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Frequency-selective manipulation of spin waves: micromagnetic texture as amplitude valve and mode modulator

Xiangjun Xing, Qingli Jin and Shuwei Li

1 College of Physics and Electronic Information Engineering, Wenzhou University, Wenzhou 325035, People’s Republic of China
2 State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-sen University, Guangzhou 510275, People’s Republic of China

E-mail: xxjun@wzu.edu.cn

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Abstract
Spin–wave devices are regarded as one of the most promising candidates for future computation and data processing. How to manipulate spin–wave propagation is a key issue in realizing the functionality of these of devices. The existing manipulation methods have serious drawbacks for constructing practical spin–wave devices. Here, we propose an approach to harness the amplitude and mode excitation of traveling spin waves by introducing unique micromagnetic textures in a permalloy waveguide directly exchange-coupled to a pair of cobalt nanomagnets. We demonstrate that the imprinted micromagnetic textures, i.e., the 360° domain wall and magnetic buckle, which play different roles in spin–wave manipulation, can be interchanged with each other repeatedly by using a sequence of homogeneous magnetic fields. Moreover, the suggested architecture could easily be tailored to implement fundamental logic-NOT operation. In light of the internal-field profile of the micromagnetic textures, speculation is offered concerning the physical origin underlying the observed spin–wave modulation phenomena.

Introduction
Spin–wave-based signal processing [1–9] is widely recognized as a potential successor to semiconductor-based technologies [10]. Besides the advantages of power efficiency and miniaturization [10, 11] spin–wave devices possess, it appears feasible to integrate spin–wave logic [2–9] and racetrack memory [12] on a single chip, enabling a one-chip, all-metal, computation architecture, considering that the racetrack memory and a majority of proposed spin–wave logic devices have a common magnetic strip structure [5–7, 12]. Realization of logical operation is a primary step in the design of spin–wave logic circuits, and furthermore, the manipulation of spin–wave propagation is the basis for logic operation.

Over the past decade, a variety of spin–wave logic devices have been put forward, with a series of strategies for spin–wave manipulation suggested [2–9]. As early as 2004, Hertel et al found a way of using a domain wall to control the phase of passing spin waves, and thereby suggested a spin–wave logic-XOR gate [5]. However, it is not easily attainable to produce localized domain walls in elongated magnetic strips [6]. The approach developed recently to generate domain walls requires an extra injection pad [13] and thus is detrimental to device compactness. Instead, Lee et al explored a new route of modulating the phase of spin waves by using a current-generated Oersted field, which was further utilized to build a set of Mach–Zehnder-type logic gates [6]. Spin–wave manipulation using current-generated Oersted fields has been the most prevalent choice to perform logic operation, and was adopted in those spin–wave logic gates demonstrated experimentally for the first time [8, 9]. Unfortunately, the control method based on Oersted fields would be subjected to lower and lower operational efficiency with downscaling in the waveguide, as pointed out by Vasiliev et al [14]. Recently, Au et al provided a means with which either the amplitude or the phase of spin waves in a magnonic waveguide could be harnessed depending on the spacing between the waveguide and a control object [15]. This finding is scientifically
interesting, but the separation-dependent toggle of the observed valve and phase-shift effects is highly undesired in device application. Thus, it is urgent to find efficient ways of controlling spin–wave propagation.

360° domain walls [5, 13, 16–19] belong to a remarkable micromagnetic texture in the family of magnetic nonuniformities, which have been proven to play significant roles in spin–wave manipulation in a broad range [20]. Furthermore, 360° domain walls are even superior to transverse walls to be used in racetrack memory due to their short-range stray field [17]. In this article, we report on the controlled injection and transformation of two different micromagnetic textures, viz. a 360° domain wall and a magnetic buckle, in a magnonic waveguide by using a sequence of uniform magnetic fields. The propagation characteristics of the spin waves passing through these micromagnetic textures are addressed. We find that for a range of low frequencies, the micromagnetic textures act as a spin–wave amplitude valve, while for a range of high frequencies they become a wave–mode coupler. Namely, the imprinted micromagnetic textures could modulate either the amplitude or the mode occurrence of the propagating spin waves, depending on the carrier frequency. The observed modulations of spin–wave propagation likely arise from the difference in the internal fields of the two micromagnetic textures. Additionally, a reprogrammable logic–NOT gate is conceived based on this finding.

Methods

Micromagnetic models

Figure 1(a) shows the layout of a hybrid waveguide. The Py strip is 4 μm long and 100 nm wide. Two waveguides with an individual thickness equal to 10 nm and 8 nm, respectively, were examined. A pair of Co nanomagnets is attached on top of and perpendicularly to the Py strip, and the narrow Co bar is atop the middle length of the strip. The double bars have an identical length of 140 nm and individual widths of 40 and 20 nm, respectively. The thickness of these Co pairs is equal to that of the Py strip. The ends of the Co bars are tapered to enhance the shape anisotropy [21]. No bias field is applied to the hybrid structure, and thus the magnetization is aligned along the strip by the shape anisotropy of the latter, forming backward-volume propagation geometry [22] for the spin waves in regions not in contact with the Co bars. In the areas below the Co bars, a very small traverse component of magnetization is induced in response to the exchange field of the bars. The microstrip antenna for spin–wave emission sits at a position 1 μm away from the left edge of the Py strip. Near the ends of the strip, the damping coefficient is largely increased to reduce the back reflection of incident spin waves [23]. A radio-frequency (rf) field in the form of \( h_f(t) = H_0 \sin(2\pi ft) \hat{e}_z \), with the field amplitude \( H_0 \) equal to 100 Oe and the frequency \( f \) being in the gigahertz range, is supplied to the antenna to excite spin waves. (On the experimental side, a microwave voltage should be fed to the antenna to generate the required rf Oersted field).

Numerical simulations

Micromagnetic simulations [24] were carried out to search the spin–wave dynamics in the hybrid Co/Py structure by numerically solving the Landau–Lifshitz–Gilbert equation [25] in the linear region [26]. The entire structure was discretized into cubic meshes, whose side lengths are 5 nm and 4 nm for the Co/Py samples with layer thicknesses of 10/10 nm and 8/8 nm, respectively. The material parameters selected are as follows. For the Py strip, typically, the saturation magnetization is 860 emu cm\(^{-3}\), the exchange stiffness is \( 1.3 \times 10^{-6} \) erg cm\(^{-1}\), and the magnetocrystalline anisotropy was set to zero. For the Co bars, the saturation magnetization is 1414 emu cm\(^{-3}\), the exchange stiffness is \( 3.05 \times 10^{-6} \) erg cm\(^{-1}\), and the uniaxial anisotropy constant is \( 4.0 \times 10^6 \) erg cm\(^{-3}\) with the anisotropy axis pointing \( \pm y \). The Gilbert damping factor was set to 0.1 and 0.5 in the light–gray and dark–gray end areas, respectively, and it is 0.01 for both Co and Py outside the overdamping end regions. At the interface between the Co bars and the Py strip, the exchange stiffness equal to \( 1.823 \times 10^{-6} \) erg cm\(^{-1}\) is given by the harmonic mean of those values of Py and Co as in references [27, 28]. (Results obtained from numerical simulations for the 10/10 nm or 8/8 nm thick Co/Py samples are qualitatively consistent. So, all the results used in the figures for presentation and discussion are from the 10/10 nm sample.)

Results and Discussion

Generation of micromagnetic textures

To make micromagnetic textures in the long Py strip, naturally, a random arrangement of magnetization is chosen as the initial state for the whole Co/Py structure. Homogeneous external fields are applied to tailor the magnetization. At the first step, a suitable field is imposed on the Co/Py sample, and after full relaxation of the system, an equilibrium magnetic buckle is injected into the Py strip (figure 2(g)). A 360° domain wall could be written into the Py strip in place of the magnetic buckle by using an appropriate sequence of uniform fields. To do so, the field sequence should be elaborately devised. Additionally, the Py strip in the 360° domain wall state can be driven back to the buckle state by a single magnetic field. Namely, the 360° domain wall and the magnetic...
buckle can be transformed cyclically into each other in the Py strip under the action of certain field sequences, as illustrated in figure 1(b) where the magnitude, direction and duration of a sequence of magnetic fields are denoted. The magnetization configurations in the Co/Py structure at specific times after the application of a field or free relaxation are represented in figure 2. Note that each of these moments has been marked on the time axis in figure 1(b). Once excited, the spin waves travel along the Py waveguide and are subjected to modulation of a micromagnetic texture situated underneath the Co bars.

Figure 1. (a) Sketch of the hybrid Co/Py waveguide for spin–wave propagation and manipulation. No insertion between the Py strip and the Co bars. The Py strip is 4 μm in length. The light-gray and dark-gray areas with large damping constants ensuring spin–wave antireflection are each 100 nm wide in the x direction. The Co pairs are 140 nm long along the y axis. The spacing between the wide and narrow Co bars is 50 nm (48 nm) for the 10/10 nm (8/8 nm) thick Co/Py sample. The magnetization arrangement characterizing a 360° domain wall is overlaid on the architecture. An rf field is fed to the micro-antenna to excite spin waves at a given frequency. Once excited, the spin waves travel along the Py waveguide and are subjected to modulation of a micromagnetic texture situated underneath the Co bars. (b) Field sequence and duration used to toggle the 360° domain wall (360DW) and the magnetic buckle (BUCKLE). The magnitude and orientation of each field as well as the duration of each event are given. In the ‘relax’ stage, the whole system is freely relaxed with zero fields applied. Process (i) from the buckle to the 360° domain wall and (ii) from the 360° domain wall back to the buckle. (c) Magnetic hysteresis loops for the Co elements decoupled from the Py waveguide. The magnetic field H is along the long axis of each Co bar. The variation in widths of the two Co bars makes them show different coercivities, forming the basis of the field-driven transformation of the two micromagnetic textures in the Py waveguide.
During the next duration $\Delta t_2$, the second field $H_b$ is turned on. It includes a small component antiparallel to the axial magnetization component of the wide Co bar, and thus drives the wide Co bar to flip its magnetization. Meanwhile, the magnetization in the Py strip beneath the wide Co bar rotates downward. Because of the difference in width, the two Co bars have unequal shape anisotropies (figure 1(c)), which makes it harder to reverse the magnetization of the narrow Co bar. After full relaxation, the Co/Py structure arrives at the magnetization configuration as shown in figure 2(c). Here, the magnetizations in the local areas of the Py strip underneath the two different Co bars point in opposite directions, which is a prerequisite for generating a 360° domain wall (see [18]). To obtain this state, the double Co bars with different widths and the two magnetic fields ($H_a$, $H_b$) with opposite $y$ components are chosen. Subsequently, a magnetic field $H_c$ is open in the duration $\Delta t_4$ in order to reverse the Py magnetization vectors outside the Co/Py contact region, thereby yielding a 360° domain wall (figure 2(d)). The magnetizations beneath the two Co bars are tightly bound to the latter by exchange coupling, so that the small $H_c$ cannot rearrange them. After free relaxation of the whole system, the equilibrium 360° domain wall is formed in the Py strip. If a strong external field $H_d$ is imposed on the Co/Py sample in the same direction as $H_c$, the structure of the 360° domain wall will be destroyed rapidly, and then all magnetizations are toggled to the field direction. After relaxation, a magnetic buckle reappears in the Py strip.

The process of generating a 360° domain wall (figure 2(d)) from the intermediate configuration state (figure 2(c)) involves injection and annihilation of a magnetic vortex [29, 30] at the lateral edges of the strip, implying that the transition from the magnetic buckle to the 360° domain wall is nontrivial. Consequently, the structure design for the field $H_c$ is essential to the formation of the 360° domain wall. The sequence of $H_a$, $H_b$, $H_c$ and $H_d$ (figures 1(b) and 2) used to demonstrate the feasibility of injecting these desired micromagnetic textures is only an exemplary solution out of the available ones, and does not necessarily represent the best one with respect to operational efficiency. At any rate, we accomplish controllable injection of localized micromagnetic textures into a Py strip by using globally uniform magnetic fields in combination with a pair of Co traction bars. Quite recently, Oyarce et al [19] demonstrated a route of injecting a 360° domain wall into a similar magnetic strip, on top of which two nonmagnetic conducting wires capable of carrying a current as large as $10^{12}$ A m$^{-2}$ were fixed to generate sufficiently strong Oersted fields in the strip for domain–wall nucleation. This method might bring the heat accumulation problem into the device design.

Figure 2. Configuration of magnetization vectors in the Co/Py structure at a time after each event in the cyclic process starting from the magnetic buckle to the 360° domain wall as defined in figure 1(b). The denotations have exactly the same meaning as in figure 1(b). For clarity of representation, here the Co pairs are detached from the Py strip. The displayed proportion of the strip is 600 nm long and 100 nm wide. Color encodes the $m_y$ component of magnetization. Arrows symbolize the in-plane (i.e. xy plane) component of magnetization.
Effect of micromagnetic textures on spin waves

To check the impact of the 360° domain wall and the magnetic buckle on spin–wave propagation, a spin wave is excited at the antenna position by using an rf field with the target frequency. Once emitted, the spin wave travels through the Py strip. Figures 3(a1) and (a2) show the snapshots of spin–wave distribution at 10 GHz in the Py strip including either a 360° domain wall or a magnetic buckle, clearly indicating the different roles of these textures in modifying the spin–wave propagation. When the spin wave passes through the 360° domain wall, it maintains considerable magnitude, but when the same spin wave extends past the magnetic buckle, it loses almost all of the energy. The fact becomes clearer in figures 3(a3) and (a4) where the fast-Fourier transform (FFT) amplitude maps for the same spin waves are given. In short, the micromagnetic textures act as an amplitude valve for spin waves propagating in the Py waveguide. In other words, the Py strip containing the 360° domain wall is a low-resistance waveguide, while the strip bearing the buckle results in a high-resistance state for spin–wave transport. If the low resistance is defined as logic input ‘0’, the high resistance as logic input ‘1’, and the strength of the spin wave probed at a collection point in the right arm of the Py strip is used as the logic output, the Co/Py structure becomes a logical NOT gate [see figure 3(c)]. The frequency band over which the valve effect of the micromagnetic textures on spin–wave transport holds is about 2 GHz wide, as seen from figure 3(b), in which the amplitude ratio of the two spin waves past the 360° domain wall and the magnetic buckle is plotted against the carrier frequency of the spin waves.

If the carrier frequency of the spin waves is increased, the scenario will be totally different. Now, the amplitude modulation of the spin waves around 10 GHz by the micromagnetic textures changes to the mode modulation of the spin waves around 18.5 GHz by the same micromagnetic textures. Figures 4(a1) and (a2) depict the spin–wave distribution at 18.5 GHz in the Py strip with a 360° domain wall or a magnetic buckle. Here, the spin–wave profile behind the 360° domain wall is nonsymmetrical about the middle axis of the Py strip, exhibiting a zigzag propagation pattern [7, 31] (figure 4(a1)). By contrast, the spin–wave distribution behind the magnetic buckle remains as symmetric as that in front of the buckle with respect to the strip’s central axis. In our opinion, the zigzag-like propagation pattern for the spin waves across the 360° domain wall suggests the emergence of asymmetric spin–wave modes [31, 32]. Interference [28] of the original, symmetric and the
newly excited asymmetric spin waves leads to the observed zigzag propagation of the spin waves[7, 31]. The antenna used for spin–wave excitation is a micro strip and can only selectively activate the spin–wave modes that have the same symmetry as the antenna itself, i.e., exhibiting mirror-like symmetry relative to the spin–wave propagation direction [33].

The mode number \( m \) is a good parameter to describe the symmetry of the spin waves propagating in a one-dimensional magnonic waveguide [34]. In this article, \( m = 2n - 1 \) for symmetric waveguide modes, and \( m = 2n \) for asymmetric modes, where \( n = 1, 2, 3, \ldots \). For the excitation geometry of the chosen antenna, the higher is the order of the spin wave, the lower the excitation efficiency for it [33]. Correspondingly, only the first- and third-order modes can be substantially driven by the rf antenna field. The spin–wave pattern formed on the left side of the Py strip stems from superposition of the two lowest symmetric modes (see references [7] and [35]), and accordingly, is of perfect symmetry about the waveguide axis. When the spin waves enter into the territory of the 360° domain wall, the asymmetric second-order mode is activated therein, causing at least three modes to coexist inside the right arm of the Py strip. However, the original, symmetric modes are heavily attenuated and lose most of the carried energy inside the domain wall, so that the second mode dominates the spin–wave propagation in the right arm of the Py waveguide. The situation for the spin waves flowing into the magnetic buckle is different. Here, no conversion from the original first- and third- to the second-order modes occurs. As a consequence, the passing spin waves keep a symmetric propagation pattern. The FFT phase maps for spin waves are presented in figures 4(a3) and (a4), from which the mode profiles of the spin waves in the Py strip with various micromagnetic textures can be identified. Figure 4(b) plots the phase difference of the spin waves travelling along the upper and lower halves of the waveguide as a function of the propagation distance of the spin waves. The phase difference is around \( \pm \pi \) for the spin waves past the 360° domain wall, and is around zero for the spin wave passing through the magnetic buckle. As expected, the phase difference is zero for both spin waves in front of the 360° domain wall and the magnetic buckle.

These results corroborate that, at the frequency around 18.5 GHz, the 360° domain wall is a mode converter for the travelling spin waves, and comparatively, the magnetic buckle does not introduce new modes into the passing spin waves. If a double-branch element is connected to the right end of the Py waveguide, the spin waves...
past the 360° domain wall would be split into two beams with a phase shift of \( \pi \), as demonstrated in [7]. When the split beams merge in the collection arm, destructive interference should happen, resulting in a low spin–wave signal. When the same spin wave is sent into the setup with a magnetic buckle included in the arm ahead of the splitter, a constructive interference fringe should form in the collection arm, enabling a large spin–wave signal. In this way, the constructed Mach–Zehnder setup performs a logic-NOT operation [see figure 4(c)]. With the spin waves at \( \sim 10 \) GHz as carrier, the logic gate in figure 4(c) can also do NOT operations as long as the logic input is recoded. Namely, this logical gate can be programmed with two independent coding schemes based on separate frequency bands of the travelling spin waves. The functionality of this Mach–Zehnder logic-NOT gate is evident, considering the similarity in the main structures of the gate suggested here and those demonstrated in [6, 7]. The frequency-selective property of the spin–wave manipulation in the hybrid Co/Py waveguide makes it easy to reprogram the gate.

From figures 3 and 4, it is clear that by changing the type of micromagnetic texture underneath the Co bars, it is possible to control the amplitude and mode excitation of the spin waves in the Py waveguide, and depending on the excitation frequency, the micromagnetic textures could serve either as a spin–wave valve or as a mode modulator. Figures 5(a)–(d) show the FFT amplitude and FFT phase of the spin waves inside the 360° domain wall and the magnetic buckle, in order to stress the influence of these micromagnetic textures on the transmission characteristics of the spin waves. Comparing figures 5(a) and (b), it can be found that the spin waves are allowed to exist in the interior of the 360° domain wall, but are forbidden inside the magnetic buckle, since the strength of the spin waves is considerable over the 360° domain wall, but negligible throughout the buckle. This feature can be explained according to the internal-field profiles of the micromagnetic textures. In figure 5(e), the internal field of the 360° domain wall is highly inhomogeneous, with a zero-field core enclosed by two high-field shells along the lateral edges of the Py strip, and the shell’s field has opposite directions on the two sides of the 360° domain wall. The zero-field core enclosed by the high-field shells serves as a channel to conduct spin waves [36, 37]. As shown in figure 5(f), the internal field of the magnetic buckle is relatively uniform, involving neither the zero-field channel nor the reversal of the field direction. For spin waves around 10 GHz, the occurrence of the zero-field region is indispensable to spin–wave transmission into the right arm of the Py strip, because the zero-field core forms a potential well [35] in which spin waves are allowed, while the high-field shell creates a potential barrier where spin waves are prohibited. For spin waves of around 18.5 GHz, both internal fields of the 360° domain wall and the magnetic buckle are not strong enough to lead to a potential barrier. Therefore, the spin waves around 18.5 GHz can penetrate not only the domain wall but also the buckle. In this high-frequency case, the spatial symmetry of the internal field of the micromagnetic texture determines

Figure 5. FFT amplitude distributions of the spin waves at 10 GHz inside (a) a 360° domain wall and (b) a magnetic buckle, stressing the local strength of magnetization oscillation. FFT phase distributions of the spin waves at 18.5 GHz inside (c) a 360° domain wall and (d) a magnetic buckle, emphasizing the symmetry of magnetization oscillation. The distributions of internal field in (e) a 360° domain wall and (f) a magnetic buckle. The homogeneity (symmetry) of this total internal field decides the behaviors of the penetrating spin waves at 10 GHz (18.5 GHz).
the propagation characteristics of the past spin waves. The internal field of the 360° domain wall has stronger inhomogeneity and lower symmetry than that of the magnetic buckle. The reduced symmetry of the internal field makes the 360° domain wall become a defect in the propagation path of spin waves, causing the asymmetric second-order mode to be re-excited [7] (figure 5(c)). The internal field of the magnetic buckle is too uniform to modify the original modes of the propagating spin waves (figure 5(d)).

Note that the stray fields from the Co pairs do not contribute to the observed effects in figures 3 and 4; that is to say, the amplitude-valve and mode-modulation effects are caused by the spin textures themselves, as evidenced by the additional micromagnetic simulations we performed with the saturation magnetization artificially set to 1 emu cm$^{-3}$ (versus its actual value 1414 emu cm$^{-3}$) for the Co bars, while all the other parameters remained invariant (this tiny value of the artificial Co saturation magnetization produces negligible dipolar fields). The choice of the geometric width, orientation, and strength of the antenna field strongly affects the spin–wave dynamics in a waveguide, as already revealed in references [7] and [35]. In the current simulations, the continuous rf field for the antenna is localized to a 5 (4) nm wide region (i.e. 1 simulation cell) in the length direction of the 10 (8) nm thick Py waveguide. Small values down to several Oe of the antenna field were examined, and no significant difference in the results of the spin–wave dynamics driven by various field strengths was found. The orientation of the antenna field is always along the z-direction (i.e., the hard axis) of the Py strip. Consequently, the antenna field cannot excite the Co bars, and even for the strongest used 100 Oe rf field, the magnetizations in the Py waveguide can only be driven to slightly deviate from the equilibrium direction, not inducing nonlinearity in the observed effects. In real experiments, one can reduce the rf field and/or increase the distance between the antenna and the Co pair to prevent excitations in the Co elements.

Conclusion

In conclusion, we have developed an approach of generating special micromagnetic textures, namely a 360° domain wall and a magnetic buckle, in a magnonic waveguide made of soft magnetic Py material directly coupled to a pair of magnetically hard Co nanobars; we have also investigated the effect of these micromagnetic textures on the spin–wave propagation in the Py waveguide. Using this method, localized micromagnetic textures have been successfully injected into a one-dimensional magnonic waveguide by using a sequence of homogeneous magnetic fields. The resulting micromagnetic textures can serve either as an amplitude valve or as a mode modulator for the passing spin waves depending on the used carrier frequency. By using appropriate coding, we have conceived of a logical NOT gate with the micromagnetic textures in the Co/Py section as a control unit. In the current study, we did not pay much attention to the phase-shift effect of the spin waves due to the presence of the bound 360° domain wall or magnetic buckle, since it is not as remarkable as in the waveguide system including a free domain wall. For that system, the phase shift, presumably resulting from the acquisition of a Berry phase, is decided by the ratio of the spin–wave wavelength to the domain-wall width [5]. By contrast, in our case, the amplitude-valve and mode-modulation effects seem to be of strong relevance to the relationship between the carrier frequency of the spin waves and the internal fields of the micromagnetic textures. Compared to the control method established in [15] where the presence of the valve- or phase-shifting effect is spacing-dependent, the function of our control unit (the micromagnetic textures) relies solely on the used frequency of the carrier spin waves, not on the structural parameters of the waveguide. Our proposed control strategy for spin–wave manipulation opens up a potential road toward reprogrammable magnonic signal processing.

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