states that BLS best suits larger DMI strengths (D) and ferromagnetic film thicknesses, while domain-wall methods are suitable for smaller D values and SOT applies to small D but with higher ferromagnetic layer thicknesses. All three methods are applicable in an intermediate range and a direct comparison of the methods on the same sample is possible in this regime [31].

Current and future challenges

Magnonics works naturally at rf frequencies (from single to hundreds GHz) with state-of-the-art magnetic materials and ultra-low power consumption while keeping the dimensions of a device on the nanometer scale, thus making magnonics a promising platform for beyond-CMOS technologies. The phenomenon of SWs propagating distinctively along specific directions allows the design of non-reciprocal (one-way) magnonic devices [38–40]. Such behavior can also lead to unidirectional coupling among two magnetic layers, which can be realized, for instance, with the aid of DMI and dissipative coupling (in the form of non-local damping) from the interplay of spin pumping and spin transfer [41]. See section 12 about non-Hermitian magnonics and references therein.

To achieve high values of Δf and pronounced non-reciprocity, a large interfacial DMI is needed and the film thickness of the state-of-the-art ferromagnet should be around 1 nm. The heavy-metal layer that provides the SOC for the interfacial DMI also increments magnetic damping, a drawback for magnonic applications. Dipolar systems (see figure 5) do not require ultrathin films or heavy metals, avoiding the undesired increment of damping.

Regarding materials challenges, a general limitation of magnonic devices is the high intrinsic SW damping in conductive metallic magnets used in conventional spintronic applications. To decrease the magnetic dissipation observed in the ferromagnetic/heavy metal bilayers, magnetic garnet films

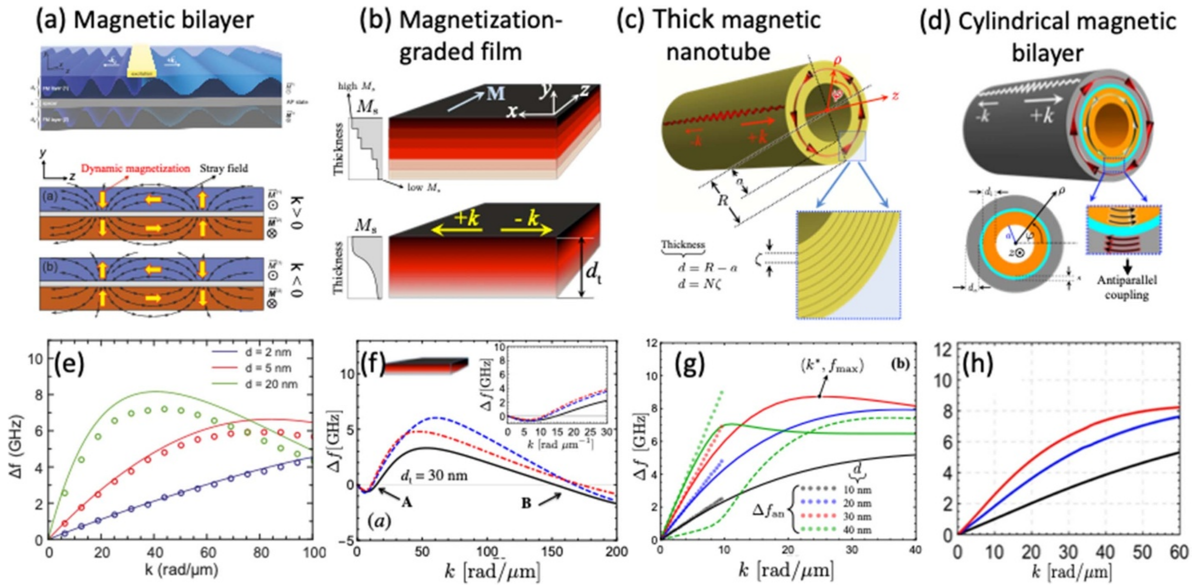

Figure 5. Illustration of dipolar non-reciprocal magnonic systems: (a), (e) magnetic bilayer. Reprinted figure with permission from [32], Copyright 2019 by the American Physical Society, (b), (f) magnetization-graded film. Reproduced from [34]. © IOP Publishing Ltd. CC BY 3.0. (c), (g) thick magnetic nanotube. Reprinted figure with permission from [35], Copyright 2022 by the American Physical Society. and (d), (h) cylindrical magnetic bilayer (or cylindrical synthetic antiferromagnet) [33], with the corresponding behavior of the frequency shift Δf vs. the wave vector k (e)–(h). In general, the dipolar Δf increases with the film thickness because the cooperative dipolar interaction becomes more relevant for large volumes. Reprinted figure with permission from [33], Copyright 2022 by the American Physical Society.

(YIG), well-known for their low damping, have been recently synthesized in contact with a heavy-metal layer, where a small DMI constant emerges [31]. Here, the main challenge is to grow nanometer-thin epitaxial YIG films with smooth surfaces and defect-free clean interfaces, by using liquid phase epitaxy classical technology. The main drawback is that the YIG growth requires high temperatures and an oxygen environment which can cause significant inter-diffusion and oxidation of the metal layer, consequently leading to poor structural and electrical properties in both metal and YIG layers.

Interest in magnonic metamaterials [4] is freshly renewed by the possibility of inducing flat bands [42] and controlling the non-reciprocal SW frequency dispersion and hybrid systems composed of magnonic crystals coupled to superconducting materials, which have been experimentally demonstrated by BLS and FMR, respectively [43]. Of course, there are challenges associated with the low temperature to achieve a functioning system but, at the same time, it may appear to be adequate for application in cryogenic temperatures.

Non-reciprocal SWs can also be observed in chiral antiferromagnet due to the broken time-reversal and spatial-inversion symmetry. The sign of non-reciprocity depends on the field direction as well as the sign of chirality index. Such chiral magnetic structure and the ensuing non-reciprocity may also arise from the competition of symmetric exchange interactions even in the absence of DMI [44].

As for the efficient SW excitation and detection on the nanoscale, state-of-the-art spin transfer nano-oscillators (or spin-Hall nano-oscillators) and the inverse-spin Hall effect, provide the means to address the main challenges associated with the downscaling of magnonic devices and allow for a straightforward integration in scalable circuits compatible with CMOS technology.

As for the experimental-technical challenges, when measuring interfacial DMI by BLS on planar structures, the Damon–Eshbach geometry limits the measurement to only in-plane magnetized systems and that requires a large enough in-plane field to saturate samples with perpendicular magnetic anisotropy (PMA). TRMOKE and PSWS measurements require microfabrication of antenna structures on the samples while delivering no additional insights to the BLS technique. The current-induced shift in AHE is a relatively simple method as it does not involve complex mathematical modeling. However, it requires PMA of the ferromagnetic material. Besides, non-square shapes of the AHE loops also lead to inaccuracies in determining the DMI field (H_{DMI}).

Advances in science and technology to meet challenges

While most of the magnonic devices and functionalities have been demonstrated in planar 2D systems (magnon transistor, direction coupler), multilevel magnonics exploits the vertical (out-of-plane) dimension in multi-layered structures. It offers versatile coupling conditions, i.e. dipolar and interlayer exchange (RKKY) coupling, due to the smallest possible separation to harness the vertical direction for propagating and manipulating SWs actively. This enables the transition from 2D, where realizing multiple interconnections is topographically impossible, to 3D architectures (section 7), thus providing a possible roadmap for further scaling, permitting more functionality in a smaller space and a larger number of vertical interconnections between the layers [40, 45]. For example, combining 3D directional couplers, vertically-coupled conduits with nm spacer thickness and non-reciprocal phenomena, ferromagnetic/heavy metal bilayer waveguides, will bring new unidirectional functionalities for future magnonic devices canceling cross-talk between transmitted and received signals along magnonic conduits and interconnections. From the technological point of view, it requires breakthroughs in design and multilevel hierarchical nanofabrication processes and technology, including developing suitable planarization techniques for elements interconnections in terms of necessary flatness and the capabilities of lithographic methods to align the different layers with precise control of the structural geometry with a nm overlay precision.

All technology developed should be suitable for industrial application or at least have a counterpart suitable for upscaling (e.g. planarization in the research laboratory devices is mainly done by thin film coating while an industrial process would include chemical and mechanical polishing). Moreover, together with validating characterization methodologies, efficient layer-selective generation and detection systems to excite and pick up the SW signal at different heights of the device should be developed.

Regarding curved induced non-reciprocal effects, magnetic thin film conformally deposited on top of 1D periodically corrugated surfaces, with a half-cylinder profile, could represent a valid alternative to single (isolated) cylindrical nanotubes. This requires the combination of electron-beam fabrication of grooved substrate and chemical deposition methods for conformal coverage of the magnetic layer with control down to the nm. At the same time, the complexity of 3D structures pushes researchers to introduce both interlayer exchange and dipolar coupling as well as surface curvature into theoretical models. Furthermore, obtaining large non-reciprocal effects from dipolar coupling requires thicker films, where the oversimplified picture of uniform magnetization along the thickness is no longer valid and the several SW modes can be excited with characteristic profiles along the thickness [35].

Concluding remarks

In this work, we have reviewed several symmetry breaking mechanisms to induce chirality in coupled and hybrid magnetic heterostructures that induce frequency nonreciprocity for the SWs. Although there are several challenges to address in terms of novel materials, nanofabrication of complex heterostructures, SW excitation and detection on the nanoscale, we anticipate non-reciprocal magnonics will play a pivotal role in the field of nanoscale microwave devices, leading to the development of a novel class of non-reciprocal on-chip signal processing devices compatible with the existing semiconductor technology.

Acknowledgements

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4. Amplification of SWs

Johan Akerman, Ursula Ebels and Philipp Pirro

Status

The amplification of SW signals was identified early on as one of the most critical points for magnonics due to the finite lifetime of magnons. Amplification can be described as the increase of the spin-wave intensity at a certain location of the magnonic circuit by a gain factor g_r relative to the unamplified case (*relative amplification*) or by the increase of the spin-wave intensity along the signal propagation direction (*absolute amplification* with gain factor g_a) (compare figure 6). In recent years, magnonic logic (section 6) has also added the problem of fan out of logic elements, i.e. the ability of one element to deliver signals to several downstream logic elements. Obviously, a fan out greater than one in an extended network requires absolute amplification $g_a > 1$ of the signal even in a dissipationless system.

The amplification of SWs is often divided into two main mechanisms: on the one hand, *parametric amplification* based on a coherent, periodic modification of the magnetic energy of the system and, on the other hand, the use of quasi-continuous (DC) *electronic spin currents*, e.g. in spin valves or by means of SOTs. These two mechanisms are qualitatively different as the first selects a particular SW mode to be amplified, whereas the second provides anti-damping to all available modes. The most prominent example of parametric amplification is parallel pumping [46] where traditionally a dynamic Oersted field created by a radio frequency (RF) current of twice the frequency of the amplified SW is applied parallel to the static magnetisation. In the quasi-particle picture of this process, one microwave photon splits into two magnons under conservation of energy and momentum. As mentioned, this process is mode selective both in frequency and wave vector and has demonstrated large absolute gain $g_a > 1000$, in macroscopic structures based on YIG [47]. Additionally, it conserves the phase of the signal and is even able to convert phase into intensity information (non-adiabatic parallel pumping) [46]. It has been successfully applied to macroscopic and nanoscopic systems made of insulating materials like YIG or metallic structures like NiFe (see figure 7(a) and applications described in section 9). Mode selective and phase coherent optical SW pumping using femtosecond laser frequency combs has also recently been demonstrated [48, 49]. The second mechanism, the spin torque amplification, uses a spin current to create an anti-damping like torque which can partially (strict amplification) or completely (auto-oscillation) compensate the Gilbert damping leading to either SW amplification [50] (see figure 7(b)) or SW auto-oscillations [51]. Common examples are the injection of spin-polarized charge currents, as in GMR stacks and magnetic tunnel junctions, or the injection of pure spin currents created by the spin Hall effect in a heavy metal layer adjacent to a magnetic layer or a magnonic system

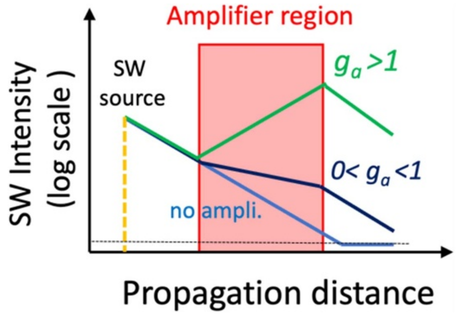

Figure 6. Amplification with different absolute gain g_a. Note that both amplified signals have a relative gain g_r larger than 1.

(SOT-based amplification). These processes are only suitable for thin-film micro- and nanostructures because the required current densities are large, resulting in significant Joule heating.

Current and future challenges

The biggest challenge is to increase the energy efficiency of the amplification process. The energies required to amplify SWs can easily exceed the pure SW energy by more than three orders of magnitude [52], especially if electrical currents are used. In the case of mode selective amplification, another challenge is the increase in selectivity of the amplification process, i.e. that only the signal-carrying mode is amplified and no energy is lost in the parasitic amplification of thermal SWs, which would also worsen the signal-to-noise ratio. Furthermore, for coherent magnonic systems, it is crucial to understand whether and how the amplification process affects the phase of the SWs. These two challenges often (but not exclusively) affect spin torque-based amplification where the amplification of thermal SWs often leads to auto-oscillations and detrimental magnon scattering processes. A large success for SOT-based amplification was recently achieved in a system which, due to a particularly low magnon-magnon interaction and nonlinearity, reached an absolute amplification of SWs ($g_a \approx 5$) by means of SOTs (see figure 7(b)). Another challenge of this approach is that the used bilayers (heavy metal layer combined with magnetic layer) show an increased damping due to spin pumping. For materials with very low intrinsic damping such as YIG, this spin pumping induced damping effect dominates the overall damping and one must apply a significant charge current to restore the propagation length of the SWs in pure YIG, which of course also limits the energy efficiency of this amplification method.

Advances in science and technology to meet challenges

To improve the energy efficiency, novel ways and systems to realize the amplification schemes discussed above need

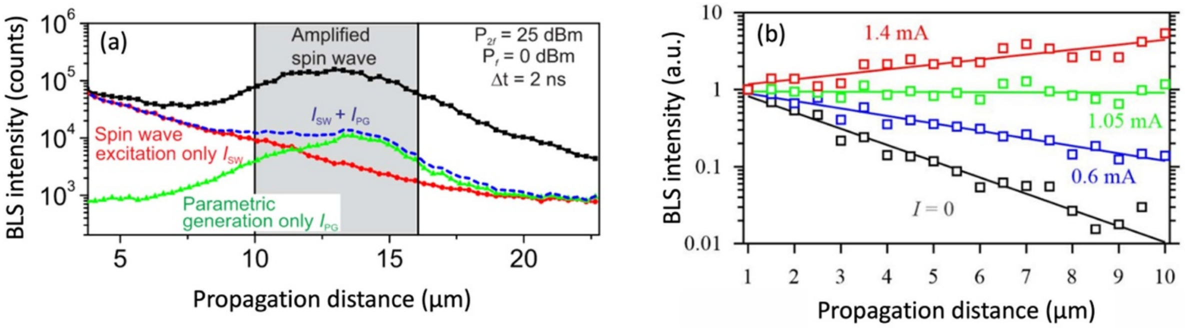

Figure 7. (a) Parametric spin-wave amplification in a NiFe waveguide by a localized amplifier (grey area) which uses a parallel pumping field at twice the SW frequency. Adapted from [46], Copyright (2017), with permission from Elsevier. (b) SW amplification by spin–orbit torques in a waveguide structured from a BiYIG(20 nm)/Pt(6 nm) bilayer. Reproduced from [50]. CC BY 4.0. An absolute amplification is achieved for DC currents larger than ≈ 1 mA.

to be realized. For the parametric amplification, switching from RF-current-driven Oersted pumping fields to voltage-driven effective magnetic fields (section 2) is very promising to strongly reduce the Ohmic losses. Possible realizations are based on voltage controlled magnetic anisotropy, multiferroic materials, hybrid magnon-photon [53], magneto-elastic or magneto-rotational systems driven by piezo-electric transducers or optical pumping using short laser pulses. For this, new materials and hybrid systems with low damping for magnons (and the involved phonons and (microwave) photons) need to be developed which show at the same time strong magneto-elastic or magneto-electric coupling. From the technological side, means to couple these systems efficiently to RF sources need to be implemented, which is nontrivial due to the different impedance. For SOT amplifiers, superradiance [54] and the magnonic Klein paradox [55] enable novel amplifier designs working in reflection. For spin torque-based amplification, a reduction of the needed (charge) currents is necessary. This could be achieved using spin-valve structures or non-local spin injectors on top of the magnonic waveguide. These systems do not require SOC which could reduce the overall spin-wave damping. As spin-valves are not compatible with insulators, the use of low damping half metals with high spin polarization like Heusler alloys seem to be most promising for this approach. In addition, emerging new methods to create spin currents using topological insulators, the conversion of orbitronic angular momentum and the predicted non-relativistic generation of spin currents in altermagnets [56] need to be explored to create higher energy efficiency for magnon spintronic devices. In addition, novel approaches to amplify magnons can be developed, e.g. the use of non-equilibrium magnons to realize the stimulated amplification of SWs [57] or the synchronisation of spintronic auto-oscillators to incoming spin-wave signals.

Advanced spin-wave amplification schemes for logic operations can be realized if the behavior of the amplification process itself is nonlinear, i.e. if the gain depends on the incoming spin-wave signal. In this context, magnonic bistabilitites [58] can provide an interesting option. If an incoming spin-wave signal overcomes the threshold to switch the bistability into its high amplitude state, the signal is amplified but the outgoing spin-wave intensity, frequency and phase are independent of the incoming signal intensity and frequency. Thus, this amplification process provides a build-in signal renormalization which can be used to created extended magnonic logic circuits based on the spin-wave intensity as information carrier.

Concluding remarks

To reach energy efficient, scalable spin-wave amplification is one of the crucial milestones of magnonics. Several systems have demonstrated their potential, but a large variety of suitable physical processes remain relatively unexplored, mainly because of technical challenges to realize complex hybrid devices.

Acknowledgements

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5. Non-linear magnonics

Vladislav E Demidov, Katrin Schultheiss and Gyorgy Csaba

Status

For many decades, dynamic magnetic nonlinearities have been known as the source of a large variety of fascinating phenomena. On the one hand, magnetic media constitute a unique model system for fundamental studies in nonlinear physics. On the other hand, nonlinear phenomena accompanying the propagation of SWs have long been considered for the implementation of signal-processing devices. Traditional examples include limiters, signal-to-noise enhancers, frequency converters, parametric amplifiers, etc. One of the most important advantages provided by magnetic systems is the great flexibility in engineering the dispersion and nonlinear characteristics of SWs. Both can be controlled in a wide range by varying the orientation of the static magnetization and the direction of wave propagation, by balancing the contributions of the dipole and exchange interactions, as well as by designing magnetic anisotropies.

In recent years, nonlinear magnonics has experienced a renaissance associated with several general advances. First, the efficient downscaling of spin-wave devices to the nanometer scale allows a strong concentration of energy in a small volume making it easier to reach the nonlinear regime. Second, the advent of the spin-torque effect provides novel possibilities for highly-efficient excitation and control of high-frequency magnetization dynamics and SWs using direct currents. Third, the recent progress in materials growth led to the preparation of high-quality nanometer-thick films of YIG, in which nonlinear phenomena are strongly enhanced due to its extremely low magnetic damping. All these developments provide new opportunities for utilizing dynamic magnetic phenomena for advanced signal processing, including non-Boolean data processing and neuromorphic computing [52, 59–63]. It is well-established that nonlinearities are essential for computing. Today, neuromorphic computing schemes are promising to make a transformative difference and generate extensive interest among researchers in various fields.

One of the possible routes for neuromorphic computing is reservoir computing which relies on the internal nonlinearities of a system to separate patterns in a high-dimensional output space, where it can be solved. The functionality of the system is defined by the output layer, which is a linear classifier and is trained to a particular task [61, 62]. Alternatively, the internal nonlinearities of the magnonic scatterer can be trained to perform a particular task—the training is done by machine-learning methods on a numerical model of the magnetic system as shown in figure 8 [38, 60]. Computing with magnons is addressed in section 6.

Current and future challenges

Since dynamic non-linear phenomena are extremely diverse and often occur simultaneously, one of the most important challenges in non-linear magnonics is associated with maximization of nonlinear effects that are important for a particular application while minimizing unwanted non-linear effects. Application-relevant dynamic nonlinear magnetic phenomena can be roughly divided into two groups. First, increasing amplitude of the dynamic magnetization is known to result in the modification of the spin-wave dispersion (often referred to as nonlinear spectral shift), in analogy to the Kerr nonlinearity in optics. Similar to optical systems, this phenomenon leads to the amplitude-dependent wavelength and velocity of SWs. It lies at the heart of devices utilizing nonlinear wave interference, which is, for example, a key phenomenon for real-space neuromorphic computing platforms [60]. Furthermore, the nonlinear spectral shift can be used to control the wave propagation in networks of coupled waveguides [52] and to shape short spin-wave packets via the self-modulation effect [64]. Second, in the large-amplitude regime, different spin-wave (magnon) modes do not evolve independently from each other and can exchange energy and angular momentum. This phenomenon is often referred to as magnon–magnon interaction. Taking active control of such nonlinear interactions via their stimulation makes them promising, for example, for the implementation of reservoir computing in the reciprocal space [62] and for the generation of new spectral components [65, 66]. Additionally, it has great potential for implementing the amplification of SWs by the transfer of energy between a high-intensity pump wave and a low-intensity signal wave (section 4).

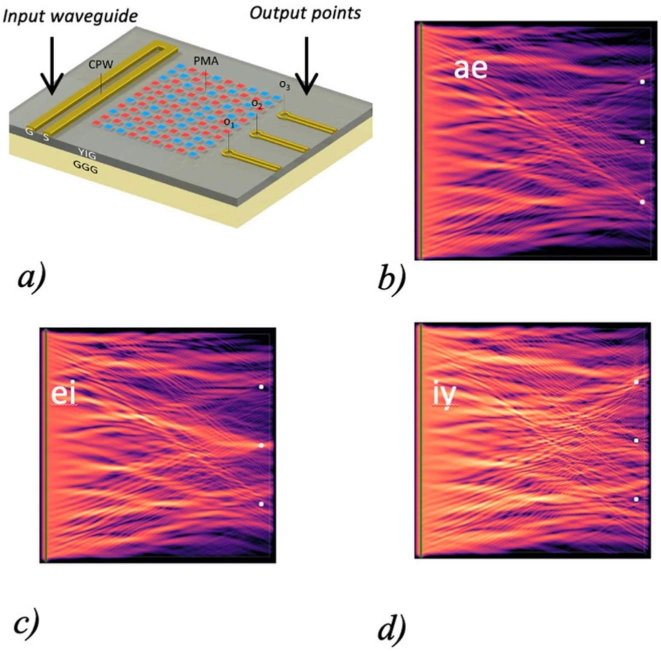

Figure 8. Neuromorphic computing using non-linear spin-wave interference. (a) is the sketch of the system, (b)–(d) nonlinear interference patterns, classifying the input waveforms, which correspond to the, ei, iy vowels. Reproduced from [60]. CC BY 4.0 under the Creative Commons Attribution 4.0 International License, labels added for clarity.

Although the nonlinear spectral shift and magnon-magnon interactions in themselves are very useful for applications, the coexistence of these two phenomena leads to limitations. In particular, the energy losses due to nonlinear mode interactions can be considered as an additional amplitude-dependent damping (nonlinear damping) mechanism. This prevents the amplitude of a particular spin-wave mode from increasing above a certain level and, as a result, limits the achievable nonlinear spectral shift [67]. Conversely, the nonlinear spectral shift often results in strong limitations for the nonlinear interaction of spin-wave modes. Indeed, efficient interaction requires phase synchronization of the interacting modes, which is lost due to the spectral shift with increasing mode amplitudes.

Nonlinear phenomena may significantly reduce the dynamic range of magnonic devices, as the amplitude of magnonic signals must remain in a certain range for computationally useful nonlinearities to occur.

Advances in science and technology to meet challenges

Traditionally, a simple approach to control the nonlinear spectral shift and the effects of nonlinear magnon-magnon interactions requires an appropriate choice of the static magnetization configuration. For example, in an extended magnetic film magnetized normally to the plane, nonlinear interactions become very weak while the nonlinear spectral shift is maximized. The minimization of mode interactions is due to the vanishing ellipticity of the magnetization precession, which is known to be essential for interaction processes. Although this approach works well for extended films and large-scale structures, it becomes inefficient for nanostructured spin-wave waveguides. Therein, inhomogeneous demagnetizing fields result in a strong variation of the ellipticity across the waveguide section. Therefore, additional physical mechanisms are required to control the ellipticity and ensure further developments in nano-scale nonlinear magnonics.

Recently, it was shown that the ellipticity and the resulting nonlinear interactions can be efficiently controlled in materials with PMA [68]. As shown in figure 9(a), even in an in-plane magnetized film, an almost circular precession trajectory can be achieved by adjusting the strength of the anisotropy. In the absence of PMA, the strong ellipticity results in an efficient energy transfer from the initially excited spin-wave mode at the frequency f_0 into many other modes over a wide frequency range (figure 9(b)). This results in an abrupt decrease of the precession amplitude of the initial mode after a certain development time (figure 9(c)). In contrast, in systems with tailored PMA, this process is not observed and the initially excited mode remains stable (figure 9(c)).

This example shows that the possibilities to control magnetic nonlinear phenomena are far from being exhausted. In addition to the search for new materials, one can consider varying the shape of waveguides to optimize the spatial distribution of the demagnetizing fields and the ellipticity. Alternatively, exploiting the different time scales of nonlinear phenomena may allow their separation in the time domain.

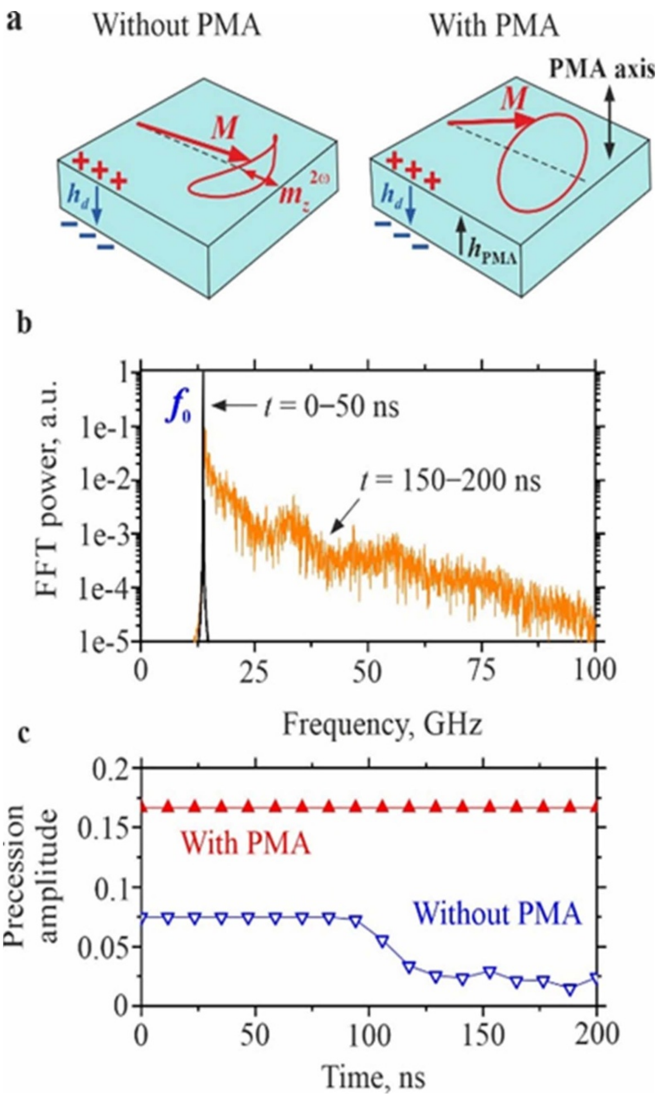

Figure 9. Control of nonlinear mode interactions by PMA. (a) Ellipticity of the magnetization precession in Py is caused by the dipolar anisotropy (left). The PMA reduces the ellipticity. (b) Fourier spectra of magnetization oscillations in Py before (time $t = 0$–50 ns) and after ($t = 150$–200 ns) the onset of nonlinear damping. (c) Temporal evolution of the free precession amplitude starting with a large initial amplitude at time $t = 0$ at $T = 300$ K. Reproduced from [68].

Concluding remarks

Magnonics offers a fertile playground to study and utilize nonlinear phenomena. There are several knobs to adjust the strength and type of these nonlinearities. This fact, combined with the low-power, high-frequency nature of magnons offers great potential for nano-scale signal processing and unconventional computing devices.

Acknowledgements

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6. Computing with magnonics

Qi Wang, Florin Ciubotaru and Dmitri E Nikonov

Status

Due to the rapid development of AI towards a society where everything is intelligent and connected, humanity is now faced with an unaffordable energy consumption for data processing. Novel computing devices are important for the future development of AI, which needs to reduce the energy required for computing to avert an energy shortage [69, 70]. Many magnonic logic devices have been demonstrated. The first spin-wave logic gate was realized in the macroscale by using the configuration of the Mach–Zehnder interferometer [71]. Subsequently, a series of works pushed the size of a single spin-wave logic device down to the nanometer scale. In most of the Boolean-based logic gates, the information is carried by the amplitude of the SWs, which does not fully exploit the wave properties of SWs. In recent years, the phase-encoding spin-wave majority gates [72], spin-wave-based integer factorization [73] and data-based search [74] have been demonstrated, showing the enormous potential of SWs in the field of unconventional computing. More recently, a novel field of inverse design magnonics [38, 60] has been proposed, in which both Boolean and neuromorphic computing building blocks have been demonstrated. This method paves the way for the design of complex magnonic circuits.

Current and future challenges

Nowadays, most spin-wave logic gates operate at wavelengths ranging from hundreds of nanometers to a few micrometers in the dipolar exchange region. In this region, the group velocity of the SWs is around a few kilometers per second, which corresponds to an operating speed of tens of nanoseconds, i.e. a frequency of megahertz. Although the power consumption of magnonic logic gates is lower than that of electronic logic gates based on CMOS technology, the operating frequency is much slower. The most straightforward way to increase the operating frequency of spin-wave logic gates is to increase the group velocity and decrease the device size by using the pure exchange SWs with wavelengths of tens of nanometers. Although various methods have been used to excite short SWs, including magnonic grating couplers, magnetic vortex cores, parametric pumping, geometry-induced wavenumber convertors and spin Hall effect [6], most of these methods have drawbacks such as low excitation efficiency, selective excitation wavelengths, complex spin-wave emissions, or unrealistic integration. Therefore, it remains a challenge to develop an on-chip method for short-wavelength spin-wave excitation with high efficiency (sections 2 and 8).

In addition, an integrated magnonic circuit containing multiple logic gates and suitable for further cascading has not yet been experimentally demonstrated. In general, there are two approaches to the realization of magnonic circuits. One is the development of magnonic circuits using magnetoelectric cells and modern spintronic structures, which act as transducers that convert information between magnons and electrons. This approach suffers from a large number of required conversions from spin to charge and vice versa, which have been identified as a serious bottleneck, especially due to the relatively low conversion efficiencies achieved so far. The second approach is based on the development of all-magnon circuits in which one magnonic gate is directly controlled by the magnons from the output of another magnonic gate without any intermediate conversion to the electrical signal [52]. However, an efficient on-chip spin-wave amplifier to compensate for the damping loss is still under development (section 4). The current challenges on the way to an integrated magnonic circuit are an efficient magnon charge transducer and a magnonic amplifier.

Advances in science and technology to meet challenges

The magnetoelectric effect offers a way to solve the problem of high-power consumption of transducers. The magnetoelectric effect couples voltages to magnetic fields without moving electrons and is therefore predicted to enable highly efficient transducers. These transducers consist of piezoelectric and magnetostrictive multilayers, which are driven by an alternating voltage rather than an electric current and therefore expected to be more energy efficient [25]. Thus, the high frequency pure exchange SWs are expected to be efficiently excited using this transducer with lateral size of a few nanometers. Another completely different approach to decrease energy consumption is to reduce the complexity of the circuit, thus reducing the number of the transducers to achieve the goal of reducing power consumption. Recently, spin-wave-based unconventional computing devices (section 5) dramatically reduce the circuit complexity and circumvent some of the above challenges. Majority gate, spin-wave based integer factorization and data-based search are the typical representative of the application of unconventional computing [73–75]. The phase of SWs plays an important role in all of these applications. Therefore, a full exploration of the wave properties (amplitude, phase, interference, diffraction, etc) of SWs will be key to enable magnonic devices to compete with electronic devices.

In addition, theoretical studies indicate that any wave with nonlinearity can be used to construct neural networks, which has been experimentally confirmed in photonics. SWs have more pronounced intrinsic nonlinearity and shorter wavelengths compared to light. Therefore, SWs are more suitable as a medium for neuromorphic computing. More importantly, the method of inverse-design magnonics has been proposed, which makes it possible to design a complex neural network based on SWs [38, 52, 60]. The inverse design magnonics is a fascinating field of magnonics in which any functionality can be specified first and a feedback-based computational algorithm is used to obtain the device design. It has been used to develop highly efficient RF applications as well as Boolean and neuromorphic computing building blocks [38, 60]. This method will greatly reduce the effort of designing novel spin-wave devices and then enrich the library of spin-wave devices.

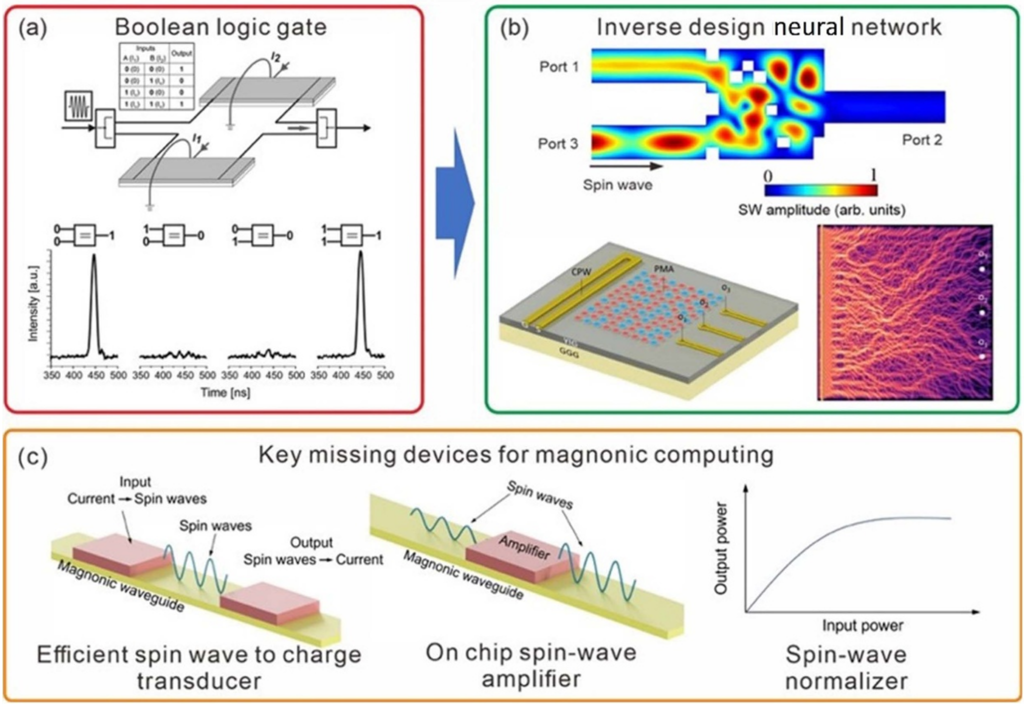

Figure 10. Magnonic computing from Boolean logic gates to inverse-design unconventional computing. Adapted from [71], with the permission of AIP Publishing. Adapted from [38] and [60].

Concluding remarks

In general, SWs differ from other technologies in that they have wavelengths ranging from micrometers down to atomic scales, exhibit a variety of pronounced nonlinear phenomena and promise lower-energy computing without charge flow. In conventional Boolean logic systems, magnonic computing faces many challenges that are difficult to solve in the short term. Recently, it has been shown that wave-based computing offers tremendous potential for the application of unconventional computing techniques compared to electronic logic gates based on CMOS technology. Figure 10 shows the evolution of magnonic computing from Boolean logic gates to inverse-designed unconventional computing and the lower orange box lists three of the most important devices for realizing of magnonic computing. In addition, many novel physical effects have recently been found in the interaction of magnons and other quasi/particles (phonons, photons, etc). Further research on these interaction effects (part II) can in turn provide new ideas for magnonic computing.

Acknowledgements

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7. 3D magnonics

Ping Che, Riccardo Hertel and Teruo Ono

Status

Three-dimensional (3D) magnonics has recently received significant attention as it opens a path towards miniaturized magnonic circuits with higher integration density on a chip. Via 3D magnonic waveguides and functional elements, charge-less information transmission and data processing become possible in all three dimensions. However, the interplay between the dipolar-exchange magnons and the geometry of either 3D artificial structures or natural 3D spin systems such as a tubular magnetic skyrmion lattice still pose fundamental physical questions. Related theoretical and experimental investigations will be key to engineer and functionalize topological properties of magnons such as unidirectional propagation characteristics and immunity against back scattering in three dimensions. Research on these topics may open new pathways towards dense and complex 3D networks with controlled nonreciprocity.

By means of nanofabrication techniques such as two-photon lithography followed by thin-film deposition (figure 11) and direct writing by FEBID (focused electron beam induced deposition) nanostructured 3D magnetic elements of almost arbitrary shape have been generated [76]. Amongst them, there are prototypical 3D structures such as ferromagnetic buckyballs. They stimulated advancements in simulating spin dynamics in 3D (figures 11(b) and (c)). From conventional top-down nanopatterning along lateral directions it is already known that a magnetic thin-film-element's shape significantly impacts its properties. Accordingly, 3D magnetic nanopatterning is expected to open up vast unexplored opportunities of tailoring magnetic properties through the careful design of the object shape into the third dimension. So far, studies on artificially structured 3D magnetic nano-objects have mostly focused on the impact of surface curvature on magnetic textures, like vortex-type DWs in nanotubes and their protection against Walker breakdown [77]. Recent progress in 3D nanopatterning, magnetic imaging and micromagnetic simulations now opens promising perspectives for 3D magnonic applications, in particular in the case of interconnected networks of nanowires and nanotubes which operate as waveguides with curvature-engineered dynamics.

Topological solitons, such as tubular magnetic skyrmions, form natural 3D spin structures down to the nanoscale thanks to the competition between, e.g. DMI, exchange interaction, magnetic anisotropies and field. Self-organized structures are good candidates for investigating 3D magnonics without challenging nanofabrication (figure 11(d)). The topology of the soliton textures offers a robust protection and stable 3D magnonic band structures which provide peculiar properties. The solitons imprint their topology on the magnons as a novel engineering degree of freedom to manipulate the propagation properties. Additionally, magnons display nonreciprocity when propagating along the skyrmion tubes suggesting them to be information transmission lines [81]. Micromagnetic simulations further reveal new individual solitons like magnetic hopfions and torons (figure 11(e)), considered as twisted or closed skyrmion tubes can host localized SWs in their textures and channel magnons [82].

Current and future challenges

Despite important progress in 3D nanomagnetics, SW propagation in 3D patterned magnetic materials remains so far scarce. Major challenges in this domain include the efficient generation and readout of SWs in such networks, control over the SW propagation characteristics and the multiplexing and channeling of waves in a reconfigurable fashion. Moreover, the accurate modeling of such structures—an essential prerequisite for understanding and interpreting magnonic phenomena in 3D systems—requires efficient numerical algorithms different from those traditionally applied to study thin-film or bulk magnetism. Because of their ability to model objects with complex geometric shapes, low volume occupancy and large size, micromagnetic finite-element-based algorithms with graphical-processor acceleration represent a promising avenue [83].

Current excitation and detection methods of magnons in natural 3D spin textures mostly utilize inductive coupling in the near field of a planar microwave antenna and all-electrical spin-wave spectroscopy at gigahertz frequencies as in [81]. The control of the magnon wavevector was realized by the lateral dimensions of antennas to which bulk chiral magnets were integrated. Technical difficulties of integrating impedance-matched nanoscale antennas limit however the wavelength of the magnons such that the direct observation of higher order minibands has not yet been achieved. New excitation mechanisms and detection techniques are required to exploit fully the magnon band structure across the first Brillouin zone (BZ) in integrated circuits. Tailoring the textures as magnon waveguides to realize neural networks and wave-logic circuits in 3D is still lacking, most likely due to the complexity of targeted creation and stabilization of the topological solitons in high-frequency experiments.

In 3D spintronics, a three-dimensional magnetic memory, the so-called race-track memory, has been proposed which aims at exploiting high-speed DW movement driven by applied electrical currents. Later, a 3D magnetic memory using artificial ferromagnetic materials, shown in the figure 12(a) [84] was proposed. This 3D spintronics scheme avoids the movement of DWs and concomitant emission of SWs in an uncontrolled manner. Each column has an alternating overlapping structure of a recording layer (green), which has large magnetic anisotropy and is responsible for bit recording and an intermediate layer (yellow), which has no magnetic anisotropy and acts as an artificial DW layer. For writing, a current is applied to the bottom electrode to invert the magnetization direction of layer 1 by SOT. A DW is then generated in layer3. The current is then passed through the column to shift this DW upwards to any DW layer. The next information is then written by inverting the magnetization direction of layer1 by

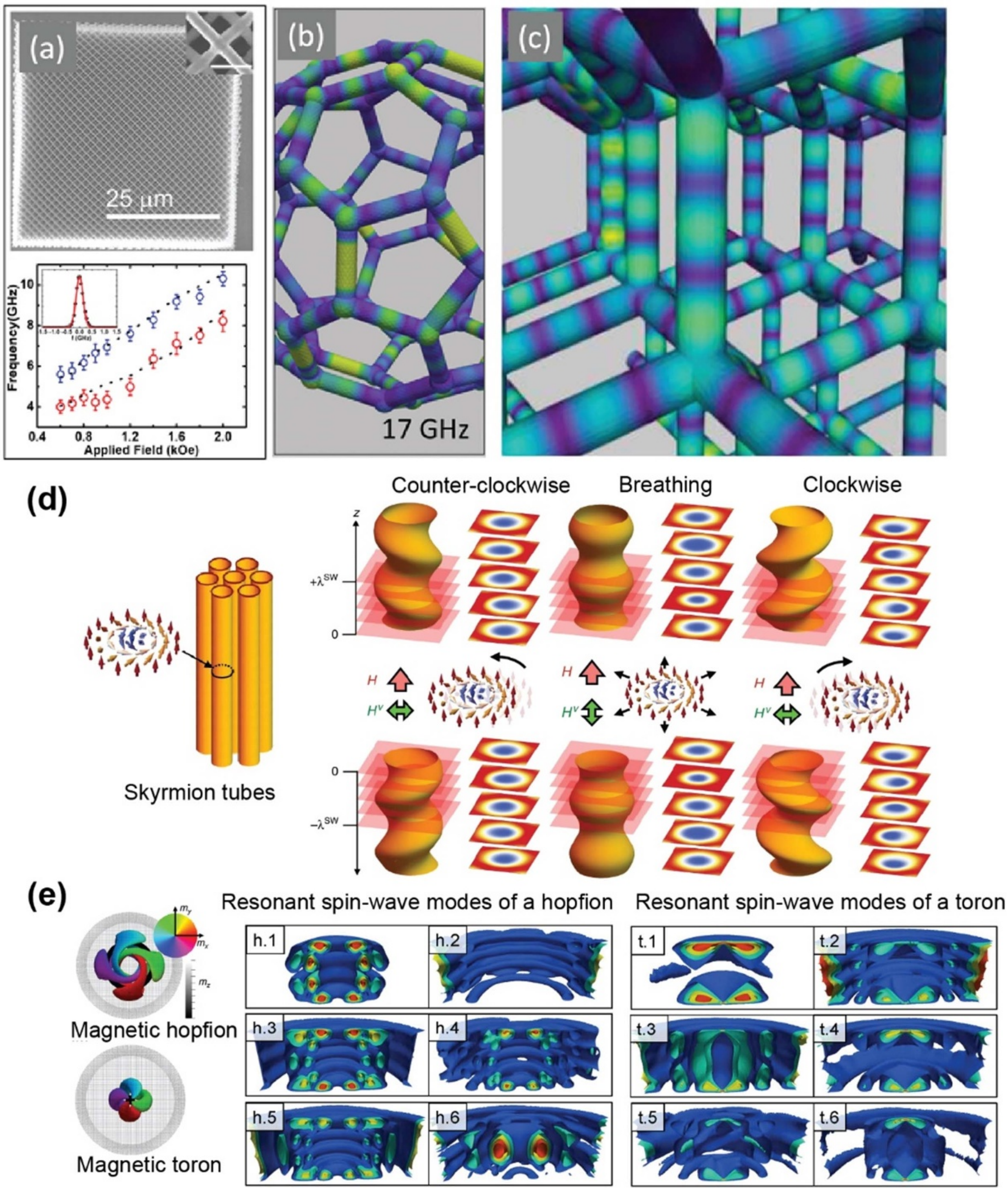

Figure 11. (a) Top: Experimental realization of a 3D array of interconnected nanowire array in the form of a diamond-bond lattice. Bottom: Brillouin-Light Scattering measurement of spin wave frequencies in the lattice. Reproduced from [78] with permission from ACS. Further permission related to the material excerpted should be directed to the ACS. (b) Micromagnetic simulation of magnetic high-frequency oscillations in a buckyball geometry. Reproduced from [79]. CC BY 4.0 and (c) in a diamond-type 3D array. Reproduced from [80]. CC BY 4.0. (d) Schematic illustration of the skyrmion tubes in chiral magnet Cu_2OSeO_3 and the counter-clockwise, breathing and clockwise excitation modes on skyrmion strings. Reproduced from [81]. CC BY 4.0. (e) Magnetic hopfion spin textures with linked magnetization isosurfaces, magnetic toron spin textures with unlinked isosurfaces and their localization of the resonant spin-wave modes (a half-disk cross section cut). The marks from h.1 to h.6 (t.1 to t.6) indicate the six resonant modes of a magnetic hopfion (toron, respectively) from low frequency to high frequency. Reprinted figure with permission from [82], Copyright (2021) by the American Physical Society.

applying a current to the lower electrode. By repeating this operation, any bit sequence can be stored in the column. Reading out can be done in batches by reading. Future 3D magnonic circuits might also contain nanocolumnar architectures consisting of engineered layer sequences. In this case, the flow of angular momentum by propagating magnons can be used for magnetic bit writing via magnon-induced reversal and DW movement [85, 86]. The proposed data-writing process using propagating magnons is sketched in figure 12(b). Here, the heavy metal wire may be substituted by a magnetic metal with two separate antennas for magnon excitation. Magnons at f_1 switch the pinning layer (shown in blue) and generate the DWs and magnons at f_2 drive the DW motion in the nanocolumnar cell. The variations in magnon amplitudes and phases can be used to readout information. Thereby, the

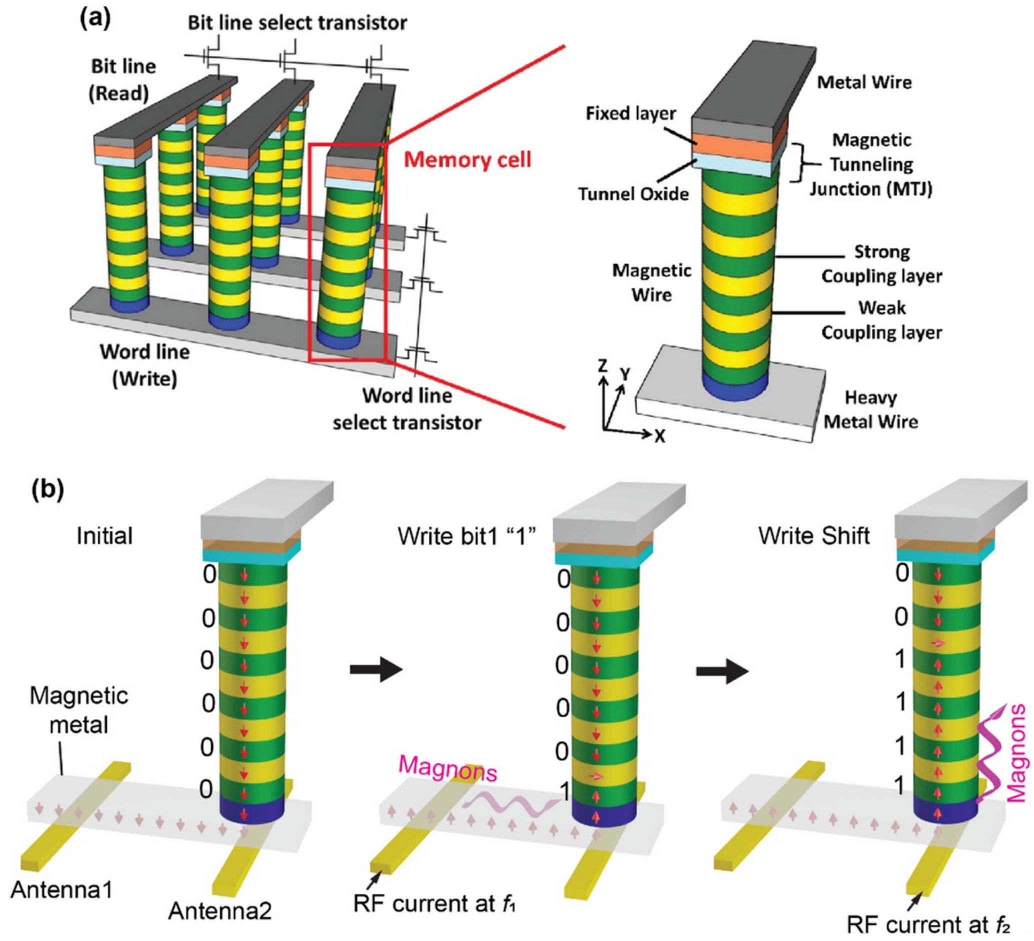

Figure 12. (a) Illustration of vertical DW motion memory with artificial ferromagnets. Left panel: memory array with perpendicularly arranged word line and bit line. The columns inside array are the multi-bit storage memory cells constructed with artificial ferromagnets. Right panel: detailed structure of one column. Reproduced from [84]. CC BY 4.0. (b) Sketch of the proposed data-writing scheme using propagating spin waves in the memory device. Spin waves are excited in the magnetic metal at f_1 to reverse the magnetization in the pinning layer with perpendicular magnetic anisotropy (blue layer) and form the DW in the cell. Spin waves at f_2 propagate through the cell and move the DW to achieve the write shift motion.

distributed generation of Joule heating in 3D spintronics will be avoided. Combined with the developed 3D patterning and magnon detection techniques, the experimental exploration of magnon-switching 3D magnetic memory bears timely importance for both magnonics and spintronics research.

Advances in science and technology to meet challenges

Scientific advances on the topic of magnonics in 3D nanostructured materials have recently been achieved on the experimental and theoretical side. On the one hand, pioneering BLS experiments on a diamond-bond lattice geometry (figure 11(a)) demonstrated the occurrence of coherent SWs in a 3D network of crescent-shaped nanowires [79]. On the other hand, micromagnetic simulations have been used to investigate the high-frequency dynamics in various systems of interconnected magnetic nanowires [80, 84]. The studies put into evidence a sensitive dependence of the high-frequency dynamics on the magnetic configuration at the vertex points at which the nanowires intersect. This configurational sensitivity, known from artificial spin-ice lattices, paves the way towards reprogrammable 3D magnonic devices in which SW propagation and, more generally, the dynamic magnetization response to a high-frequency excitation can be controlled by modifying the array's static magnetic structure.

The laminography technique based on the x-ray magnetic circular dichroism, combines rotational control of the samples and a graphics processing unit that implements the gradient-based arbitrary projection magnetic reconstruction algorithm to reconstruct spin structures inside bulk materials. Recent advancements on the time-resolved magnetic laminography, employing a pump-probe experimental setup, has visualized the magnetization dynamic of three-dimensional magnetic structures in GdCo microdiscs [87]. Further advancements of this technique towards higher spatial and time resolution, will improve the imaging capabilities for studying high-wavevector magnons in individual nanoscale magnetic solitons.

Concluding remarks

The study of high-frequency oscillations and propagating SWs in artificially patterned 3D magnetic materials is still in its early stages, but promising experimental and simulation results indicate exciting possibilities for high-density magnonic applications. Further studies may lead to an expansion of the research on this topic towards 3D magnonic metamaterials, i.e. artificially patterned materials whose magnonic properties could be fine-tuned by varying the geometric parameters of their microstructure. The topological magnetic solitons offer natural hosts for 3D magnonics research. Thanks to the topology of the solitons, novel magnon band structures and propagation properties were reported. Advancement in both the geometry control in artificially induced magnetic solitons in 3D nanoarchitectures and detection techniques would lead to deeper understanding of the control of magnons in soliton systems.

Acknowledgements

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8. Ultrafast magnonics

Dmytro Afanasiev, Johan Mentink and Theo Rasing

Status

Ultrafast magnonics refers to the use of ultrashort pulses of light to launch and to control high-frequency THz coherent spin-waves (magnons) in future high-speed and energy-efficient nanoscale magnonic devices, see figure 13. To excite coherent spin-waves (SWs), it is necessary to perturb the magnetic order both quickly and locally, so that the spectrum of the perturbation covers the frequency ω and wavevector k of the wave to be excited. Traditionally, excitation of coherent SWs is achieved using a direct coupling of the radio-frequency (RF) magnetic field component via subwavelength size microstrip antennas or coplanar waveguides to magnetically ordered spins. This inductive method however is limited to tens of GHz and thus is not applicable to access SWs in the high-frequency exchange-driven THz regime of ferro-, ferri- and antiferromagnets. One way to resolve this problem is to replace the traditional RF magnetic field with a time-varied field of another nature, e.g. an electric field, a strain field, or any other field that is strongly coupled to the magnetic order, such as an effective optomagnetic field created by ultrashort optical pulses.

Femtosecond (fs) pulses of light are the shortest (Δt < 100 fs) and thus the most broadband stimuli ($\Delta t^{-1} > 10$ THz) in experimental condensed matter physics. These pulses have convincingly demonstrated their unique ability to excite ultrafast coherent spin dynamics in practically all classes of magnetically ordered materials [88]. Selectively acting on microscopic magnetic interactions, such as the exchange interaction or magnetic anisotropy, the optical excitation acts akin to a pulse of ultrashort effective optomagnetic field. Although strongly material specific, optomagnetic fields can be made as large as 1 T. Such fields were shown to be large enough to drive spin precession with an amplitude sufficient to switch the orientation of the magnetization. Ultrashort optical pulses have not only a unique ability to excite and control the phase of coherent spin precession but, once performed in a so-called pump-probe scheme, they also allow to track the spin dynamics on the most demanding *fs* timescale where traditional electric methods fail to operate.

Current and future challenges

Although optical excitation allows broadband excitation of coherent SWs across nearly the entire BZ, the large mismatch between the photon and magnon momentum (resulting from a group velocity difference of more than five orders of magnitude), leads to the excitation and detection of only low wavenumber ($k \simeq 0$) quasi-uniform magnons, see inset figure 13. These low frequency modes typically do not support propagation, crucial for magnonics applications. Consequently, optical excitation and detection of propagating short-wavelength coherent magnons is non-trivial and represents a major challenge toward the practical integration of opto-magnetic methods in magnonics.

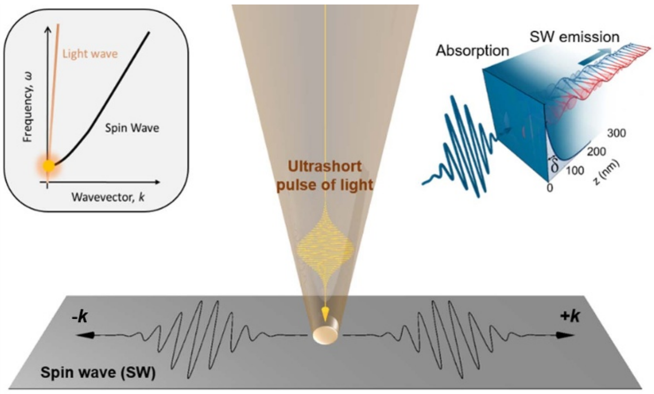

Figure 13. Ultrafast light-driven magnonics: excitations of a pair of counterpropagating ($\pm k$) coherent propagating spin-waves with the help of an ultrashort ($\Delta t < 100$ fs) pulse of light. The left-side inset shows schematic dispersions of spin and light waves. A large momentum mismatch is seen. The right-side inset shows excitation of a nanoscale packet of coherent SWs in an antiferromagnet via absorption of light, recently reported in [26].

The smallest accessible wavelength of the optically excited SWs is defined by the size of the illuminated volume and is thus diffraction limited. Subwavelength localization of opto-magnetic fields can be achieved by manipulating the penetration depth of light, thereby surpassing the diffraction limit, see right-side inset in figure 13. Indeed, the above-bandgap absorption of light in antiferromagnetic orthoferrite has been shown to confine the optomagnetic field below 50 nm, thus creating a highly inhomogeneous profile of the spin excitation and enabling emission of a broadband wavepacket of coherent THz SWs [26]. Although excitation of the SWs with wavelengths down to 50 nm is also anticipated, their detection using visible optics is challenging. The shortest-wavelength coherent magnons detected optically have wavelengths of about 125 nm and are observed using the magneto-optical Kerr effect. Moreover, the existing magneto-optical methods often operate in reciprocal space and thus are hard to apply to observe fine structure and real space propagation of the SW packets.

An appealing alternative for the generation of high-frequency SWs is based on the concomitant excitation of a pair of counterpropagating magnons. The total momentum of the pair matches that of photons such that SWs across the whole BZ will be excited. Several experiments reported such coherent excitation in various antiferromagnets [89], where it is widely known as the two-magnon (2M) mode. Whether the 2M mode can support propagation and is thus suitable for magnonics is yet a highly debated question. Indeed, excitation of the 2M-mode is dominated by pairs of magnons at the edges of the BZ ($k = \pm k_{\mathrm{B}}$), where their group velocity approaches zero. Recent theoretical work, however, shows that quantum effects can enhance the propagation velocity of the coherent 2M-mode even above the highest possible SW velocity [90].

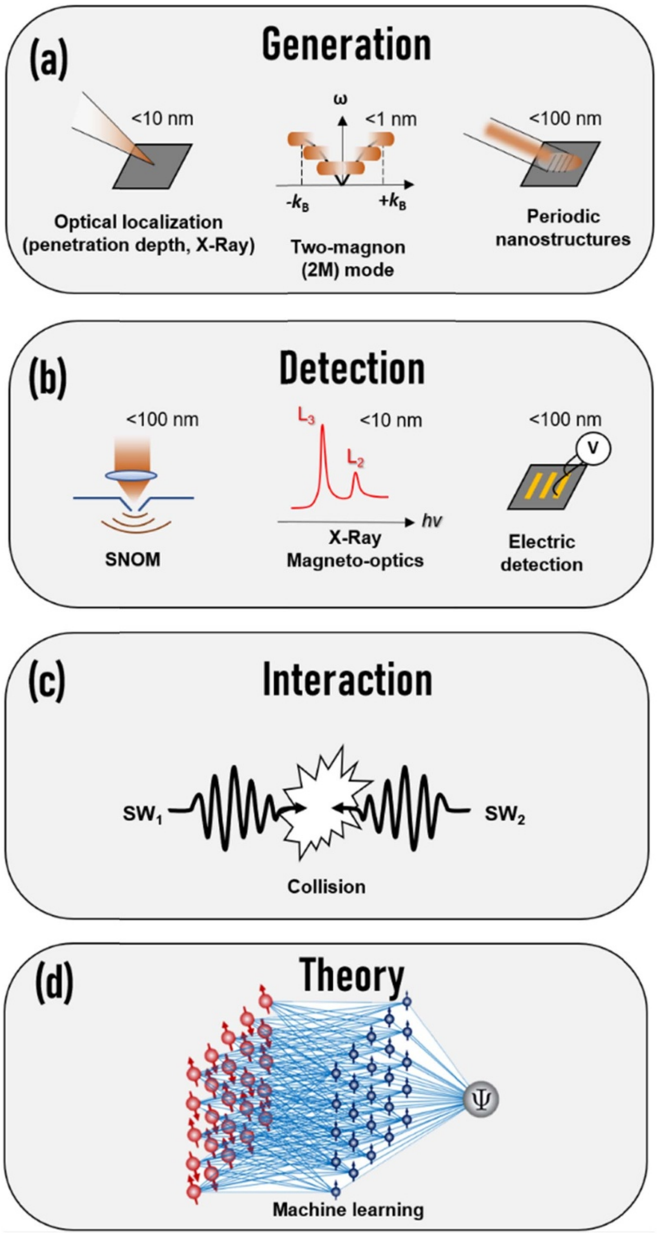

Figure 14. Topics of future research to develop ultrafast light-driven nanomagnonics. (a) Optical generation of nanoscale wavelength magnons. (b) Various magnon detection methods with potential nanoscale resolution. (c) Spin-wave collision experiments to study the nonlinear regime of their interaction and scattering mechanisms. (d) Machine learning techniques to predict and explain quantum effects in ultrafast short-wavelength magnonics.

Advances in science and technology to meet the challenges

Figure 14 summarizes the various topics of further research to develop the field of ultrafast light-driven nanomagnonics and exploit its fundamental and practical merits.

One obvious strategy to address the challenges of generating short wavelength magnons is to shorten the central wavelength of the fs pulses, see figure 14(a). Recent advances in x-ray free-electron lasers have enabled generation of ultrashort and intense hard x-ray pulses with wavelengths down to nearly 1 nm. Particularly appealing for ultrafast magnonics is to employ the hard x-ray transient grating spectroscopy technique, which recently has been successfully used for the generation and detection of submicron-wavelength coherent phonons [91]. Reducing the duration Δt of light pulses enables the excitation of ever higher frequency 2M-modes, the frequency of which scales with the strength of the exchange interaction and thus broadens the applicability of optical driving magnons at the edges of the BZ to various magnetic systems. The dramatic progress in the thriving field of femtosecond and attosecond optics can easily address this issue. Another strategy to push ultrafast magnonics towards the nanoscale is to employ nanopatterning of periodic structures, enabling the formation of a (quasi-)periodic perturbation pattern. The nanostructures effectively break the translational invariance that leads to momentum conservation between the photons and the short-wavelength SWs and thus do not require a highly demanding localization of the optomagnetic field. Various grating couplers were shown to be very effective for sub-diffraction coupling of the free-space optical fields into media [92]. Extending this approach to effective optomagnetic laser fields will enable generation of SWs with the wavelength limited only by the intrinsic resolution of the nanopatterning technique, thus offering ultrafast coherent control of magnons at the nanoscale. In the case of extreme ultraviolet lithography this limit can be set down to less than 10 nm.

To improve the spatial resolution necessary to detect short wavelength SWs, time-resolved near-field imaging techniques offer opportunities, see figure 14(b). Magneto-optical scanning near-field optical microscopy has recently shown a potential for sub-100 nm spatial and sub-100 fs temporal resolutions but has not been applied to SWs yet [93]. Another possibility is to use a THz near-field apertureless microscope which can directly probe nanoscale electric or magnetic THz fields associated with SWs [94]. In the most general case this requires a special design of the metallic tips to sense magnetic rather than electric near-fields—a problem which is not addressed up to now. To detect SWs of even shorter wavelength, x-ray circular and linear dichroism at the L edges of magnetic ions, can be used. Moreover, recent advances in time-resolved resonant inelastic x-ray Scattering can greatly facilitate tracking the spatial dynamics of 2M-modes but yet require a better temporal resolution [95]. To successfully bridge the optomagnetic excitation with existing magnonic logic, it is crucial to realize an electronic readout of the optically excited SWs. In both ferromagnets and antiferromagnets, propagating SWs can be associated with spin currents which can be measured electrically, e.g. via inverse spin Hall effect or tunnel magnetoresistance. Time-resolved on-chip experiments with fs optical excitation and electronic readout using an Auston switch can be employed to realize time-resolved readout of SW propagation.

Finally, collision experiments in which pairs of optically generated THz SWs are moving toward each other hold a promise to reveal the conditions at which SW interactions go beyond a trivial superposition and thus enter the nonlinear regime crucial for magnon based computing, see figure 14(c). Moreover, collision experiments can reveal fundamental processes governing scattering mechanisms of THz SWs, via monitoring the redistribution of their energy and momentum directly in the time-domain.

This approach is particular promising in a joint endeavor with theory to gain understanding of the quantum aspects, which inevitably come into play but have largely unknown physical consequences. New methods inspired from machine learning appear very effective [90] and may be key to predict experimental fingerprints and develop more intuitive models of genuine quantum magnonics at the edge of the BZ, see figure 14(d).

Concluding remarks

Light-driven ultrafast magnonics is an emerging field with a high potential to push traditional magnonics into the high-frequency THz domain. For a long time being limited to uniform spin precessions, fs optical excitation has recently revealed its potential to drive broadband and highly nonuniform THz SWs. While optomagnetically driven SWs continue to present practical challenges, the solutions to these obstacles are expected to be similar to those already discovered in traditional magnetic-field driven magnonics and can likely be addressed through advances in time-resolved ultrafast techniques and nanopatterning methods. The discovery of a magnetic system that can combine high efficiency of optomagnetic SW excitation with a long lifetime and thus low damping is highly desirable, as it can function as an analogue of the much-praised yttrium iron garnet films in traditional magnonics. Rare-earth perovskite orthoferrites ($RFeO_3$, with R representing a rare-earth element) showing very strong optomagnetic effects can serve the purpose [96].

Acknowledgements

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9. Hybrid quantum magnonics

Burkard Hillebrands, Silvia Viola Kusminskiy and Wei Zhang

Status

The common underlying theme of hybrid quantum magnonics [97] is the interference of wave functions. This can be set up in the purely classical domain or based on true quantum principles. The term 'hybrid' indicates that magnonic degrees of freedom are interfaced with other excitations, such as photons, phonons, plasmons, etc. In this way, the benefits of specific properties of each subsystem can be exploited and combined. Key to this promising potential lies the highly tunable excitation of magnons and versatile coupling capability to other dynamic media and platforms. Hybrid quantum magnonics comes in three major flavors: (i) true quantum systems, usually operating at very low temperatures and where, as a rule, a cavity setup is needed in order to boost coupling strengths. (ii) Quantized wave systems, still in the classical domain, can mimic many quantum functionalities, often called quantum-classical analogy systems. (iii) In the continuous-mode regime, nonlinear properties enabling multi-magnon scattering processes can lead to new phenomena, such as magnon Bose–Einstein condensation. Often quantum mechanical phenomena have a counterpart in this classical regime, although this does not capture the full phenomenology.

The perspective of incorporating magnons as information carriers in quantum hybrid systems was triggered by the demonstration of coherent coupling between magnons and a superconducting qubit, mediated by a microwave cavity [98]. Strong coherent coupling between magnons and microwave photons has been reported in several platforms, whereas coherent coupling to optical photons has been demonstrated in YIG resonators [97], an important step towards magnon-based quantum transduction. In tri-partite hybrid systems coupling coherently magnons, phonons and microwave photons, control of the phonon frequency and dissipation via magnon-induced dynamical effects has been reported (see figure 16(b)), a prerequisite for applications such as quantum thermometry [99].

Magnon interference effects are widely used, see e.g. [97] and many interference-based devices have been proposed and some realized. A prototype example of a quantum-classical analogy device is the STImulated Raman Adiabatic Passage device [100], as shown in figure 15. Here, the concept of coupling between reservoirs and dark states has been transferred to magnon-photon degrees of freedom, when discrete magnon modes are coherently coupled by means of electromagnetic fields outside the magnetic waveguides. In this way, ideas from quantum mechanical systems migrate to classical systems, allowing new functionalities that work under ambient conditions. Along this line, the magnonic qubit calculus has recently been demonstrated numerically at room temperature [101]. Here, a qubit is represented by the superposition of two magnon Bose–Einstein condensates. Effects such as the magnon Josephson effect and information transport by magnon supercurrents have been realized [102].

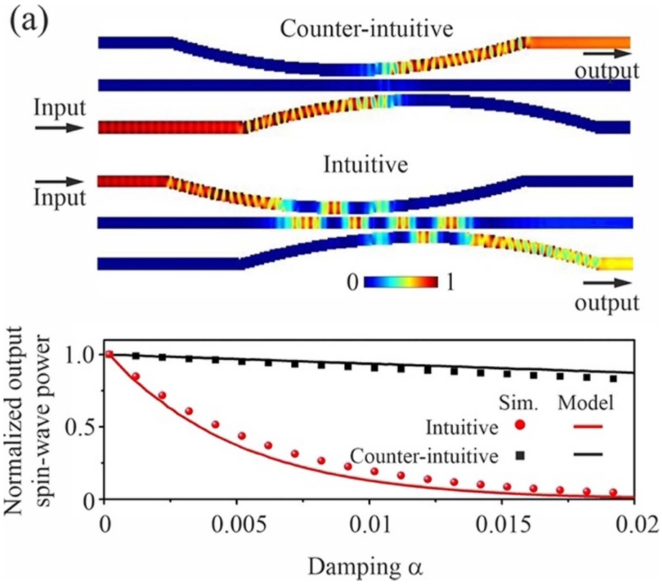

Figure 15. Magnonic STIRAP device as an example of a quantum-classical analogy device. The functionality is based on the electromagnetic coupling between three magnon waveguides, which locally is enhanced pairwise by a near-proximity region. Top panel: spin-wave intensity distributions for the so-called counter-intuitive coupling scheme, where the proximity region between the input waveguide and the center waveguide is located after the proximity region between the output and the central waveguide. Middle panel: intuitive coupling scheme. Bottom panel: output intensity as a function of the Gilbert damping of the center waveguide, demonstrating the pronounced insensitivity of the coupling on the damping in the center, so-called dark-state, waveguide in the counter-intuitive scheme. Adapted from [100]. CC BY 4.0.

Current and future challenges

Hybrid quantum magnonics has the potential to provide solutions to major challenges in information processing and sensing. Of particular advantage are potentially the wave properties with wavelengths down to atomic distances, the nonlinearity of the magnonic (sub-)systems, the (ultra-)low energy consumption, facile tunability with electronic and spintronic toolkits and the realization of long propagation lengths when combined with e.g. photonic or phononic degrees of freedom. Specific eigenstates of the system, such as Bose–Einstein condensates, allow new all-magnonic computational schemes. For example, qubit computation at room temperature has been demonstrated in a quantum-classical approach, building on the fact that qubit computation algorithms exist that do not use quantum entanglement and thus can be realized at room temperature, still with polynomial scaling [74, 97]. Many device proposals have been made and it is currently a key challenge to realize them and demonstrate their practical applicability.

The demonstration of coherent coupling of magnons both to microwave and optical photons shows promise for quantum frequency transduction. One figure of merit for operations in the quantum realm is the cooperativity, which is a measure of the strength of the magnon-photon coupling compared to the losses in both channels. A pressing challenge is boosting cooperativity values in order to achieve, among other

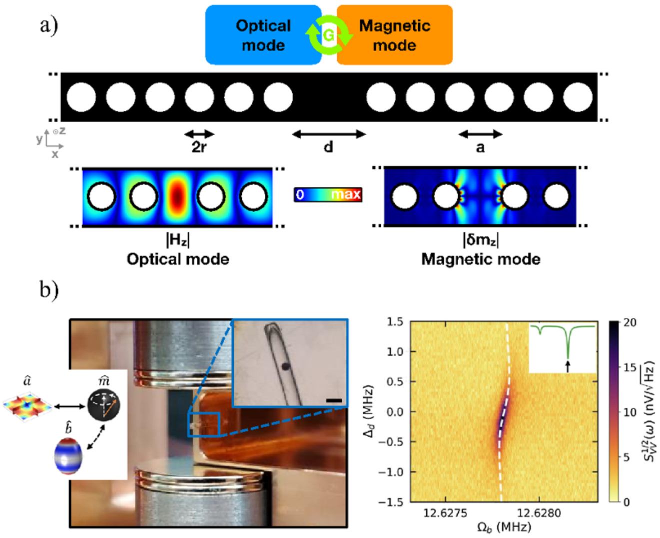

Figure 16. (a) Example for the design of a one-dimensional opto-magnonic crystal based on a thin magnetic dielectric such as Yttrium Iron Garnet. The array of holes with a defect in the middle (the absence of a hole) serves as a Bragg mirror both for optical and magnon modes, which can be co-localized at the defect. The small mode volumes combined with low losses can give rise to enhanced cooperativities with respect to the state of the art. Adapted from [103]. CC BY 4.0. (b) (left) Prototype experiment to demonstrate the coupling in a cavity magnon-mechanical system. A yttrium-iron-garnet sphere is placed in a microwave cavity. The Kittel mode is resonantly coupled to the cavity and off-resonantly coupled to a mechanical mode of the sphere. (right) By tuning the system to operate in the triple resonance condition, where the phonon mode is in resonance with the transition between the upper and lower polariton modes, dynamical backaction effects such as the magnon spring effect can be measured and controlled. Adapted from [99]. CC BY 4.0.

applications, a good transduction efficiency. This is particularly challenging in the optical regime due to intrinsically low coupling (relying on the Verdet constant of the material) and difficult mode matching at the microscale. To this end, to predict an optimal geometry is also challenging from a theory perspective. Proposals [103] to overcome these issues include the realization of photonic crystals based on magnetic dielectrics (see figure 16(a)), or harnessing the coupling to phonons, or leveraging the magnon's self-hybridizations in complex heterostructures [104].

Another prominent challenge is to push 'hybridized magnons' toward an all-on-chip platform, which is key to circuit application and device integration. However, this poses the dual challenge of achieving large coupling to microwaves with a small magnetic volume and having planar geometries with low resistive loss (quality factor). One direction is to use superconducting coplanar resonators, which have both chip-compatibility and high-quality factors. Another approach lies in the material engineering of the magnonic counterpart, such as its dissipation rate. In addition, the development of tri-partite interactions may allow external pumping and driving of the system via complementary, intermediate excitations, thus realizing new degrees of coupling strength and controllability. Finally, these efforts will be pursued in parallel with concurrent developments in on-chip photonic circuity and phonon device architectures.

While the state-of-the-art technology is ripe for the realization of true quantum magnonic states [105], a challenging endeavor in view of possible competitive applications involving quantum state transfer and readout is to enhance the current magnonic lifetimes. This may require the development of new materials and/or structures beyond those commonly used in classical magnonics and to design platform-specific quantum protocols. A theory of magnon quantum transport also needs to be developed.

Advances in science and technology to meet challenges

The technological development of hybrid quantum magnonics is still in its infancy. The field requires an interdisciplinary approach combining new experimental techniques, materials science, quantum engineering and theory methods ranging from quantum information and quantum optics to condensed matter. The development of powerful computational methods and capabilities allow to explore the design of hybrid magnonic devices at the microscale and to describe their quantum dynamics. New fabrication techniques will enable their implementation. Many promising device concepts have been proposed—the challenge now is to demonstrate their practical applicability.

One major goal of hybrid magnonics is to encode, transfer and process information with magnons and magnon circuits. With many device proposals based on magnon interference and phase control, coherent generation and manipulation of magnons are crucial. Demonstrators of magnon logic circuits such as the majority gate, spin-wave amplification such as the magnon transistor, magnonic neurons, magnonic memory, magnonic transducer and more have been reported. A coherent magnonic network can be further augmented by signal transfers via Rabi-like oscillations between different magnon modes with preserved phase correlation and the states of magnon propagation can be determined by the gate control, a protocol that find its analogy in entangled qubit networks. By utilizing the dissipative coupling, it is also possible to selectively converge a hybrid system to a specific ground state. On the way to a complete magnonic circuit board, technologies for long-distance information transport ('backbone communication') as well as for input/output functionalities have to be developed, e.g. using spintronic-based rectifications, such as spin Hall effect, Rashba effect and magnetoresistance. If we consider possible applications in the field of neural networks, given that each neuron is connected to other neurons by about 10 000 synapses, a corresponding magnonic network to implement this will most likely require 3D geometries.

It is not yet clear to what extent non-classical, quantum mechanical functionalities will be used in these future developments. Promising work on this challenge has been reported, e.g. by the demonstration of a single-shot single magnon detector, which opens the door to realizing 'quantum optics' with magnons [98]. Very recently, the deterministic generation of quantum magnon states such as a Fock state has been demonstrated [105]. Both of these developments use a superconducting qubit in order to enable detection or state preparation. What seems to be clear is that, in order to enable applications in the quantum regime, leveraging both on the versatility of magnonic systems and their compatibility with hybrid quantum systems will be required.

Concluding remarks

Hybrid quantum magnonics has a surprisingly large potential for future applications in computing and sensing. Strong efforts are now needed to overcome the challenges of translating the concepts into practical devices and developing the corresponding technologies.

Acknowledgements

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10. Quantum sensing

Chunhui Rita Du, Aurore Finco and Toeno van der Sar

Status

Quantum sensing has become one of the pillars of quantum science and technology. It relies on the large sensitivity of quantum systems to their environment to probe physical quantities. Optically-active defect spins are excellent magnetic-field sensors, with a sensitivity and spatial resolution that has enabled applications in physics, biology, geology and chemistry. The most popular is the NV center in diamond, which has now been used for ∼15 years to study nanoscale magnetism [106]. In addition, the spin of the boron-vacancy (V_B^-) defect in hexagonal boron nitride (h-BN) has recently emerged as a sensor [107], with the asset of an easy integration in vdW heterostructures. Both sensor spins are increasingly being used for magnonics research.

SWs are collective, wave-like modes of the spins in magnetic materials, with quasi-particle excitations called magnons. Their intrinsically strong interactions give rise to a rich many-body physics that could unlock new regimes of spin transport. Imaging SWs with electronic sensor spins is a new technique, with the unique aspect that it detects the SWs by their microwave magnetic stray fields. The sensor spins can be brought within nanometer proximity to the magnetic material of interest, where the evanescent magnetic fields produced by the SWs can be large. This enables the magnetic imaging of both coherent SWs (e.g. excited through microwave driving) and thermal or other incoherent magnon mixtures—even in very thin magnets. A similar approach could be followed with another type of quantum sensors: nanoscale SQUIDs, but no SW related experiments have been reported so far.

The stray-field detection of SWs relies on the spin-dependent optical properties of the sensor spins: both the NV and the V_B^- defects (figures 17(a) and (b)) have an $S = 1$ electron spin with a spin-dependent photoluminescence. Under laser illumination, this spin is continuously pumped into its $m_s = 0$ state while emitting a bright photoluminescence. A resonant microwave signal, originating e.g. from a coherently excited SW, can drive spin rotations between the $m_s = 0$ and ± 1 states (figure 17(c)). This is detected through a reduced photoluminescence (figure 17(d)). The strength of the spin-wave stray field directly follows from the sensor spin's rotation rate. Similarly, the strength of magnetic-field fluctuations generated by incoherent magnon mixtures (e.g. thermal magnons) follows from the spin relaxation rate.

Current and future challenges

For characterizing magnonic systems via spin-based microwave magnetometry, two situations can be distinguished. In the first, the sensor-spin ESR frequency lies within the spin-wave energy band, causing resonant spin-wave modes to dominate the sensor-spin response [108]. Sweeping the ESR frequency relative to the spin-wave band using a magnetic bias field enables imaging low-frequency spin-wave modes such as those in YIG (figures 18(a) and (b)) or DWs [109, 110]. A challenge for the scheme is its limitation to spin-wave frequencies in the low-gigahertz regime. However, the magnetic nature of the imaging enables probing SWs at buried interfaces, for instance to study spin-wave interaction with electric currents or spin excitations in metals. Future challenges include harnessing this capability to study e.g. gate-control of spin-wave transport or magnetization auto-oscillations, or to shed light on so-called magnon 'condensates' that could arise under spin pumping by spin-Hall electrodes.

In the second situation, the sensor-spin frequency lies below the spin-wave band. This situation is more typical as crystal or shape anisotropies of typical magnets quickly pushes their magnon spectrum to the tens of gigahertz. In this situation, the sensor spins primarily pick-up spin-wave mixing processes that lead to longitudinal magnetization dynamics resonant with their ESR frequency [111, 112]. Even in the absence of microwave driving, the thermal spin-wave mixing products provide a probe of the magnon-band occupation, with the proximity of the sensor spins enabling probing weak magnets such as canted antiferromagnets [113]. More generally, the sensitivity to longitudinal magnetization fluctuations has been proposed as a probe for characterizing the nature of magnon transport [111], where diffusive, ballistic, or hydrodynamic transport should lead to a characteristic power-law decay of the magnetic stray fields. Finally, mixing between *driven* spin-wave modes enables probing magnon bands at frequencies that are detuned from the sensor spins [114]. The future challenge for expanding to other magnets is to deliver the required high microwave frequencies to the sample. We anticipate that off-resonant detection schemes will enable studying magnon transport in materials that are appealing because of their tunability, such as atomically-thin vdW magnets.

In addition to imaging magnon systems, the quantum nature of the sensor spins provides an opportunity for studying quantum interactions between magnons and spins. Localized magnon modes such as those in DWs or magnetic microbars have been proposed as channels for mediating spin–spin entanglement (figure 18(c)) (see, e.g. [9], for an overview), with the potential for medium-(micron-)scale spin–spin coupling. This challenging scheme however requires reducing thermal magnons, e.g. by going to millikelvin temperatures, as well as positioning the spins with nanoscale precision with respect to the magnon field.

Advances in science and technology to meet challenges

Despite the progress made to date, several technical challenges remain to be resolved in order to fully unlock the potential of spin-based sensing in spintronics research. A recurring

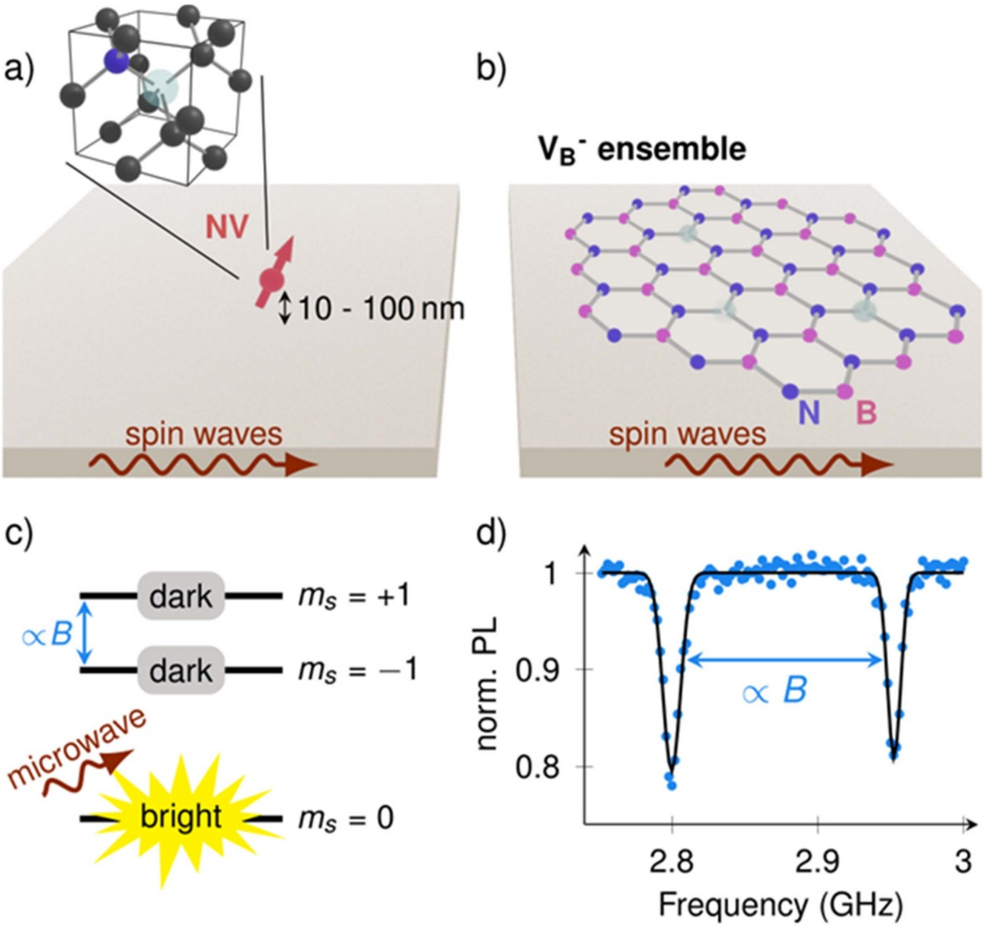

Figure 17. Probing magnonics using magnetometry based on optically active spin defects. Nitrogen-vacancy centers in diamond (a) and boron vacancies (V_B^-) in hexagonal boron nitride (b) are point-like magnetic-field sensors that can be brought within nanometer proximity of a magnetic sample. The sensitivity to microwave magnetic stray fields enables probing a sample's spin-wave physics. The schematics show the atomic structure of the lattice defects. (c) Level structure of the sensor spins, highlighting the optical response to microwave-induced spin transitions. (d) An optically detected electron spin resonance (ESR) spectrum of a single NV center (PL: NV photoluminescence). The ESR contrast is proportional to the amplitude of the microwave magnetic drive field, enabling imaging spin waves via their magnetic stray fields. The detection frequency is tunable by the application of an external magnetic field B.

challenge concerns establishing nanoscale proximity between sensor spin and sample, required for high-resolution detection of weak spin-wave signals. While advanced scanning microscopy with single NV centers in patterned diamond cantilevers reliably provides such proximity, it remains challenging especially at cryogenic temperatures or other extreme experimental conditions. In comparison with spin defects embedded in three-dimensional solid-state-media, emergent ones hosted by layered vdW crystals, such as V_B^- centers in nanometer-thick h-BN, provide new opportunities. In particular, the readily established atomic-scale proximity between the sensor-spin host material and other materials could benefit magnetic studies of vdW heterostructures. For instance, understanding spin decoherence in vdW materials is an open field of research.

Developing high-field, high frequency setups could expand the application range of spin-based sensing to a wider set of magnetic materials. A technical challenge is that most existing NVor other spin-defect-based-metrology platforms do not support few-tesla functionality and the associated tens-of-gigahertz-capable microwave electronics. Meeting this challenge requires developing high-frequency circuitry, as well as compatible spin-control and readout protocols for high-field magnetometry.

Finally, SWs may be used to transmit quantum correlations between two or multiple 'distant' NV centers, with the potential for mesoscopic-scale spin–spin entanglement (figure 18(a)). However, an outstanding challenge for experimentally realizing this ambitious proposal is the development of a suitable, millikelvin NV measurement platform that minimizes thermally induced quantum decoherence or other perturbations.

Concluding remarks

Probing magnonic systems using magnetometry based on optically active sensor spins is providing an increasing range

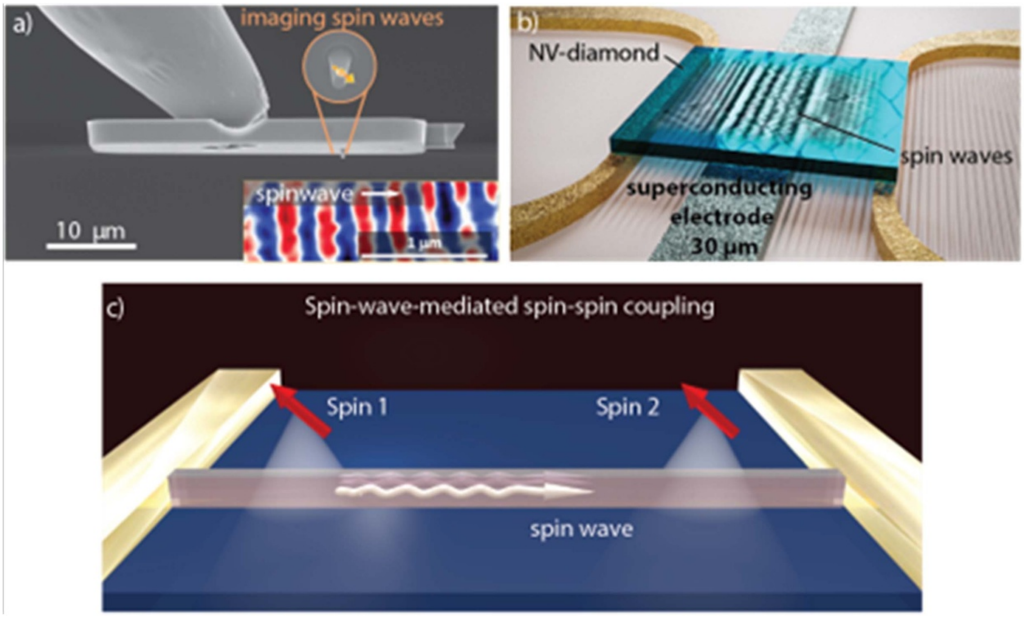

Figure 18. Imaging coherent spin waves using NV sensor spins and envisioned spin–spin entanglement via a spin-wave transducer. (a) A scanning NV-probe enables near-field imaging of a nanoscale coherent spin wave. (b) Because the imaging is magnetic, spin-based spin-wave sensing enables probing spin waves underneath metals, as depicted here for a 30-um-wide, 140 nm-thick superconducting MoRe stripline using and ensemble of NV centers [110]. Image credit: Michael Borst. (c) Sketch of spin-wave mediated coupling between two sensor spins. Nanoscale positional control of the two spins, as well as a sub-Kelvin measurement platform to mitigate decoherence by thermal magnons, are likely required.

of new research opportunities. These opportunities will likely expand into the direction of vdW magnets, as the nanoscale proximity of the sensor spins readily enables the detection of monolayer magnetic stray fields. The unique, magnetic nature of the imaging offers opportunities for probing hybrid material systems and devices such as gated magnon-transport layers, superconductor-magnet hybrids, or systems where magnons interact with nanoscale spin textures such as skyrmions or DWs. Studies of spin transport parameters, controlled via spin-injection or magnetic fields, would benefit from the local nature of the microwave-detection capabilities. Finally, combining sensor spins with magnonic systems carries the opportunity for assessing the feasibility of advanced spin–spin entanglement protocols mediated by magnons in confined structures.

Acknowledgements

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11. Novel materials

Yunqiu Kelly Luo, Yoichi Shiota and Joseph Sklenar

Status

Layered antiferromagnetic materials with modest interlayer exchange interactions have emerged as a playground for fundamental investigations into magnon-magnon interactions. Since the experimental demonstration of two-dimensional magnetism in materials such as CrI_3, $Cr_2Ge_2Te_6$, 1T- $MnSe_x$ and 1T-VSe_2, tremendous progress has been made in expanding the list of vdW magnets that hosts intrinsic magnetic orderings down to the monolayer limit. This new class of exfoliatable magnetic materials [115–117], where layers of atoms are assembled through vdW interactions, provides opportunities for future memory, logic and communication devices. Their magnetic properties are highly tunable, for example, by applied electric fields (section 2), strain and external magnetic field and they can be straightforwardly integrated within complex heterostructures by mechanical assembly. SAF, consisting of two (or many) antiferromagnetically coupled ferromagnetic thin films, represent an alternative material system with qualitatively similar magnetic behavior and magnonic properties to vdW magnets [118–120]. Because SAFs are multilayer structures that can be created through sputter-deposition processes, they can be designed with a variety of options in terms of materials, thickness and stacking order. Furthermore, SAFs are typically metallic and magnetically ordered at room temperature which makes them an attractive material platform for spintronic/magnonic device technologies.

Because the strength of the interlayer exchange coupling between vdW or SAF layers is typically much weaker than the direct exchange or superexchange coupling in conventional three-dimensional crystal antiferromagnets, both optical and acoustic magnons can be excited in the gigahertz range with conventional microwave electronics [115]. In SAFs, recent experiments have demonstrated that interactions between these acoustic and optical magnon modes can be tuned by an application of a tilted magnetic field (figure 19(a)) [118] or by dynamic dipolar interactions due to nonuniform spin precession (figure 19(b)) [120]. More recently, in layered hybrid perovskite antiferromagnets having qualitatively similar magnetic properties to $CrCl_3$, the interlayer DMI was shown to generate a magnon-magnon interaction capable of hybridizing optical and acoustic magnons without the need for a symmetry-breaking external field [121]. In vdW magnets, the recent advance in the coupling of coherent magnons with sub-millielectronvolt energies to excitons in the electronvolt region, can enable direct coupling between microwave photons and near-infrared to visible photons [116]. Moreover, strong tunable interactions between excitons and hybridized magnons by an in-plane magnetic field (figure 19(c)) [115] and by strain [117] have recently been achieved ranging from fully uncoupled to a regime of strong magnon-magnon coupling.

Current and future challenges

Hybrid magnonic systems based on vdW heterostructures hold potential for IT due to their high tunability and versatile couplings to an array of information carriers. Compared to photons, magnons generally have higher damping and stronger interactions. The interactions enable magnon control, but at large excitation amplitudes they can also lead to strong nonlinear damping and instabilities, which have been the bottleneck for development of magnon waveguides and amplifiers. To address these challenges, topological magnon insulators with optimized sample geometries are needed to take advantages of the topological edge mode for long magnon propagation lengths. Alternatively, developing low damping materials with damping compensation by methods such as SOT is desired (section 4).

Moreover, 'agile' methods to adjust magnon-magnon interactions within vdW magnets and SAFs are needed. The most common experimental technique for tuning the interaction between optical and acoustic magnons involves rotating the external magnetic field into an oblique orientation [115, 118]. More agile strategies, such as electrically controlling magnon-magnon interactions, have been proposed. For instance, simulations have shown that the electrical modulation of magnetic damping in multilayers containing four or more magnetic layers can open and close avoided energy level crossings in the energy spectrum (figure 20(a)) [122]. To date, this strategy has not yet been experimentally demonstrated.

Fundamental to the device efforts are high quality materials. In particular, low-damping materials at the atomically thin limit are essential for next-generation magnon interconnects. One promising approach is to develop high quality epitaxial vdW magnetic heterostructure via molecular beam epitaxy, such as 2D magnets directly grown in topological insulators to detect magnon via spin-charge interconversion [124]. Another innovative method is to fabricate high-crystalline-quality oxide membranes via epitaxial growth and selective etching of a water-soluble sacrificial thin layer. This method allows freestanding single crystal membranes integrated with multifunctional device engineering for example using strain [125] to control and modulate magnons transportation.

In addition, one of the promising features of antiferromagnetic magnons is the ability to use magnon polarization. Because the microscopic magnetic moment in ferromagnetic materials can precess only in a counterclockwise direction with respect to the effective magnetic field, the ferromagnetic magnons always possess right-handed chirality. On the other hand, collinear antiferromagnets have magnon modes with both right-handed and left-handed chirality owing to the antiparallel coupling between two sublattice, allowing a polarization degree of freedom in magnonics. Although the nonlocal transport of magnon spin current in antiferromagnets has been observed, effective excitation, control and detection schemes of coherent antiferromagnetic magnons remains challenging due to their field-immunity and extremely high resonance frequency compared to ferromagnets.

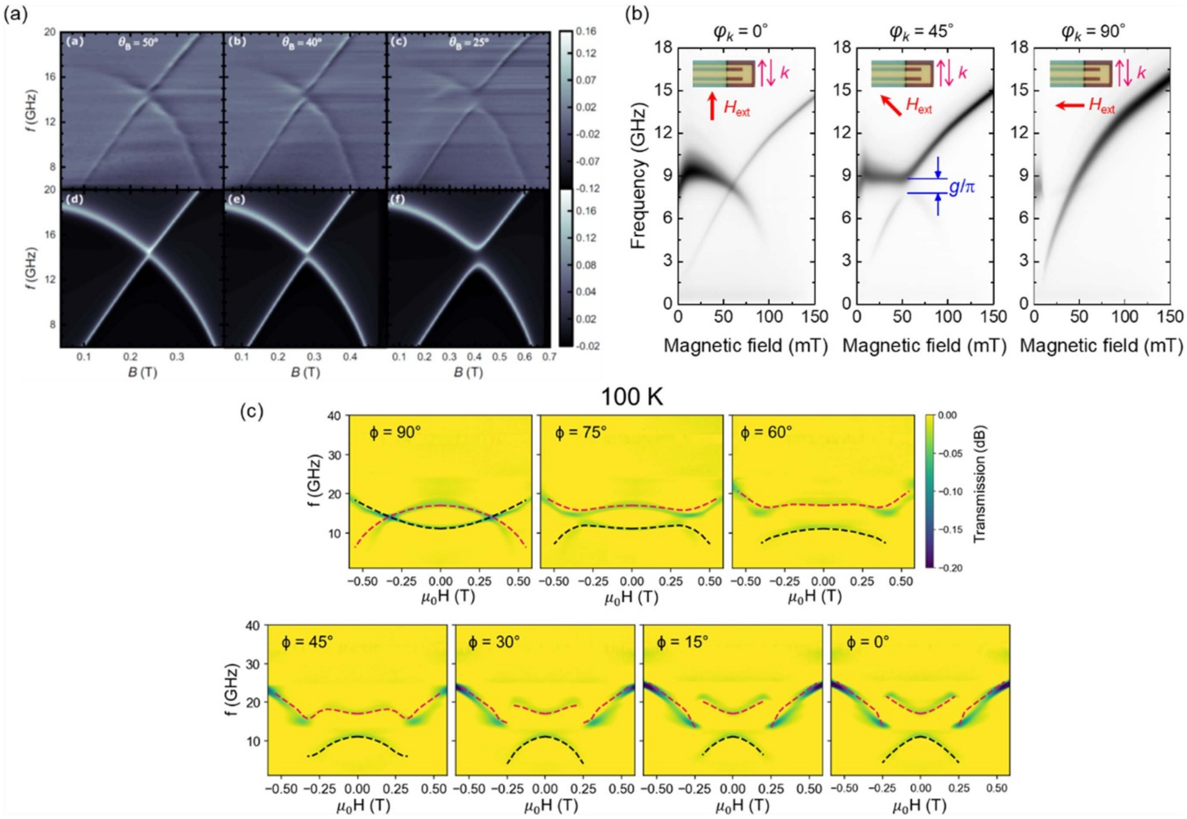

Figure 19. (a) and (b) Microwave absorption for in-plane magnetized SAFs as functions of microwave frequency and applied magnetic field (a) for uniform precession ($k = 0.0\ \mu\mathrm{m}^{-1}$) at different tilted field angle and (b) for nonuniform precession ($k = 1.2\ \mu\mathrm{m}^{-1}$) at different in-plane field angle with respect to the spin wave propagating direction. The anticrossing gap between acoustic and optical modes appears due to the symmetry breaking by tilting the magnetization toward the out-of-plane direction or by dynamic dipolar interactions. Reprinted figure with permission from [118], Copyright (2020) by the American Physical Society. Reprinted figure with permission from [120], Copyright (2020) by the American Physical Society. (c) Evolution of an antiferromagnetic mode crossing as a function of orienting the in-plane applied magnetic field away from high symmetry axis ($\phi = 90°$) in vdW AFM CrSBr bulk. Reprinted with permission from [115], Copyright (2022) American Chemical Society.

Advances in science and technology to meet challenges

The use of damping-like and field-like SOTs (section 4) to drive magnetization dynamics in layered antiferromagnets may help to excite a wider range of modes and interactions in these materials. Recent work demonstrated the excitation of both optical and acoustic magnons in a SAF composed of two antiferromagnetically coupled layers that were adjacent to both a Ta underlayer and overlayer [119]. This work represented the first time a spin-torque ferromagnetic resonance (ST-FMR) technique was used to excite magnetization dynamics in SAFs. Expanding this method to vdW magnets would be an important development since it would allow researchers to use an all-electrical experimental method to investigate magnon-magnon interactions on a layer-by-layer basis, e.g. bilayers, trilayers, tetralayers, etc. However, compared to SAFs, vdW magnets represent a larger challenge since these materials are both air-sensitive and often insulating. Nevertheless, there is potential as the ST-FMR method has been previously used to drive and detect the magnetization dynamics of ferromagnetic insulators that are adjacent to spin Hall metals. Therefore, the technique could potentially be applied to vdW magnets provided these materials are 'encapsulated' within conducting layers capable of providing the driving torques.

VdW magnets uniquely possess strong crystalline anisotropy built into their atomic layer unit, which is critical for device scalability to ultra-high density. Their high tunability allows future development of magnon switches and modulators controlled by electric field, strain and interface engineer. Undoubtedly, the investigation of vdW magnets for applications remains in its infancy. Major challenges include, among others, magnetic stability at room temperature, wafer-scale device fabrication with high-yield, read-out mechanism with suitable impedance and long-term chemical stability. New materials discovery and new device concepts will provide the scientific foundation to address the fundamental length scale of device dimension and the speed of the device operation based on vdW magnets.

The coherent spin pumping effect in heterostructures incorporating bulk antiferromagnets and heavy-metals provides an electrical detection of the chirality of antiferromagnetic dynamical modes [126]. However, the broadband frequency measurements of such a scheme remain to be developed. Recently, the polarization-selective excitation of antiferromagnetic resonance in perpendicularly magnetized SAFs

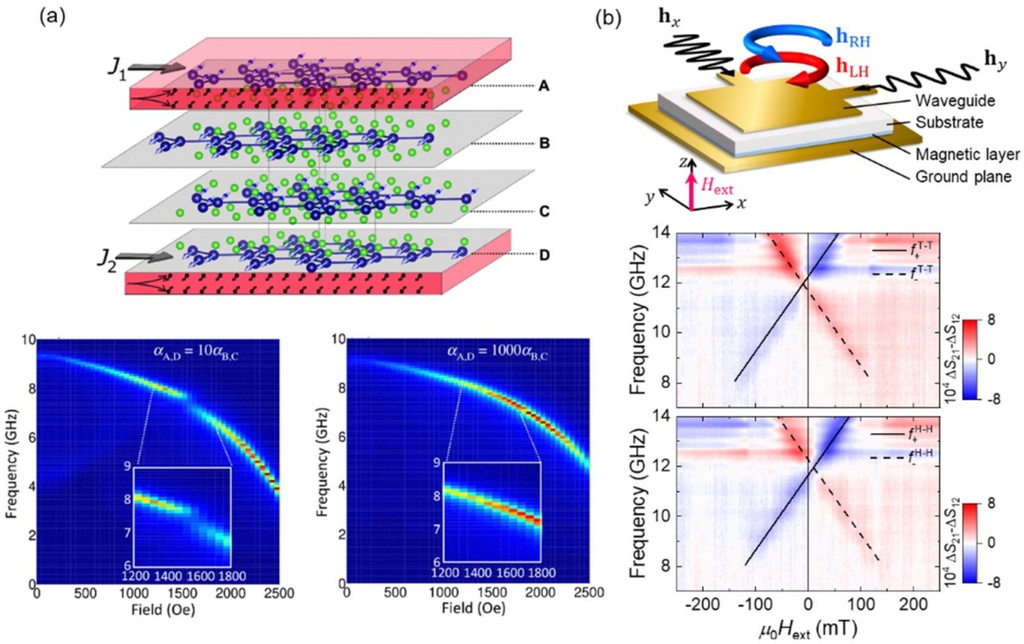

Figure 20. (a) A schematic of a tetralayer structure of $CrCl_3$ is shown in the upper panel. The schematic illustrates how the damping of the surface layers A and D can be controlled relative to the interior layers B and C via the application of current induced damping-like torques from materials that encapsulate the tetralayer. The lower panels illustrate how an avoided energy level crossing, in the magnon energy level spectrum of the tetralayer, can be electrically closed provided that the damping of the surface layers is increased relative to the interior layers. Reprinted figure with permission from [122], Copyright (2021) by the American Physical Society. (b) Schematic illustration of the measurement setup and results for the polarization-selective excitation of magnetic resonance in perpendicularly magnetized synthetic antiferromagnets using a wideband crossed microstrip circuit. Reprinted figure with permission from [123], Copyright (2022) by the American Physical Society.

using circularly-polarized microwave field has been demonstrated (figure 20(b)) [123]. However, direct observation of coherent antiferromagnetic magnon propagation, especially in thin films, remains challenging. Since antiferromagnetic magnon polarization can possibly carry spin angular momentum with arbitrary polarization, which is not present in ferromagnetic magnon, vdW antiferromagnets and SAFs can be expected as one of the promising material platforms to advance antiferromagnetic magnonics.

Concluding Remarks

We have presented selected recent studies and our perspectives on layered antiferromagnets including vdW magnets and SAFs. The hybridization of distinct magnon modes enables researchers to create new magnon states by coherent coupling, which can potentially yield applications in devices, circuits and information processing. In addition, the antiferromagnetic magnons are appealing because they offer further degree of freedom of magnon polarization, providing the spin angular momentum with arbitrary polarization in the magnon spin current. Harnessing the full potential of antiferromagnetic spin dynamics is still a significant challenge. However, layered antiferromagnets exhibit spin dynamics like those of conventional three-dimensional crystal antiferromagnets with readily controllable magnetization configurations. Therefore, the functionality and tunability of these material systems should be a strong advantage for further progress in the future magnonic devices.

Acknowledgments

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12. Non-Hermitian physics in magnetic systems

Tao Yu and Jinwei Rao

Status

Recent studies demonstrated that the dissipation, which is often regarded as detrimental in devices, can be exploited to achieve non-Hermitian topological phases or properties that are topologically robust to perturbations with unexpected functionalities for potential applications. Magnonic devices are low-energy consumption instruments for reprogramable logic, non-reciprocal communication and non-volatile memory functionalities, in which engineering of dissipation may lead to several non-Hermitian topological phases or properties of magnons, with *spin functionalities* possibly superior to their electronic, acoustic, optic and mechanic counterparts [127, 128], such as strongly enhanced magnonic frequency combs, magnon or spin-wave amplification, scattering enhancement of magnons, (quantum) sensing with unprecedented sensitivity, magnon accumulation, perfect absorption of microwaves and magnon bound states in the continuum.

Researchers have approached non-Hermitian magnonics from both theoretical and experimental perspectives. These progresses towards engineering dissipation have achieved many non-Hermitian topological phases or properties in magnonic systems, including exceptional points (EPs) [129–131], exceptional nodal phases [132], non-Hermitian Su–Schrieffer–Heeger (SSH) model [133] and non-Hermitian skin effect [134, 135] (refer to figure 21 for an overview). The EPs are singularities in the parameter space, where the eigenvalues and eigenvectors of a non-Hermitian Hamiltonian matrix coalesce. Studies have developed two pathways to achieve such EPs with magnons. One is to manipulate either the photon-magnon coupling strength or the gain or loss of a subsystem in cavity magnonics (refer to 9 for hybrid quantum magnonics) [129, 130]. The other one is to design magnetic heterostructures with ferromagnetic and nonmagnetic metal layers [131]. Particularly, when the EPs are located in the reciprocal wave-vector space, they are referred to as the exceptional nodal phase, which was predicted in magnetic junctions [132]. They are topologically protected, characterized by so-called ‘bulk Fermi arc’ (a branch cut of the complex energy), which disappears only when a pair of EPs annihilate by very strong perturbations. SSH model holds the topological edge state. Its generalization to the non-Hermitian magnetic system in terms of an array of spin-torque oscillators promises the topological magnonic lasing edge modes when excited by spin current injection [133]. Non-Hermitian skin effect promises a macroscopic number of *bulk* eigenstates piling up at one boundary. It is predicted recently in an array of nanomagnets coupled dipolarly via magnetic substrate, in which the combination of non-reciprocity and dissipation drives all the modes to one edge [134]. Such non-Hermitian skin modes are predicted as well in a vdW ferromagnetic monolayer honeycomb lattice [135], driven by DMI and non-local magnetic dissipation. Strong aggregation of magnon modes at one boundary significantly enhances the sensitivity in detection of small signals [134].

Most predictions in the exceptional nodal phases [132], non-Hermitian SSH model [133] and non-Hermitian skin effect [134, 135] with unique functionalities beyond the Hermitian scenario still await the experimental confirmation in the future.

Current and future challenges

Theory: The present theoretical descriptions in magnonics strongly rely on a prerequisite that magnon is weakly coupled to other degree of freedoms, such that the coupling can be treated as perturbations. Approaches describing magnon subsystems that are strongly coupled to environment are essential but present a challenge that needs to be addressed in future theory. Nonlinearities bring about additional challenges since the approximated non-Hermitian description is often set up in the linear regime. How to precisely account the non-Markovian memory effect in the evolution of a magnonic hybridized system provides another opportunity but also a challenge.

Materials: to realize and exploit the predictions of novel hybridized magnon modes in non-Hermitian topological magnonics, magnetic materials with high-quality factors and precisely controlled magnetic parameters are favorable. So far, the most commonly used ferromagnetic materials for these purposes are YIG, CoFeB and permalloy (FeNi), because of their excellent magnetic properties. The acoustic property of YIG is excellent as well and its nanostructures such as ultrathin films and nanowires become available only recently. But high-quality YIG appears to be only compatible with thick gadolinium-gallium-garnet substrate. VdW magnet is also the material choice for non-Hermitian topological phases [135], but the convincing magnon transport experiment remains wanting. Nevertheless, it appears to be difficult to globally or locally control the interaction and dissipation when stacking the magnetic films to heterostructures such as with other non-magnetic layers [131], e.g. copper, platinum and magnesium oxide, or with the magnetic nanowire array [134].

Fabrication of devices: Loading YIG spheres of millimeter size into the cavity appears on the one hand to be the most convenient way to implement the EPs, but it encounters the difficulty to be fabricated in nanostructures on a chip. The proposal for the other non-Hermitian topological phases is still lacking in this approach. On the other hand, to fabricate nanoscale magnetic heterostructures to realize various non-Hermitian topological phases, one of the challenges is to precisely control the configurations of different layers or nanowires and to guarantee the interfacial quality between them. Both factors demand a very high-quality film growth technique. Moreover, the scalability of magnonic devices to larger sizes and higher frequencies is also a technical challenge that needs to be overcome.

Gain of magnons: the realization of gain for magnons is an important design parameter, but raises challenges since it implies ‘negative Gilbert damping’, which is, however, desired for EPs and other non-Hermitian topological phases in

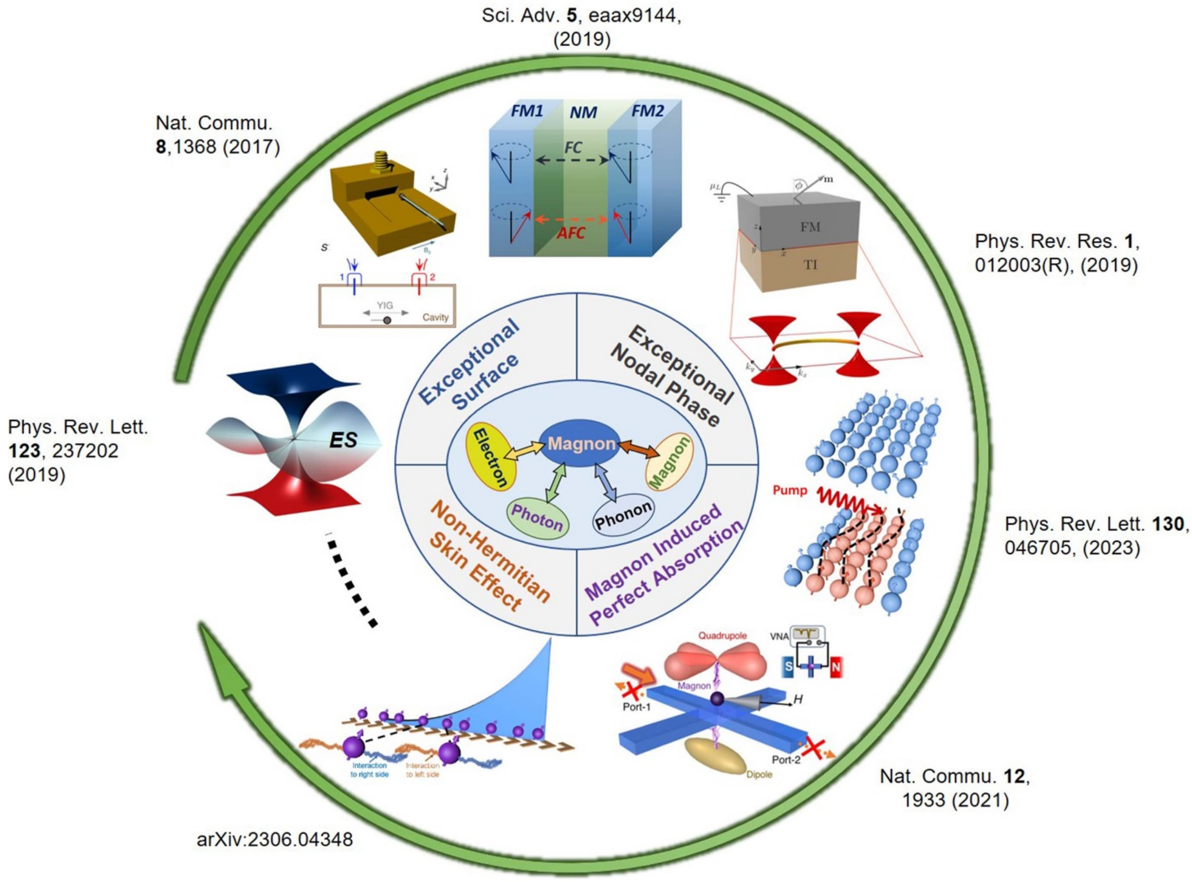

Figure 21. An overview of the present status of non-Hermitian topological magnonics. Reprinted figure with permission from [130], Copyright (2019) by the American Physical Society.

several cases. On the one hand, spin-polarized electrical currents can induce spin transfer torque to magnetization, leading to amplification of magnonic signals (section 4). On the other hand, with a feedback loop the output signal can be fed back into the input, which results in the amplification of SWs. However, several technical challenges follow as well. It is still difficult to completely overcome the damping rate of convenient metallic and insulating magnetic materials; both the excitation/detection and amplification of magnons require suitable electrical circuits; the nonlinear effects pose a challenge in achieving gain in magnonic devices, because, in some cases, the amplification of magnons leads to the generation of higher harmonics or sidebands, which interferes with the desired signals. While research in this direction encounters many obstacles, even small breakthroughs can have significant benefits in device applications.

Advances in science and technology to meet challenges

In order to progress in non-Hermitian topological magnonics, more experimental efforts are sorely needed. While significant advances in material growth, micro-nano fabrication techniques and magnon gain may be challenging in the short term, there exist alternative methods that can help to overcome current technical challenges as well.

One feasible way is to develop techniques that can independently manipulate the properties of ferromagnetic nanostructures, for example by using bias voltage (section 2), field gradient, thermal gradient, laser or microwave pump (sections 4 and 8). These external drives can excite spin currents or magnon flows, which can transfer energy and torques among different magnetic layers or spatial positions. By controlling the flow of these spin currents and magnons, it may be possible to effectively engineer the dynamics in non-Hermitian magnonic systems.

The opportunity indeed arises in the nonlinear regime (section 5). A recent effort achieves a pump-induced magnon mode in a magnet when loaded in a microwave waveguide and driven by a strong microwave pump [136]. This magnon mode displays a high level of tunability when driven to the nonlinear regime and holds the potential to overcome current technological challenges [136]. Via tuning this mode, the giant enhancement of magnonic frequency combs at EPs is subsequently observed. In addition, hybrid systems based on cavity magnonics may offer another feasible solution. Magnon modes in different magnetic materials can indirectly couple with each other on the long range via the mediation of a microwave cavity [127]. In a cavity magnonic system, interfacial quality that is vital for magnetic heterostructures becomes less important (9). Gains that may need delicate design in spintronic devices can easily be realized in a cavity magnonic system by embedding an amplifier or gain material in the microwave cavity. However, an awkward reality in this approach is that nearly all current researches on non-Hermitian cavity magnonics are implemented from the cavity side. The magnon mode is merely adopted as a tunable high-Q resonance, because the direct operation techniques on magnon mode, especially precise controlling its dissipation and realization of its gain, are lacking. Given this, a significant opportunity is to develop tuning or readout techniques that can access the photon-magnon coupling process from the magnon side.

Concluding remarks

Non-Hermitian topological magnonics is an emerging field that seeks to realize functionalities beyond those achievable in the Hermitian scenario. In this sub-field, dissipations, which are typically considered detrimental, can be harnessed as important resources for engineering system dynamics. Recent researches have unveiled a range of novel phenomena, including EPs, exceptional nodal phases, chirality as generalized spin–orbit interaction, non-Hermitian SSH model with magnons and non-Hermitian skin effect with potential device applications holding new functionalities. However, due to various experimental obstacles, most research and promising phenomena are still at the theoretical proposal stage. There are thereby high opportunities in the future experiments and device applications after an improvement in material growth and micro-nano fabrication techniques.

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Data availability statement

No new data were created or analysed in this study.

ORCID iDs

Benedetta Flebus https://orcid.org/0000-0002-2436-8569
Dirk Grundler https://orcid.org/0000-0002-4966-9712
Bivas Rana https://orcid.org/0000-0002-1076-4165
YoshiChika Otani https://orcid.org/0000-0001-8008-1493
Igor Barsukov https://orcid.org/0000-0003-4835-5620
Anjan Barman https://orcid.org/0000-0002-4106-5658
Gianluca Gubbiotti https://orcid.org/0000-0002-7006-0370
Pedro Landeros https://orcid.org/0000-0002-0927-1419
Johan Akerman https://orcid.org/0000-0002-3513-6608
Philipp Pirro https://orcid.org/0000-0002-0163-8634
Qi Wang https://orcid.org/0000-0002-5049-629X
Florin Ciubotaru https://orcid.org/0000-0002-7088-2075
Ping Che https://orcid.org/0000-0003-3317-8705
Riccardo Hertel https://orcid.org/0000-0002-0646-838X
Teruo Ono https://orcid.org/0000-0002-9629-0633
Burkard Hillebrands https://orcid.org/0000-0001-8910-0355
Silvia Viola Kusminskiy https://orcid.org/0000-0002-6373-7478
Chunhui Rita Du https://orcid.org/0000-0001-8063-7711
Aurore Finco https://orcid.org/0000-0002-0197-7476
Toeno van der Sar https://orcid.org/0000-0002-6197-4808
Yunqiu Kelly Luo https://orcid.org/0000-0002-2196-0532
Yoichi Shiota https://orcid.org/0000-0003-1199-8438
Joseph Sklenar https://orcid.org/0000-0003-1456-2023

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