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Magnonics

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Abstract

Magnonics is a young field of research and technology emerging at the interfaces between the study of spin dynamics, on the one hand, and a number of other fields of nanoscale science and technology, on the other. We review the foundations and recent achievements in magnonics in view of guiding further progress from studying fundamental magnonic phenomena towards applications. We discuss the major challenges that have to be addressed in future research in order to make magnonics a pervasive technology.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The concept of spin waves (SWs) as dynamic eigenmodes of a magnetically ordered medium was introduced by Bloch 80 years ago [1]. From a classical point of view, a SW represents a phase-coherent precession of microscopic vectors of magnetization of the magnetic medium [2, 3]. Holstein and Primakoff [4] and Dyson [5] introduced quanta of SWs called magnons. They have predicted that magnons should behave as weakly interacting quasiparticles obeying the *Bose–Einstein statistics*. Therefore, the term *magnonics* should in principle describe a subfield of magnetism connected with quantum magnetic dynamic phenomena. However, in a similar way as *electronics* addresses a broad variety of effects that are not limited by a quantized structure of the electrical current (e.g. single electron devices, shot noise, etc), there is now a broad consensus to use the term magnonics to cover a broad field of magnetism connected with SWs in general.

Early experimental evidence for the existence of SWs came from measurements of thermodynamic properties of ferromagnets, in particular the temperature dependence of their saturation magnetization M_0. The famous $T^{3/2}$ Bloch law is an indirect confirmation of the existence of SWs in nature [6]. The first direct observation of SWs was made using ferromagnetic resonance (FMR) by Griffiths for the case of uniform precession [7], which can be viewed as a SW with a wave vector $\boldsymbol{k} = 0$. Later, Brillouin light scattering (BLS) experiments performed by Fleury *et al* confirmed the existence of SWs with non-zero wave vectors [8]. In many aspects, a SW can be considered as a magnetic analogue of a sound or light wave. Several decades of experimental and theoretical research have demonstrated that SWs exhibit most of the properties inherent in waves of other origins. In particular, the excitation and propagation [9–17], reflection and refraction [18–27], interference and diffraction [28–33], focusing and self-focusing [34–43], tunnelling [44, 45] of SWs and Doppler effect [46–48] as well as formation of SW envelope solitons [49–52] were observed. SW quantization due to the finite size effect was discovered very early in thin films [53, 54]. Recently it was observed and extensively studied in laterally confined magnetic structures [55–61]. The macroscopic quantum phenomenon of Bose–Einstein condensation (BEC) of magnons was demonstrated in a few different magnetic systems [62–64]. In yttrium–iron garnets (YIG) BEC of magnons was observed at room temperature. As discussed later, this effect might be used to generate microwave signals by conversion of the energy of incoherent broadband electromagnetic radiation into monochromatic SWs or electromagnetic radiation. In spintronics, SWs are considered as a mechanism responsible for phase locking of arrays of spin transfer torque oscillators [65–70] and for rectification of microwave currents passed through ferromagnetic microwave guides [71–73].

Such a broad variety of observations has stimulated the field of magnonics [74–77]. Similar to spintronics [78, 79], the main application direction of magnonics is connected with the ability of SWs to carry and process information on the nanoscale. Here, research is particularly challenging since SWs exhibit several peculiar characteristics that make them different from sound and light waves. The dependence $\omega(\boldsymbol{k})$ for SWs is highly dispersive and usually contains a gap $\omega_0 = \omega(k = 0)$ that depends on the strength and orientation of the applied magnetic field as well as on the size of the ferromagnetic sample. Also, the $\omega(\boldsymbol{k})$ law is anisotropic even in the case of an isotropic magnetic medium. In addition, SWs are governed by different interactions dominating on different length scales, e.g. by the exchange and dipolar interactions dominating on nanoscopic and microscopic length scales, respectively. These characteristics have turned out to be decisive to understand SWs propagating in micro- and nanopatterned magnonic waveguides [80–82].

Nanostructured magnetic materials are known to possess further functionalities that cannot be achieved in their bulk constituents. So, the discovery of the phenomenon of giant magnetoresistance (GMR) in magnetic multilayers was marked by the Nobel Prize in Physics in 2007 [83, 84]. GMR read heads and those based on the tunnelling magnetoresistance (TMR), consisting of nanopatterned magnetic multilayers, are used in modern hard disk reading heads, showing magnetoresistive characteristics remarkably superior to those found in natural continuous magnetic materials. Other examples are given by metallic magnetic multilayers with high out-of-plane magnetic anisotropy [85, 86] and multilayered magnetic dielectric films (so-called magneto-photonic crystals [87]) that show such noteworthy effects as giant Faraday rotation [88] and unidirectional propagation of light [89].

The properties of SWs in nanostructured systems win a new degree of freedom connected with an inhomogeneous internal magnetic field due to structuring. Periodically structured materials play a special role in magnonics. Indeed, the propagation of waves in periodically structured materials is of fundamental interest in modern physics and technology [90]. In particular, considerable research efforts have been made in the field of artificial electromagnetic materials with periodic modulation of the refractive index in one, two or three dimensions (1D, 2D or 3D, respectively), with periodicity comparable to the wavelength of light. These materials are known as photonic crystals or photonic band gap structures [91], and they already find practical applications in optoelectronics [92]. Plasmonic [93] and phononic [94] crystals and semiconductor superlattices [95] are other typical and widely known examples of exploitation of the spatial periodicity for controlling propagation and scattering of light, phonons and electrons in electronic, optoelectronic and acousto-electronic devices.

Therefore, periodically modulated magnetic materials are now explored to form magnonic crystals [96], i.e. a magnetic analogue of photonic crystals. Indeed, the SW spectrum has been modified by patterning [97] and shows a tailored band structure in periodic magnetic materials [98]. The band spectrum consists of bands of allowed magnonic states and forbidden-frequency gaps ('band gaps'), in which there are no allowed magnonic states. One of the first attempts to study the propagation of SWs in periodic magnetic structures was made by Elachi [99]. Nowadays, the number of studies on this topic has surged and continues to grow at a fast pace.

Here, we review the history and current state of the art in magnonics and discuss challenges that need to be addressed in the future in order to implement magnonic devices in real-life applications.

2. Magnonic devices

The modern research on fundamental properties of materials is increasingly driven by their anticipated potential for technological applications. Generally speaking, due to particular properties of SW spectra, magnonic devices should offer important new functionalities that are currently unavailable in, e.g., photonic and electronic devices. For example, magnonic devices are easily manipulated by the applied magnetic field. Moreover, magnetic nanostructures are non-volatile memory elements, and therefore, their integration will enable programmable devices with ultrafast re-programming at the sub-nanosecond time scale. In magnetic data storage media magnetic nanostructures have already been combined with nanoelectronics (e.g. in read heads and magnetic random access memories) and optics (e.g. in magneto-optical disks). Hence, magnonic devices offer the integration with microwave electronics and photonic devices at the same time. Since for all practically relevant situations (in the gigahertz to terahertz frequency range), the wavelength of SWs is several orders of magnitude shorter than that of electromagnetic waves, magnonic devices offer better prospects for miniaturization at these frequencies.

Macroscopic magnetic devices have been demonstrated and implemented in microwave technology already some time ago [100]. Indeed, soft ferrites were used to fabricate linear and non-linear devices based on magnetostatic spin waves (MSSWs) and operated at frequencies up to 70 GHz. Recently, the interest in ferrites has been revived to study the fundamental wave properties of magnetization dynamics in patterned [101–103] and, specifically, periodic [104, 105] structures. However, in order to truly demonstrate the rich technological potential of magnonics, one has to design and build *nanoscale* functional magnonic devices, in particular those suitable for monolithic integration into the existing complementary metal–oxide–semiconductor (CMOS) circuits. For example, the integration into monolithic microwave integrated circuits (MMIC) has so far been a severe challenge for ferrites. Metallic ferromagnets need to be explored to substitute ferrites for integration at the nanoscale. This motivates the discussion on the potential applications of nanoscale (presumably metallic) magnonic crystals and devices presented below.

Let us begin by considering a generic magnonic device shown in figure 1. Typically, any such device should contain at least four structural elements: a source and a detector of SWs, a functional medium by which the SW signal is manipulated between the input and the output, and an external control block which is required to either re-program or to dynamically control the device.

The most commonly and thoroughly studied magnonic device is shown in figure 2. MSSWs are injected into a ferrite (usually YIG) waveguide (C) using an inductive input antenna (A). The latter can have a number of different geometries

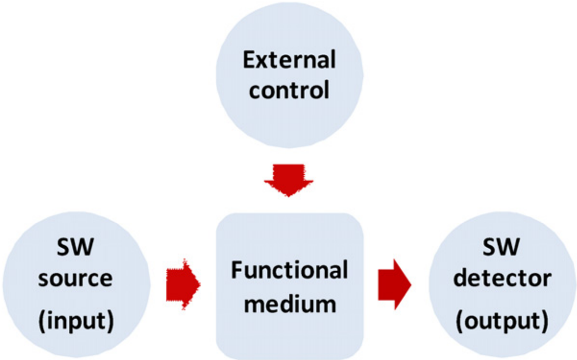

Figure 1. A block diagram of a generic magnonic device is shown. The device comprises a source, a detector of SWs and a functional medium in which the SW signal is manipulated (controlled) using an external means. The red arrows denote coupling between the different structural elements of the device. (Colour online.)

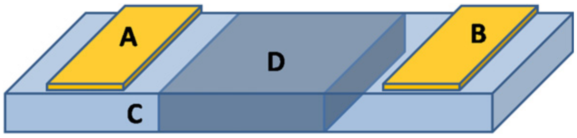

Figure 2. A generic MSSW device is schematically shown. A and B denote the input and output antennas. C is the waveguide for SWs. D is the functional region, where SW manipulation takes place. (Colour online.)

used in microwave engineering, e.g. a coplanar waveguide (CPW) or transmission line. The phase and/or amplitude of MSSWs are varied in the functional region (D) and the result is read out inductively by a further antenna (B). The functional region can have the form of either a 'built in' profile of magnetic/structural parameters [105–107], a local modification of the magnetic field [44, 102, 108–110] or a uniform magnetic field [108, 111], in which case region D virtually coincides with C. The waveguide C itself has been used as the functional region D in that the inherent non-linearity of magnetization dynamics and hence the MSSWs has been exploited e.g. as a phase shifting mechanism [112, 113]. Region D can host a functional non-uniformity provided by a local barrier ('defect') for SW propagation [44, 108, 109] or an extended (distributed) device such as a magnonic crystal [105–107, 114]. When an Oersted magnetic field is used to manipulate MSSWs, the functional region can be either static [102, 108, 109] or dynamic [110, 114]. In the latter case, 'slow' (quasi-static) and fast manipulation (at a frequency close to or higher than that of the signal) should also be distinguished.

When the functional region D is uniform and exhibits (quasi-)static characteristics, the device can act as a phase shifter or a delay line. If D is operated in a fast or dynamic mode, the device can be used to manipulate the frequency and/or to amplify the amplitude of the SW signal [115], i.e. as a frequency mixer and/or SW amplifier, respectively. If D is non-uniform, the device acts as a magnonic filter. In the non-linear regime, the device can be used to construct a power selective filter [113]. With D consisting of two localized magnetic field regions, the device can act as a dynamically controlled source of short trains of MSSWs [110].

The devices of the type shown in figure 2 can be connected together to build interferometers and logic gates, as was demonstrated, e.g., in [108, 109, 111, 112]. However, such devices have used external microwave circuits to evaluate results of the manipulation of SWs and hence had macroscopic dimensions. Logic architectures in which logic output is derived directly from the SW signal (e.g. via SW interference) were proposed theoretically in [116–118]. Experimentally, SW interference was observed in the response of microscopic rings to uniform microwave field [119–122]. However, experimental demonstration of an all-magnonic interferometer or logic gate is still a challenge for researchers. The closest to an all-magnonic design of logic gates was developed in [123, 124], and recent progress will be reviewed by the authors in a separate paper of this cluster. It is also important to note that in all-magnonic logic gate designs developed so far non-magnonic signals (e.g. electrical currents) are used as the input whereas the output is based on SWs. Therefore, combining several such gates in series necessarily involves conversion of the SWs into electrical currents, which is always associated with additional power losses.

Magnonic devices discussed in [116–124] were all based on magnonic waveguides made of ferromagnetic metals. Such waveguides are known to experience a larger SW damping when compared with ferrites. Moreover, the geometric confinement of SWs in the nanostripe geometry can itself affect the SW damping, e.g. via enhancement of damping due to a non-linear resonant three-magnon confluence process that occurs at a particular bias field determined by the quantized SW spectrum in the waveguide [125]. However, it has been demonstrated that SWs in such a metallic magnonic waveguide can also be confined to the sub-100 nm length scale in channels that are remote from the edges [80, 81]. Such SWs can be expected to experience reduced scattering from the always present edge roughness, and thus to have a longer relaxation length.

In order to use the magnonic device shown in figure 2 as a magnetic field controlled logic element, one must be able to shift the SW phase by π in region D shown in figure 2. This might be accomplished by changing the SW wave number k by varying the value of the bias magnetic field H, which is used to control the magnonic device performance. The required variation of H depends upon the derivative

$$\partial k/\partial H = -(\partial\omega/\partial H)/(\partial\omega/\partial k) = -(\partial\omega/\partial H)/v_g, \quad (1)$$

where v_g and ω are the group velocity and frequency of the SW, respectively [117]. Considering exchange-dominated SWs at this point one gets $\omega \propto h + \alpha k^2$, where α is the exchange constant of the material. From this, one finds $\partial k/\partial h = -1/2\alpha k$, where $h = H/M_0$. Thus, the shorter the wavelength of the SWs, a larger change in the bias magnetic field is required to change the output from '0' to '1'. This may present a serious limitation if miniaturization of magnonic logic devices is desired. Furthermore, since the group velocity of SWs appears in the denominator of equation (1), one may also need to compromise between the efficiency of the magnetic field control and the speed of operation of such a device. The most efficient control by the

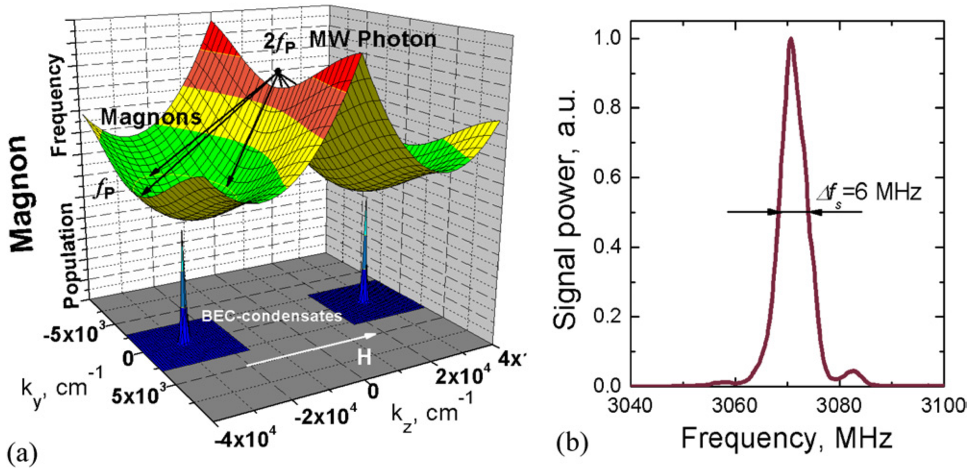

Figure 3. (*a*) The frequency of magnons in an in-plane magnetized YIG film is shown as a function of the in-plane wave vector. Magnons are excited by microwave photons and form a quasi-equilibrium magnon gas due to thermalization. Two peaks in the magnon population indicate the formation of BEC. (*b*) The spectrum of the microwave radiation emitted by the condensate is shown. Note that the value of the maximum frequency is determined by the applied magnetic field (after [129]). (Colour online.)

applied magnetic field is achieved for dipole-exchange SWs in the backward volume geometry, which have a characteristic minimum in their frequency at a particular finite value of the wave number. This might explain why all magnonic logic devices demonstrated so far have been implemented using MSSWs. A way around might be offered by either using a localized domain wall as a phase shifter [116] or embedding a magnonic crystal into the magnonic waveguide. In magnonic crystals (e.g. such as those from [126, 127]), the dispersion of SWs contains regions of reduced group velocity in the vicinity of magnonic band gaps [128]. Hence, the use of SWs with frequency near the band gap edges as signal carriers could lead to more efficient and miniature magnonic logic devices. Of course, this consideration is not limited to devices based on inductive antennas and ferrite magnonic waveguides, but is of general relevance.

A particular type of magnonic devices is associated with BEC of magnons. Contrary to the above discussed systems, such devices are not connected with data processing, but they can be used to build a source of coherent microwave radiation [129]. In fact, although the currently implemented microwave sources span a very broad spectrum of devices (from vacuum klystrons to spin-torque nano-oscillators), all of them convert dc current into microwaves. A completely different physical mechanism for creation of SWs via the conversion of an incoherent electromagnetic radiation into coherent microwaves, which takes advantage of BEC, is illustrated in figure 3(*a*), where the dependence of the magnon frequency in an in-plane magnetized ferromagnetic film is plotted as a function of the two-dimensional in-plane wave vector of the magnon. The dependence shows two degenerated minima, corresponding to two symmetric points on the wave vector plane. Magnons with frequencies higher than that of the minima are excited by means of an external incoherent source as shown in figure 3(*a*). Due to magnon–magnon interaction the excited magnons are thermalized and a quasi-equilibrium thermodynamic distribution in the magnon gas is achieved [130]. If the density of magnons at quasi-equilibrium reaches a certain critical limit, BEC of magnons occurs, which is illustrated in figure 3(*a*) by two narrow peaks in the magnon distribution close to the minima As a result, a coherent macroscopic magnon state appears, accumulating an essential part of the energy of the magnon gas. In this way the energy accumulated by the magnon gas from the incoherent pumping field is transformed by the BEC into monochromatic microwave radiation. Figure 3(*b*) shows the frequency spectrum of the radiation detected in YIG films under the condition of BEC [129]. While the frequency of the emitted coherent radiation is controlled by the applied magnetic field, its spectral width is below 6 MHz.

3. Magnonic crystals

SWs in individual magnetic thin films have attracted enormous interest in the 1960s and 1970s [131]. Following [99], the research focus shifted to magnetic superlattices in the 1980s. Along the growth direction these superlattices can be viewed as 1D magnonic crystals. They consist of a sequence of layers with alternating magnetic properties and are probably the best studied systems in which the spectrum of magnons has a band structure and contains band gaps [132–162]. We note that the authors of [163] have shown that the strong dispersion in the vicinity of band gaps in the magnonic spectrum of magnetic superlattices could be used to excite dipole-exchange SW envelope solitons. Such solitons might prove useful for creation of digital rather than analog magnonic logic. Also, interesting spectra can be observed not only in the case of periodic but also quasi-periodic and fractal magnetic structures [158, 164, 165].

From the point of view of fabrication and practical applications, magnonic crystals and devices with a planar geometry and, ideally, fabricated from a single magnetic material are preferred. Magnonic crystals fabricated by periodic corrugation of YIG and ferromagnetic metallic films were studied in [166, 167, 168], respectively.

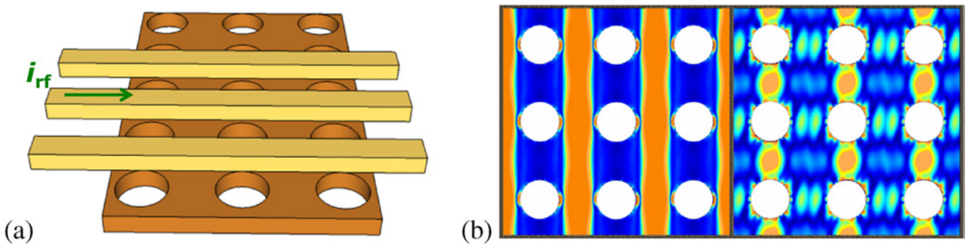

Figure 4. (*a*) Sketch of a CPW integrated to an antidot lattice prepared from a thin Permalloy film. The CPW consists of three metallic leads (ground–signal–ground leads). Adjusting the dimensions of the CPW allows one to vary the profile of the magnetic field generated by microwave current i_{rf} supplied by the VNA. This defines the wave vector transferred to the sample. The same CPW picks up the voltage induced by precessing spins. (*b*) Simulated spatial distributions of spin precession amplitudes reflecting two different standing SW excitations. The film is assumed to be 26 nm thick. The period (hole diameter) is 490 (240) nm. A magnetic field of a few 10 mT is applied in the horizontal direction. The mode pattern shown on the right belongs to a localized mode that has a frequency higher than that of the extended mode shown on the left (after [181]). Bright contrasts correspond to large amplitudes. The holes are shown in white. (Colour online.)

Magnonic crystals formed by lateral patterning of a magnetic film with a uniform thickness were theoretically studied in [169, 170] (1D comb-like structures represented by a ferromagnetic wire with periodically situated dangling branches) and in [171] (asymmetric loops). A combination of the two structures was studied in [172]. More details of the studies can be found in a review published in [173]. However, due to the complicated geometry, it can be difficult, if at all possible, to take into account analytically the long-range magneto-dipole interaction within such samples. Hence, numerical methods have to be used instead. So, magnonic crystals produced by periodically varying the width of a magnetic stripe were proposed and numerically studied in [126, 127]. Planar 1D magnonic crystals formed by alternating stripes of two different magnetic materials were studied in [174, 175], although magnonic band gaps were observed only in the latter work.

2D magnonic crystals were proposed in [74, 176], where the spectrum of dipole-exchange SWs propagating in the plane of a magnonic crystal was discussed. The magnonic crystal consisted of periodically arranged infinitely long ferromagnetic cylinders embedded in a matrix of a different ferromagnetic material. The position and width of band gaps in the magnonic spectrum were investigated as a function of the period of the structure and the depth of modulation ('contrast') of the magnetic parameters. It was found that the depth of modulation of the exchange parameter has a drastic effect upon the position and width of the band gaps. In [106], it was shown that a ferrite film with periodically etched holes can serve as a filter for MSSWs propagating in the film plane. Collective dynamics of lattices of magnetic vortices were studied in [177, 178]. FMR and time-resolved scanning Kerr microscopy (TRSKM) were used to study the localization of SWs in an array of antidots formed in a metallic ferromagnetic film in [179]. Vector network analyser ferromagnetic resonance (VNA-FMR) measurements and micromagnetic simulations were used to demonstrate the control of SW transmission through a similar array of antidots by an external magnetic field in [180, 181] (figure 4). Recently, such VNA-FMR measurements have been complemented by BLS experiments on the same antidot array [182]. By this means standing and propagating waves were evidenced.

Generally, patterning of thin magnetic films leads to the creation of arrays of non-ellipsoidal magnetic elements. In such elements, the internal magnetic effective field is non-uniform, breaking the translational symmetry and introducing additional complexity into the SW mode spectrum. The interpretation of the precessional dynamics in non-ellipsoidal elements becomes even more involved at small values of the applied magnetic field when the elements have a non-uniform static magnetic state. Recent studies of micro- and nanoscale magnetic elements revealed phenomena of localization of magnons [119, 121, 183–188], magnonic nano-optics [80], guiding of magnons via deep sub-micrometre SW channels [81, 82] (figure 5) and anisotropic coupling of square arrays of disc shaped magnetic elements [189]. Recently, the emphasis of such research has shifted to collective dynamic phenomena. For example, the spectrum of magnons in closely packed 1D arrays of magnetic nanoelements was shown to have a band structure, with Brillouin zone boundaries determined by the artificial periodicity of the arrays [190]. Giovannini *et al* showed that SWs in closely packed 2D arrays of magnetic nanoelements also form a magnonic band structure [191].

3D magnonic crystals are the least studied objects in magnonics, due to both increased difficulty of their theoretical treatment and currently limited outlook for their fabrication and experimental investigation. Collective SW modes in 3D arrays of ferromagnetic particles in non-magnetic matrices were studied in [192, 193]. Magnonic band structure of 3D all-ferromagnetic magnonic crystals was calculated by Krawczyk and Puszkarski [194, 195]. Here, again the depth of modulation of magnetic parameters is essential to generate magnon bands and forbidden-frequency gaps of significant width.

4. Excitation and detection of SWs

The excitation and detection of SWs is the major technological challenge for the realization of magnonic devices. Experimentally, even small signal levels are often sufficient to study SWs either propagating or forming standing eigenmodes in magnonic crystals and more generally magnetic nanostructures. In commercial applications, the efficiency

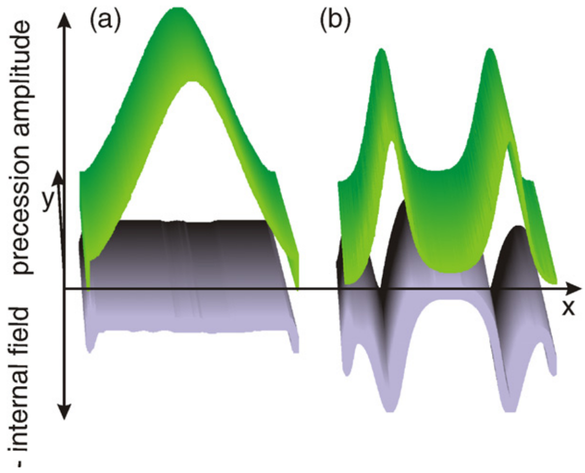

Figure 5. Spatial distribution of spin precession amplitudes and internal fields as simulated for a long and thin Permalloy nanowire (extending into the y direction). Two different magnetic configurations are distinguished in one and the same nanowire: (a) magnetization aligned along the long axis and (b) zig-zag-type magnetization generated by an in-plane magnetic field that is misaligned from the $x-$axis by a few degrees [81, 82]. In (b) deep sub-micrometre SW channels are formed. The width of one of the SW channels in the x direction is about 65 nm, i.e. much smaller than the wire's width of 300 nm. The eigenfrequencies are in the few gigahertz regime (after [77]). (Colour online.)

of the SW excitation and detection will determine the power consumption and error rates of magnonic devices. Hence, it is instructive to revisit techniques used in research labs to detect SWs and to consider them through the prism of their potential use in applications, e.g. within devices shown in figure 2.

To excite the precessional motion of magnetization, one can use harmonic [196] or pulsed [197] rf magnetic fields, ultrashort optical pulses [198–200], or dc or rf spin polarized currents [201]. The stimuli can therefore be referred to as a 'pump'. The same basic interactions and phenomena facilitate the detection of spins and SWs. For example, a magnonics researcher can take advantage of inductive [202, 203], optical [204, 205] or electrical [206, 207] probes to detect SWs. The main challenge and limitations of any such technique are associated with difficulties to match the frequency and wavelength of SWs and those in the spectra of the pump and/or the probe.

The cavity based FMR was historically the first experimental technique used to detect precession of magnetization [7] by measuring spectra of the absorption of microwaves in a cavity containing a magnetic sample. The spectra are determined by the density of states of SWs that can resonantly couple to the microwave field. The very long wavelength of microwaves, as compared with the length scale of magnetic structures of interest, limits the application of the FMR in magnonics to studies of magnonic modes with a significant Fourier amplitude at nearly zero values of the wave vector [54]. This mimics potential applications in which either the electromagnetic response of a magnonic device containing nanostructured functional magnetic elements is read out by the electromagnetic field or the magnonic (meta-)material [208] is supposed to absorb the incident electromagnetic radiation. Continuous magnetic materials and arrays of non-interacting magnetic elements are preferred for such applications near the frequency of the uniform FMR. However, more sophisticated micromagnetic engineering is required to push up the frequency of operation of such materials, e.g. using the exchange field [209, 210], which originates from the strongest of the magnetic interactions, rather than the uniform anisotropy or applied magnetic field.

The FMR is conventionally used to study magnetization dynamics at frequencies up to about 100 GHz. At higher frequencies, the mismatch between the linear momentum of a free space electromagnetic radiation (photon) and that of a magnon increasingly prohibits an efficient coupling. Therefore, higher frequencies require the use of different experimental and technical concepts to interrogate and measure, e.g., terahertz magnons. Here, methods known, e.g. from plasmonics, might help to couple light to magnons. For example, the attenuated total reflection technique has been successfully applied to the studies of magnons in antiferromagnets [211–213]. This field of research is still at its infancy.

The VNA-FMR technique represents a relatively new twist in the FMR spectroscopy where VNA highlights the use of a broadband VNA operated in the gigahertz frequency regime. Microwaves applied to a waveguide locally excite SWs that in turn induce a high-frequency voltage due to precessing magnetization (figure 4(a)). The VNA-FMR technique measures spectra of both the amplitude and phase change of microwaves passing through a magnetic sample integrated with the waveguide [214–216]. The geometrical parameters of the waveguide determine the spatial distribution of the rf magnetic field and therefore the wavelength spectrum addressed by the microwave field. Hence, the VNA-FMR can also be referred to as a 'near field' FMR. In the same way as, e.g., near field optical microscopy [217], the microwave near field allows one to couple to SWs with wavelengths of the order of the size of the microwave waveguide. The technique is therefore limited mainly by the resolution of lithographical tools used to pattern the waveguides as well as by the electrical noises in the circuitry and Joule losses in narrow waveguides. Due to the large penetration depth of microwaves, both thin film and bulk samples can be successfully investigated using the VNA-FMR. Sensitivity necessary to detect magnons in a single micrometre-sized magnet has been demonstrated [138]. Measurements have also been performed down to helium temperatures [218], which is essential for studies of samples that are super-paramagnetic at room and ferromagnetic at cryogenic temperatures. Time-resolved pulsed inductive microwave magnetometry (TR PIMM) represents a variation of the VNA-FMR technique in which the electric signal inductively picked up by the waveguide is analysed using a fast oscilloscope [219]. The FMR technique can also be used in FMR-force spectroscopy [220] and localized probe [221, 222] modes to study SWs locally, e.g. in individual micrometre-sized magnetic elements.

The BLS technique is based on the phenomenon of Brillouin–Mandelstam inelastic scattering of photons from either thermal, or externally pumped magnons [204]. The frequency and the wave vector of the scattered photons are shifted by amounts equal to the frequency and the wave vector of the scattering magnons, respectively. This facilitates a direct mapping of the magnonic dispersion in the reciprocal space [98, 175]. Because of the wave vector conservation in the magnon–photon interaction, the wavelength of SWs that can be detected in extended systems is of the same order of magnitude as that of light. Recently, the technique was modified to allow spatially resolved detection (imaging) of SW modes in magnetic structures of finite size (micro-focus BLS) [223–225]. In the micro-focus BLS measurements, the wave vector resolution is sacrificed in favour of the spatial resolution. The latter is determined by the smallest achievable optical spot size (about 250 nm for blue light), which is again limited by the optical wavelength. Recently, a phase sensitive micro-focus BLS technique has also been demonstrated [226, 227]. BLS measurements are quite demanding on the surface quality of the studied samples. Nonetheless, they have been applied to such 'rough' samples as granular [228] and rod [229] nanocomposites.

At present, it is difficult to envisage the BLS technique to be implemented in commercial magnonic devices for the detection of SWs. However, an interesting opportunity lies in using the inelastic light scattering for SW amplification [230], in particular in light of the recent discovery of room temperature BEC of magnons [63]. The sensitivity of BLS is limited to the surface region thinner than the optical skin depth and requires a high surface quality of the studied samples. Cochran pointed out that only 'acoustic' SW modes of a superlattice, in which magnetic moments of different layers precess in phase and which corresponds to the first Brillouin band of the spectrum, can be observed in a BLS experiment [231]. The higher frequency modes have an 'optical' character with magnetic moments precessing out of phase, which reduces the BLS signal from such modes dramatically.

Another way of probing magnetization is offered by measuring a change in polarization of light reflected from or transmitted through a magnetic sample, due to the magneto-optical Kerr and Faraday effects, respectively. In a time-resolved magneto-optical experiment, the sample is pumped by a method capable of exciting SWs (cf techniques discussed above), provided that the pump is both repetitive and coherent, i.e. it has a well-defined phase with respect to the probe beam. By changing the optical path of the probe beam one can trace the time evolution of the excited dynamics. To probe, one uses ultrashort optical pulses and controls their arrival time relative to the pump. The so-called TRSKM uses a focused probe beam which is scanned on the surface of the sample. The TRSKM provides images of dynamic magnetization with a spatial resolution of down to 250 nm in real space [232–235], and is suitable for studying both continuous and nanostructured samples, as demonstrated in figure 6. This is complementary to the micro-focus BLS. The temporal resolution of TRSKM can be well on the sub-picosecond time scale, therefore offering the detection of SWs in the terahertz frequency regime. The TRSKM performs a 3D vectorial analysis of the time dependent magnetization

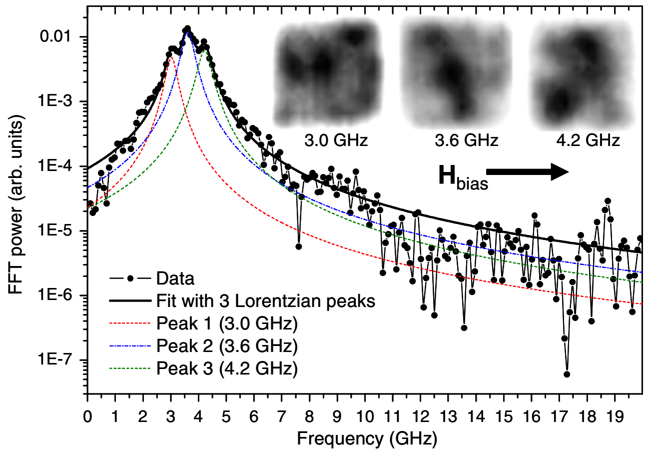

Figure 6. The fast Fourier transform (FFT) power spectrum calculated from a time-resolved Kerr signal acquired from the centre of a $4 \times 4\,\mu m^2$ array of $40 \times 80\,nm^2$ stadium shaped ferromagnetic elements at a bias magnetic field of 197 Oe is shown on a logarithmic scale together with the fit to a Lorentzian three-peak function. The inset shows the images of the modes confined within the entire array and corresponding to the peak frequencies identified from the fit. The darker shades of grey correspond to higher mode amplitudes. With respect to the long wavelength SW modes, the array acts as a continuous element made of a magnonic metamaterial. Such arrays will also act as metamaterials with respect to microwaves. Reproduced with permission from [208]. Copyright 2010, American Physical Society. (Colour online.)

[236] and is therefore phase sensitive. Alternatively, one can combine the magneto-optical detection with a VNA-FMR setup to image SW modes in the frequency rather than time domain [237]. The experimental setup is analogous to that in the VNA-FMR, except that the magnetization dynamics (SWs) in the sample are probed using a combination of a continuous wave laser and a gigahertz bandwidth polarization sensitive photo-detector rather than an inductive probe.

Recently, significant progress has been achieved in improving the spatial resolution and the signal strength in magneto-optical sensing using antireflection coatings [238], plasmonic coupling [239] and a careful control of the polarization of incident probe pulses [240]. The spatial resolution of the time-resolved technique could be improved using the magnetic second harmonic generation (MSHG) to detect magnetization dynamics at surfaces and interfaces [241].

The magneto-optical techniques have a modest outlook for being implemented with magnonic applications due to the large sizes of lasers and microwave detectors currently involved in the corresponding experiments. However, the situation might well change in the future due to the ongoing research in miniaturizing devices in optical recording and microwave communication technologies.

At synchrotron radiation facilities, techniques based on time-resolved x-ray magnetic circular dichroism (TR XMCD) have recently advanced considerably and they provide the advantage of element selectivity [242, 243]. However, in order to probe high frequency magnonic excitations, the time resolution needs to be improved further. Inelastic scattering using particle-like waves is known to address short wavelength SWs due to increased momentum transfer. For example, there is also a promise from the inelastic neutron scattering to map spectra of short wavelength SWs in superlattices [244]. Spin-polarized electron energy loss spectroscopy has already been shown to generate and detect high energy, large wave vector SWs in ultrathin ferromagnetic films [245]. Shortly afterwards magnonic dispersions on the nanoscale have been recorded using inelastic tunnelling of electrons from a scanning probe microscope [246, 247].

Let us now analyse the limitations imposed on SW frequency and wavelength addressed by the various methods. For electrical techniques, the spectrum of excited SWs is generally determined by that of the transient behaviour of the dynamical stimulus (pump). The inductive excitation is suggested to be powerful up to the frequency range of about 100 GHz. A higher coupling efficiency can be provided by 'wrapping' the magnonic waveguide around the microwave one [248]. Although some recipes for producing near field microwave wave forms have been proposed even for the terahertz range [249, 250], at higher frequencies, it becomes increasingly difficult to couple microwaves to metallic waveguides. The maximum wave vector that is transferred by such waveguides scales with the inverse width of the signal line. Considering state-of-the-art lithography one might reach a deep-sub-micrometre width here. However, at the same time the resistance increases and Ohmic losses as well as Joule heating will become a problem. In order to reduce the magnonic wavelength beyond lithographic limitations, one has to take advantage of the exchange interaction, which offers the shortest range, i.e. the atomistic length scale, and is the strongest of magnetic interactions. For example, in [251], it was demonstrated that the reversal of the magnetic vortex core results in a strong emission of short-wavelength SWs. One could extend this concept of SW excitation via 'exchange explosion' to the annihilation of domain walls in narrow nanowires. The required technology of domain wall creation is already well developed [252–255].

An attractive solution seems to be in the use of interfaces providing exchange coupling between the ferromagnetic material of a magnonic waveguide and some further magnetic material offering ultrafast dynamics, e.g. an antiferromagnet [256, 257]. One such scheme was proposed in [76]. First, the antiferromagnet is excited e.g. using either a femtosecond optical pulse [256–259] or a terahertz wave [211, 213]. The terahertz waves can directly couple to SWs in antiferromagnets more easily than in ferromagnets since the SW frequency in the former generally scales with the square root of the exchange field [213, 256]. The optical excitation can be either thermal [258, 259] or non-thermal [199, 256, 257]. The SW in the antiferromagnet then couples to the ferromagnet, in which the SW can be manipulated e.g. using means discussed above. The coupling is possible since the antiferromagnet and the ferromagnet interact via the exchange field localized in the atomically thin region at the interface. The SW signal is then transferred from the ferromagnet to another antiferromagnet (again across the interface) from which the signal is read out. In principle, the magnonic waveguide could also be antiferromagnetic, in which case any scattering at the interfaces is avoided but new means to manipulate the SW will have to be developed.

Finally, we note rich opportunities existing in the application of spintronics methods to magnonic studies [48, 67, 125, 206]. This, however, is a very broad field of research that can well be a subject of a separate review and is therefore beyond the scope of this review.

5. Challenges and future directions

Arguably, nanofabrication is the core of modern technological progress and will remain so in future. In the context of nanoscale magnonics, the principle nanomanufacturing challenge is to fabricate micrometre to millimetre scale periodic structures consisting of or containing magnetic materials precisely and controllably tailored at the nanometre scale. This challenge is certainly at the limit of current lithographic tools. Hence, bottom-up technologies might have to be exploited instead. For example, protein based colloidal crystallization techniques can be used to produce macroscopic 3D ordered magnetic arrays [260, 261]. In order to integrate such arrays into magnonic devices, researchers will need to combine the protein based nanomanufacturing with such more conventional top-down techniques as laser-interference lithography [262], focused ion beam (FIB) and electron-beam lithography and with such advanced 3D material deposition techniques as atomic layer deposition (ALD) [263] and electrodeposition tailored for use with multiple magnetic materials. ALD film growth is self-limited, thereby achieving atomic scale control of the deposition. Recently, ALD was used to deposit ferromagnetic thin films (such as Ni, Co and Fe_3O_4) into deep-etched trenches and membranes [264–266]. The complementary topology is also possible by, e.g., conformal coating of templates consisting of tailored nanowires [267]. Such possibilities make ALD a promising tool for the fabrication of 3D magnonic devices. Electrodeposition is also very well suited for deposition into complex templates [268]. It is fast and thereby suitable for scaling up to produce a large number of devices. For example, arrays of cylindrical magnetic nanowires deposited electrochemically within porous membranes [269–271] have attracted much attention due to their potential for use as microwave [272] and terahertz [273] devices, and recording media [274]. Reprogrammable dynamic response has been demonstrated through different remanent states of planar arrays of nanomagnets [275]. The reconfiguration of a 1D magnonic crystal has recently been demonstrated via variation of the orientation of neighbouring ferromagnetic nanowires from parallel to anti-parallel magnetic states (figure 7) [276]. Experiments and simulations have shown that SWs propagating perpendicular to the long axis of such coupled nanowires experience different artificial magnonic band structures in configurations (*a*) and (*b*). Magnonic dispersions have thus become reprogrammable. Such characteristics applied to complex 3D magnonic devices might generate unforeseen functionalities. Quasi-static [277, 278] and, more visionary, gigahertz-modulated strain by surface acoustic waves [279] might also be used to reconfigure the magnetic state [280] and the dynamic response at remanence. These techniques offer new routes to the control of

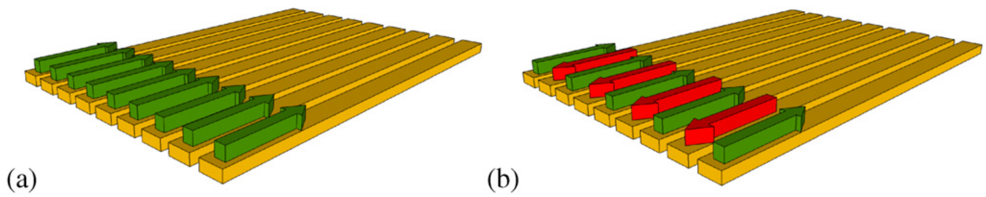

Figure 7. Two different remanent magnetic configurations of a 1D magnonic crystal formed by interacting ferromagnetic nanowires are shown for (*a*) parallel and (*b*) anti-parallel alignment of neighbouring nanowires. Arrows illustrate the orientation of the magnetization of the individual nanowires. In (*b*), the magnetic unit cell of the magnonic crystal is twice as large as the geometrical one, suggesting zone folding effects of magnon dispersions in the reciprocal space. (Colour online.)

magnonic devices by electrical fields complementing already existing means based, e.g., on external magnetic fields and electric currents [227]. Magnonic devices fabricated directly from multiferroic materials or multilayers [281] promise unprecedented characteristics and multi-functionality.

Concerning materials research it is of utmost importance to create materials with significantly reduced values of the magnetic damping parameter. Such materials should be in particular compatible with the advanced nanofabrication techniques. For example, the latter requirement renders existing microwave ferrites unsuitable for magnonic architectures. Permalloy is currently the most widely used ferromagnetic material with a low damping parameter down to $\alpha = 0.008$ [282–284]. This has so far been sufficient to generate coherent effects such as SW interference on the micrometre scale [122]. However, at least an order of magnitude reduction of the value is required to make the magnonic technology competitive. It is interesting to note that the same issue is faced by the spin transfer torque technology [285–287]. The effects connected with modulation of the damping strength that is expected to occur in magnonic crystals were studied in [75, 156, 288] for 1D magnonic crystals. In particular, it was found that the effective damping of SWs varies from band to band, leading to anomalously weak attenuation in cases when the amplitude of SWs is 'concentrated' in layers with a weaker damping. Recently, in [289], the calculations have been extended to the case of 2D magnonic crystals similar to those considered in [74, 176]. It was suggested that the variation of the effective damping could be used for channelling of SWs along directions where the reduced damping is observed.

The periodicity of magnonic crystals and inherent non-uniform magnetic fields within their constituent elements not only offer a range of opportunities to control magnons, but also make their propagation remarkably more intricate than propagation of, e.g., electrons and electromagnetic waves through semiconductor superlattices and photonic crystals, respectively. Due to the complexity of magnon propagation, the theory of magnonics requires a major improvement in the case of involved 3D topologies. In particular, theoretical tools suitable for the calculation of SW dispersion and susceptibilities in samples with irregular geometries are required. This has led to the development and successful use of numerical algorithms to simulate the high frequency magnetization dynamics in real space and time [290–294]. However, despite the continuous improvements in the processor speed and computational power, micromagnetic simulations are not yet capable of handling large 3D magnetic nanostructures. In the dynamical matrix method [295, 296], a sample of an arbitrary shape is discretized into a mesh of cells of equal size. The system of linearized equations of motion of magnetization of individual cells is reduced to an eigenvalue problem, with a corresponding system of algebraic equations solved numerically. So far, the dynamic matrix method has only been applied to periodic arrays of magnetic particles embedded in a non-magnetic medium. Future theoretical approaches will need to incorporate, both, modified magnetic interaction between nanoelements and the effects of non-linearity in the case of large-amplitude spin precession excitation in nanomagnet arrays [297].

In order to study coupling of magnonic devices to other excitations, a number of further challenges in micromagnetic modelling should be addressed. The mathematical formalism of micromagnetic solvers should be extended beyond the classical Landau–Lifshitz equation, crossing boundaries with such sub-fields of magnetism and, more generally, solid state physics, including e.g. antiferromagnetism and ferrimagnetism, semiconductor and metallic spintronics, optics and electromagnetic emission, thermodynamics and statistical physics. In many cases, modelling at the atomic scale and a proper account of the quantum-mechanical effects are essential. To line up with the recent progress in ultrafast science, non-equilibrium electron and lattice dynamics should also be rigorously treated. Such diverse phenomena naturally extend through very different time and length scales. The anisotropy and exchange fields define the frequency of SWs with wavelengths from the nanometre to micrometre length scales. Magnetic domain walls have widths of a few (tens of) nanometres, while the domain structure depends upon the size and global shape of the entire sample. The time scales on which magnetic systems respond to external perturbation by fields, stress or temperature vary from femtoseconds in the case of ultrafast demagnetization to hours in the case of slow thermal decay of magnetization. A simultaneous and accurate account of these different phenomena within the same formalism is infeasible, due to unrealistic demands for computational power. Hence, new algorithms and methods are required to bridge the time and length scales each extending over several orders of magnitude. Finally, the global challenge for magnonics is to scale the experimental research reviewed in the previous sections of this paper to the nanoscale. Indeed, the experimental techniques used in magnonics are operated at the limits of their resolution and/or sensitivity. Hence, novel techniques breaking the limits are urgently required.

6. Conclusions

Brought about by major advances in nanotechnology and magnetic experimental techniques, magnonics is a novel interdisciplinary research field benefitting from old roots. Alongside remarkable challenges, there are also a number of unexplored opportunities for further exciting advances and significant potential for practical applications. We hope that this review will guide current and future researchers through the challenges towards new fundamental and applied achievements in the field of magnonics.

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