Domain-Wall Induced Phase Shifts in Spin Waves

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We study the interaction between two important features of ferromagnetic nanoparticles: magnetic domain walls and spin waves. Micromagnetic simulations reveal that magnetostatic spin waves change their phase as they pass through domain walls. Similar to an Aharonov-Bohm experiment, we suggest to probe this effect by splitting the waves on different branches of a ring. The interference of merging waves depends on the domain walls in the branches. A controlled manipulation of spin-wave phases could be the first step towards nanoscaled ferromagnetic devices performing logical operations based on spin-wave propagation.

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When a nanosized ferromagnetic particle, as it is used in storage media and in spin-electronic devices [1], changes its direction of magnetization, the process involves the generation of magnetization waves. Magnetization reversal in an external magnetic field is connected with the release of Zeeman energy. After the reversal, this energy is dissipated and converted into spin waves [2]. In thin-film elements, these spin waves are usually magnetostatic modes that may persist for several nanoseconds in the magnetic particles [3,4], which is a long time if one wants to read and write information with operational speeds in the GHz range. Therefore, these waves are technologically undesirable, and considerable effort has been made to find ways to suppress them [5]. Magnetic thin-film elements in spin-electronic devices are typically a few nm thick and on the order of 100 nm large. They often consist of magnetically soft material, such as permalloy ($Ni_{81}Fe_{19}$), so that the magnetization direction can be switched with small external fields, usually a few mT. These elements have a strong tendency to keep the magnetization parallel to the surface plane in order to avoid magnetic surface charges [6]. To reduce the related stray field energy, the magnetization tries to close the magnetic flux by forming magnetic domains [7] separated by domain walls. In the walls, the magnetization changes its direction on a small material-dependent length scale, i.e., the exchange length. Magnetic domains are frequently observed even in particles in the submicron range [8,9]. The occurrence of both domain walls and spin waves is well known in ferromagnetic particles. The scope of this Letter is to investigate by means of micromagnetic simulations how magnetostatic spin waves are affected by magnetic domain walls.

The theory of micromagnetism had been set up by Brown in the 1950s [10] and provides the framework required to derive precise predictions of the spatial and temporal evolution of the magnetic structure. In this continuum theory the magnetic structure is represented as a directional vector field $M(r, t)$ with a constant magnitude $M_s = |M|$, where M_s is the saturation magnetization of the ferromagnetic material. The temporal evolution of this field is described by the Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{dM}{dt} = -\gamma(M \times H) + \frac{\alpha}{M_s}\left(M \times \frac{dM}{dt}\right), \qquad (1)$$

where α is a phenomenological damping constant and $\gamma = 2.21 \times 10^5\ \mathrm{mA^{-1}\,s^{-1}}$ is the gyromagnetic ratio. The effective field H is obtained from the derivative of the magnetic energy density e with respect to the magnetization, $H = -\partial e/\partial M$. The most important contributions to the energy density are the exchange, the stray field, the anisotropy energy, and the Zeeman energy in an external field [10]. Analytic solutions of the LLG equation are only obtainable for simple geometries if the magnetization is assumed to be homogeneous throughout the sample [6,11,12]. Owing to the tremendous progress in computer speed as well as in numerical techniques, reliable micromagnetic simulations using the LLG equation have become feasible. Our micromagnetic simulations are performed using the finite-element method [13]. This allows us to simulate magnetization processes in particles with curved boundaries with high accuracy. The major difficulties in micromagnetic simulations are the accurate calculation of the magnetostatic field and the time-consuming integration of the equation of motion. We calculate the stray field with high precision owing to a combined finite-element–boundary-element method. The numerical integration of the LLG equation is performed using the implicit Adams method [14]. The numerical representation of the LLG equation in a ferromagnetic particle results in large, strongly coupled, and nonlinear sets of differential equation. The size of this mathematical problem is connected with the physical size of the particle and the volume of the tetrahedral elements of discretization. Currently, the typical limit in size of particles that can be simulated reliably using the LLG equation is in the submicron range, and the time over which the integration typically can be extended is up to some nanoseconds. The size of the elements was chosen well below the exchange length $\lambda = 5.2$ nm in permalloy. Within the resulting limitations in sample size and time we can accurately simulate properties of spin waves and their interaction with domain walls. Nevertheless, the results presented are expected to qualitatively hold for larger systems that are accessible to time resolved magnetic imaging techniques [3].

Let us begin the investigations on a thin and narrow strip of permalloy of 360 nm length, 6 nm thickness, and 36 nm width. The magnetic structure of such a particle is simple. It is a single-domain particle that is homogeneously magnetized along the long edge [cf. Figure 1(a)] [15]. In order to excite a broad spectrum of magnetization waves in the particle, we start from the homogeneous state and tilt the magnetization out of the plane by 10° on a square region of 36 nm × 36 nm on one end of the slab. This nonequilibrium configuration is used as starting point for the dynamic micromagnetic simulation. Magnetization waves in the frequency range of several GHz are generated during the relaxation of the structure towards the ground state. A mechanical analogy of such an excitation of waves and oscillations could be the hitting of a chord in a guitar, where the mechanical system is suddenly put out of its equilibrium position. In the simulation we assume a damping constant of $\alpha = 0.05$, which

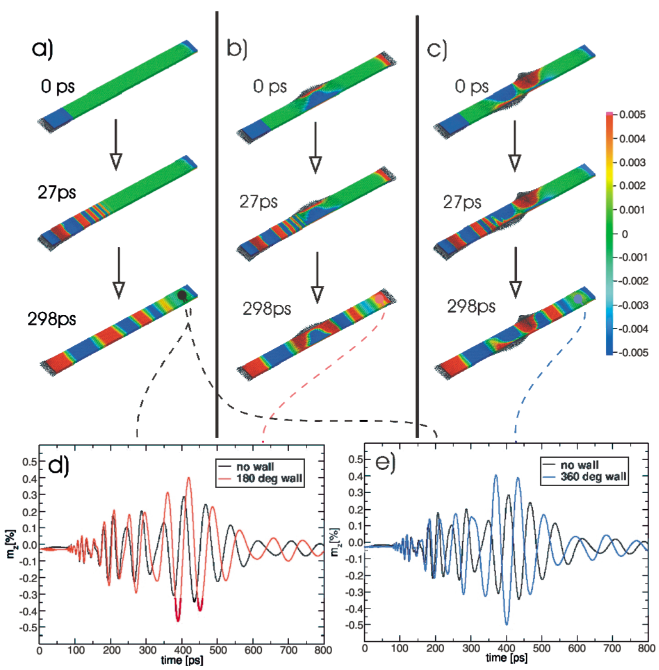

FIG. 1 (color). (a)–(c) Snapshots of the propagation of spin waves in a permalloy strip at times as indicated. To generate propagating spin waves, the magnetization initially is slightly tilted out of the surface (blue area on the left side of the first frames). The color-coding refers to the out-of-plane component as indicated by the color scale (max: 0.5%). Once the system is released, a broad spectrum of propagating waves is generated. The strip in (a) is magnetized homogeneously while the ones in (b) and (c) have a 180° and a 360° domain wall. (d)–(e) The arrival of the magnetization waves on the other side of the slab can be observed by plotting the out-of-plane magnetization component versus time at a selected point.

is low enough to ensure an underdamped oscillation of the magnetization. The process is described in Fig. 1(a). The waves are emitted from the left side of the sample and travel though the slab until the wave front reaches the opposite side. The arrival of the wave can be recorded by plotting the perpendicular magnetization component at a point located near the right end as a function of time [cf. Figure 1(d)]. The waves arrive there after about 100 ps. The first response of the perpendicular magnetization component is a series of relatively sharp "spikes" of low magnitude, resulting from waves of high frequency and short wavelength. At 300 ps a well-defined, smooth oscillation sets in, which fades out after about 900 ps. Although the analysis of wave spectra obtained in this way might be used to gain insight into the different modes of magnetization waves that can occur in such a particle, the question we are interested in here is a different one: how does the wave *change* when it passes through a domain wall?

In a thin ferromagnetic strip we can easily introduce a domain wall as shown in Fig. 1(b). Now the in-plane magnetization direction changes by 180° along the slab axis. This type of head-to-head domain wall is a magnetic structure frequently found in thin and narrow strips [17]. Taking this state with two domains separated by a domain wall as a starting point and exciting spin waves like in the previous case, we can observe the effect of the domain wall on the magnetization waves. As shown in Fig. 1(b), the wave passes through the domain wall without being scattered or damped. It generates an excitation spectrum on the other side of the slab which is very similar to the one obtained without domain wall. A closer look at the oscillations, however, reveals that the wave has been subjected to a change in phase on its way through the domain wall [cf. Figure 1(d)]. The phase shift is $\Delta\Phi \simeq \pi/2$ after the wave has passed through a region where the magnetization changes its in-plane direction by an angle $\Delta\vartheta = \pi$. Remarkably, the aforementioned high-frequency oscillations that reach the other part of the slab within about 100 ps do not seem to be affected at all by the presence of the domain wall. Only the smooth oscillations which set in after about 300 ps are phase-shifted with respect to the case without domain wall.

We can further probe the influence of domain walls on spin waves by placing a 360° wall in the strip instead of a 180° wall [see Fig. 1(c)]. This leads to a doubling of the phase-shifting effect compared to the case of a 180° wall [cf. Figure 1(e)]. Also in this case, the fast, high-frequency parts of the spectrum are not modified, but the slower quasiharmonic oscillations are now shifted by an angle $\Delta\Phi \simeq \pi$. Note that neither the speed nor the magnitude of the spin wave are affected by the domain wall. The influence of the domain wall shows up in the phase of the spin wave that is altered after the wave has passed through the domain wall. We observe a direct proportionality between the angle $\Delta\Phi$ by which the phase of the spin waves is shifted and the angle $\Delta\vartheta$ by which the magnetization rotates inside the domain wall. For the main frequencies of the wave spectrum, the proportionality factor is 1/2.

This surprising result can be exploited to generate controlled interferences of magnetization waves. The concept is similar to an Aharonov-Bohm experiment [18,19], where a wave is split on two branches. A phase difference between the waves in the branches that is acquired as the waves propagate separately becomes observable by means of constructive or destructive interference when the waves meet again. To perform this kind of investigation on magnetostatic spin waves we consider an elongated ring-shaped thin-film element (Fig. 2). This ring structure has two small plates on opposite sides, one of which is used to excite spin waves and the other to measure the response after the spin waves have traveled through the branches. The specimen can be regarded as an interferometer for spin waves. Magnetic structures in similar, circular ferromagnetic rings have recently been investigated quite thoroughly because of their potential application as magneto-electronic storage units [20,21]. One of the possible magnetization states in ring-type structures is called the "onion state" [20], which is a bi-domain state in which the sample is essentially magnetized in one direction. The structure is not perfectly homogeneous but has some curvature in the branches, since the magnetization tries to follow the shape of the ring.

By lifting the magnetization 10° out of the plane on one of the outer plates and releasing it subsequently, a spectrum of magnetization waves is generated like in the previous cases of single strips. When the wave fronts reach the bifurcation point, they ramify symmetrically on the two branches of the ring [cf. Figure 3(b)]. Similarly, the wave fronts merge smoothly when they reach the point of confluence [Fig. 3(d)]. The curvature of the branches seems to have an interesting influence on some high-frequency modes. In this geometry we observe edge-localized modes which did not occur in the straight bars. They propagate along both the inner and the outer edge of the ring [cf. Figure 3(c)]. However, these modes dissipate very quickly and fade out almost completely before they reach the opposite side of the ring. Apart from these localized modes, the excitations consist of almost plane wave fronts. The arrival of the waves on the opposite side can again be seen in the onset of oscillations in the perpendicular magnetization component at a point in the middle of the other plate. The spectrum is similar to the previous case of isolated strips. After some time (about 0.8 ns), the only remaining residual oscillations are standing waves, because the formerly propagating waves have been reflected at the particle's ends.

We can now directly probe the influence of a domain wall on the phase of the waves by placing a 360° in only one of the two branches and repeating the simulation under these conditions. Similar ferromagnetic ring structures with 360° domain walls have been the subject of recent experimental investigations [22]. The result is shown in the middle of Fig. 3. The fast, short-wavelength oscillations remain basically the same, but the low-frequency oscillation is strongly attenuated compared to the case without domain wall. The strong attenuation of the outcoming waves is a result of the superposition of magnetostatic waves with same wavelength and magnitude, but opposite phase. Identical calculations but with lower damping ($\alpha = 0.01$) show the same phase-shifting effect. However, the lower damping results in a strong ringing of the entire ring that can persist for several nanoseconds.

In conclusion, we find that magnetization waves change their phase when they pass through a magnetic domain wall. The change in phase depends on the angle by which

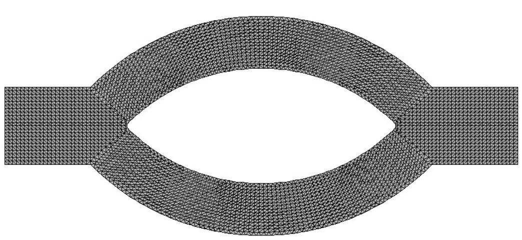

FIG. 2. Finite-element model of a spin-wave interferometer. The curved branches are two 90° segments of a circle with a radius of 170 nm and 36 nm width. The entire structure is approximately 350 nm long. The film thickness is 6 nm. About 42 600 finite elements of tetrahedral shape are used for the simulation. The average volume of the tetrahedral elements is $(3.26\ \mathrm{nm})^3$.

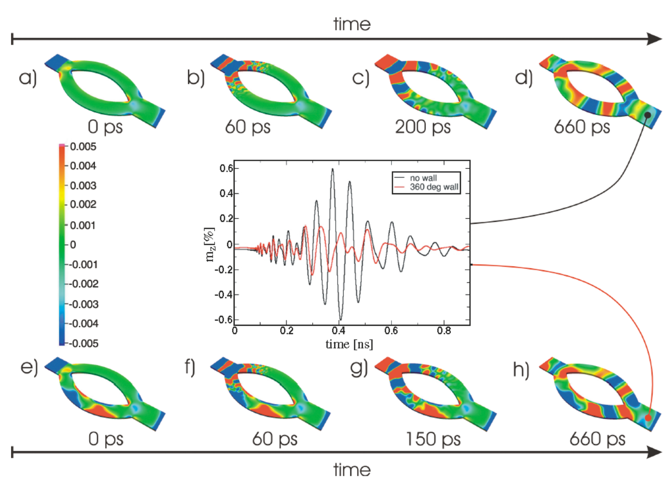

FIG. 3 (color). Snap shots of the wave propagation and interference effects in a ring at times as indicated. The series (a)–(d) shows the propagating front that is magnetized in an "onion" state, while the series (e)–(h) shows the evolution for a ring that contains a 360° wall in one branch. The phase difference induced by the domain wall becomes visible in (h), where the merging wave fronts have opposite sign. This leads to destructive interference. Correspondingly, the oscillations of the magnetization on the other end of the ring are strongly suppressed (inset). The color-coding refers to the out-of-plane component as indicated by the color scale (max: 0.5%).

the magnetization direction changes in the domain wall. It may be suspected that the acquisition of a topological phase (Hannay angle [23]) plays a role here, as it is the case in the quantum-mechanical Berry phase [24] and in several classical systems involving oscillations and rotations on disparate time scales. The value $\Delta\Phi$ of the phase shifting is proportional to the angle $\Delta\vartheta$ by which the magnetization rotates in the film plane. The influence of regularly spaced domain walls on the dispersion relation of magnons has recently been investigated in the framework of Berry phases [25]. Our observation that excitations of short wavelength are not affected by the presence of a domain wall suggests that the ratio of domain-wall width to wavelength is a decisive quantity for the phase shift effect. Our investigations have been limited to nanoscaled particles, but this is only due to the numerical restrictions of the micromagnetic simulations. There appears to be no reason why a spin-wave interferometer of mesoscopic size should not lead to the same results, provided that the spin waves do not dissipate before the branches merge again. Recent experiments [26–28] show that magnetization waves can be observed and controlled in microscopic samples. Hence, interference experiments with magnetization waves might be performed in order to confirm this prediction from micromagnetic simulations. The controlled change of phase of a spin wave could become the operating concept of a new generation of nonvolatile magnetic storage and logical devices. In such devices, information would be carried by spin waves. Ferromagnetic nanowires would act as wave guides transporting the signal, and domain walls could be used as phase-shifting units which, if properly combined, could perform logical operations [29]. For example, the ring proposed here is a switch that blocks magnetization waves if only one of the two branches is "switched on" by the presence of a 360° domain wall. In this sense, the ring can be regarded as a disjunctive XOR Boolean operator, which is a fundamental operation of any logical device. Submicron sized ferromagnetic devices performing logical operations with magnetic domain walls have been presented recently by Allwood *et al.* [30]. A significant advantage of a spin-wave based logical signal is the much faster and nondestructive operation mode as compared with a system based on domain-wall motion.

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