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Magnonics based on domain wall and skyrmion propagation

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Abstract

Magnon spintronics aims at utilizing magnons to realize information transport and storage on the microscale and nanoscale. Magnetic textures can be stabilized due to the interaction between the Heisenberg exchange interaction, dipolar interaction and Dzyaloshinskii–Moriya exchange interaction. These magnetic textures such as magnetic domain walls, vortices, skyrmions interact with magnons to realized SW-based devices, which are prime candidates for next-generation logic devices due to higher throughput and lower power consumption. In this article, we review the theoretical and experimental progress on reconfigurable magnonic waveguides based on the interaction of spin waves with magnetic textures. In addition, the effect of spin waves on magnetic texture dynamics has also been discussed.

Keywords

Spin wave; Domain wall; Magnonic waveguide; Skyrmion.

1. Introduction

Magnons (quantum states of spin waves) are the collective excitation magnetizations in a magnetically ordered systems, which was first introduced 1930 by Felix Bloch to described ferromagnetism in a lattice [1]. The field is developing rapidly due to the potential to replace CMOS-based (complementary metal–oxide–semiconductor) electronic devices [2]. Moreover, magnons can be used for efficient signal transmission and information processing [3,4]. When the spin waves are used as the information carrier, lower energy consumption and independent of charge transport lead to almost no Joule heating in the devices. In the future, magnons have important applications for device miniaturization due to high-frequency data processing in the terahertz region.

The symmetric Heisenberg exchange interaction and asymmetric Dzyaloshinskii-Moriya interaction for spin textures favor non-collinear spin arrangements with unique spin orientations, including spin spirals, skyrmions and chiral domain walls. These inhomogeneous spin textures provide an effective means to tune spin waves propagation channel in magnetic materials. In particular, the research on reconfigurable magnetic waveguides for design any form circuit needs to be further expanded. Similarly, spin textures in magnetic nanowires need to find controllable manipulations. In this paper, we review the manipulation of spin textures for magnonic waveguides at the nanoscale. Advances in effective manipulation of nanoscale spin textures using spin waves are introduced.

2. Spin wave propagation along spin textures

2.1. Spin wave propagation along domain wall

Recently, the interplay between spin wave and domain wall has attracted considerable attention. Magnetic domain walls are transition regions between different domains along which spin waves can be guided, which was pioneered by Winter in 1961 [5]. In 2015, Garcia-Sanchez *et al.* showed theoretically and simulations that spin wave can propagate through a nanochannel based on domain wall [6]. They found that spin waves can be channelled in two different 180° domain walls types (Bloch and Néel type domain walls) as shown in Fig. 1a. Furthermore, spin waves non-reciprocal propagation along Néel-type domain walls due to the Dzyaloshinskii-Moriya interaction (DMI). Xing *et al.* showed in simulations the spin-wave propagation behavior of domain wall-based self-cladding internal nanochannels [7]. In a certain frequency range, the channeling effect of the waveguide has a potential well due to the domain walls existence, and the channeling effect is nonvolatile. Beyond a certain frequency, spin waves are trapped not only within the domain walls but also within the domains.

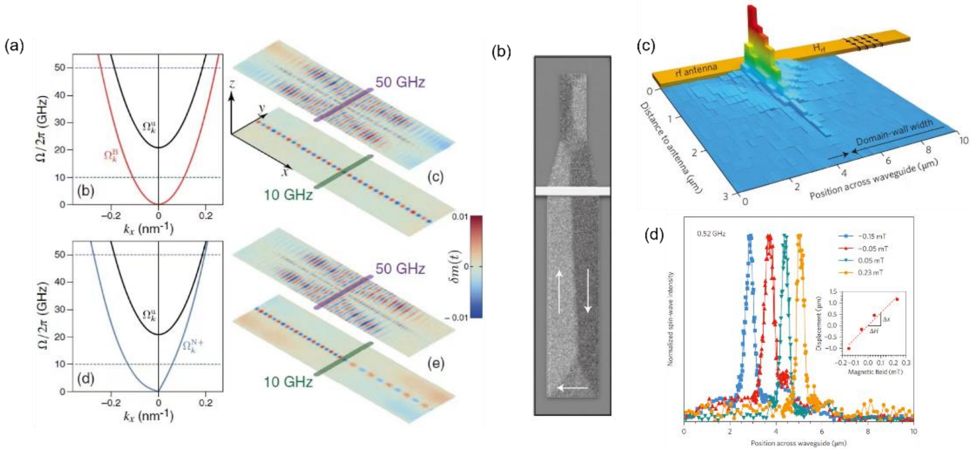

Fig. 1 Spin waves propagate through domain wall-based nanochannels. Reproduced from Ref. [6] and Ref. [8]

Notably, in 2016, Wagner *et al*. experimentally demonstrated that magnetic domain walls can be used as reconfigurable spin-wave nanochannels [8]. In micrometer samples, Wagner and coworkers demonstrated that magnetic fields can drive domain walls, realizing domain wall-based reconfigurable magnonic waveguides (see figure1(d)). Spin wave inside the nanoscale 180° Néel-type domain wall channel measured experimentally using Brillouin light scattering (BLS) and observation of magnetic domain patterns using wide-field Kerr microscopy by Wagner et al (see figure1(b-c)). Magnetic-vortex-stabilized domain wall channels propagating spin waves can also be imaged by using BLS and scanning transmission X-ray microscopy (STXM) [9,10]. Furthermore, a key advantageous route was experimentally confirmed by Ablisetti *et al*., who utilized thermally assisted magnetic scanning probe lithography (tam-SPL) to form nanoscale reconfigurable spin-wave channels in continuous exchange biased ferromagnetic layers [11]. These results indicate that strip domain walls can be further studied as magnonic waveguide channels in the future, and provide a new idea for researchers to develop miniaturized magnonic devices with low energy consumption and high processing speed.

2.2. Spin wave propagation along skyrmion strings

In a three-dimensional (3D) system, skyrmions can form a string-like structure consisting of a uniform stack of two-dimensional (2D) skyrmion spin textures, which can serve as a nonplanar magnonic waveguide. In 2020, Xing *et al.* predicted using skyrmion tubes to guide spin waves through micromagnetic simulations (see figure2(a)) [12]. Their waveguides, constructed using the skyrmion tubes, appear as arrays or lattices, with no geometric constraints on the sample. In other words, skyrmions can also be used as potential magnonic waveguides.

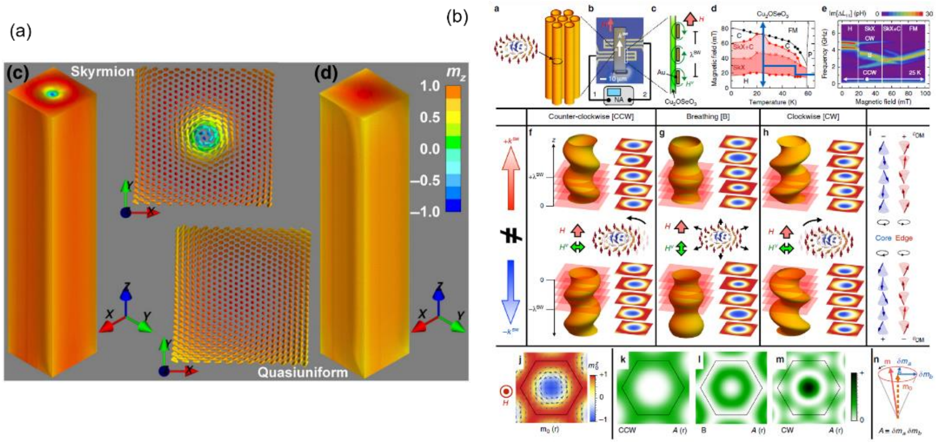

Fig. 2 The skyrmion excitation propagating along the skyrmion strings.

Remarkably, about the same time as when Xing *et al.* theoretically predicted the possibility of using skyrmions as a signal transmission channel, Seki *et al.* demonstrated in experiments that propagating spin excitation along skyrmion strings [13]. They reported the propagation of spin waves along skyrmion strings in Cu_2OSeO_3, a material capable of carrying skyrmion strings at low temperatures (see figure2(b)). The authors found that this propagation characteristic is directionally nonreciprocal, and that the nonreciprocity degree as well as decay length and group velocity of propagation are strongly dependent on the excitation modes, both of which can be interpreted as dispersion relations. The next year, Seki and his collaborators directly visualized the 3D shape of a single skyrmion strings utilizing scalar magnetic X-ray tomography under an applied magnetic field [14].

3. Spin textures motion driven by magnonics

3.1. Domain wall motion driven by spin wave emission

The role of domain walls in guiding spin waves has been discussed in the previous chapter. In addition, domain walls can also influence spin waves by adjusting phase shifts and amplitudes, and spin waves can in turn act on domain walls. Le Maho *et al.* discussed theoretically the contribution of spin waves to current-induced domain wall dynamics [15]. As we all know spin-polarization currents generate spin transfer torque or spin orbit torque on magnetization, which can be used to drive domain wall motion. Similarly, Yan *et al.* theoretically revealed that when the all-magnonic spin torque is large enough, it can also drive domain wall motion [16]. Their conclusions show that the domain wall move in the opposite direction of spin wave propagation (see figure3). Subsequently, Wang *et al.* found through mathematical description that in low fields, the spin-wave assisted domain wall transmission adopts one particular soliton velocity [17]. Recently, Han and colleagues used propagating spin-wave spectroscopy (PSWS) and magneto-optical Kerr effect (MOKE) to make experimental observations of coherent spin-wave-induced domain wall motion in cobalt/nickel (Co/Ni) multilayers [18]. Using microwave antennas to excite spin waves, the spin waves move away from the antenna, but the domain walls move closer to the microwave antenna, which is consistent with the theoretical predictions of Yan *et al*.

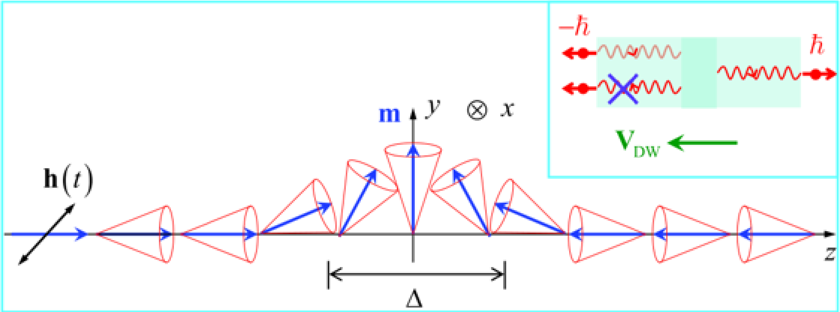

Fig. 3 Sketch describing the mechanism by which Magnons drive the movement of domain walls. Reproduced from Ref. [16].

3.2. Skyrmion motion driven by spin waves

Magnetic Skyrmions are topologically protected spin configuration in magnetic materials, which can be divided into Néel-type and Bloch-type skyrmions due to different DMI types. As with the relationship between domain walls and spin waves, there are interactions between skyrmions and spin waves. The skyrmion circuits are constructed with different geometric structures based on spin waves [19,20]. Theoretical studies by Iwasaki *et al*. showed that spin waves have the ability to drive skyrmions motion [21]. Owing to topological protection, skyrmion will not only move but will not be weakened by spin waves (see figure4).

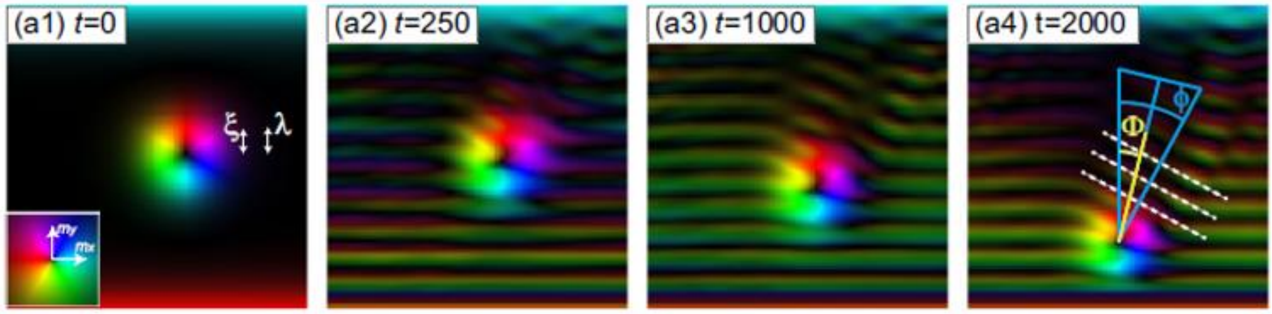

Fig. 4 Snapshots of skyrmion–magnon scattering processes. Reproduced from Ref. [21].

Acknowledgements

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