Propagation of spin waves through a Néel domain wall

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Spin waves have the potential to be used as a new platform for data transfer and processing as they can reach wavelengths in the nanometer range and frequencies in the terahertz range. To realize a spin-wave device, it is essential to be able to manipulate the amplitude as well as the phase of spin waves. Several theoretical and recently also experimental works have shown that the spin-wave phase can be manipulated by the transmission through a domain wall (DW). Here, we study propagation of spin waves through a DW by means of micro-focused Brillouin light scattering microscopy (µBLS). The acquired 2D spin-wave intensity maps reveal that spin-wave transmission through a Néel DW is influenced by a temporally enforced circular Bloch line in the DW center and that the propagation regime depends on the spin-wave frequency. In the first regime, spin waves can propagate in a single central beam through the circular Bloch line. Phase-resolved µBLS measurements reveal a phase shift upon transmission through the domain wall for both regimes. Micromagnetic modeling of the transmitted spin waves unveils a distortion of their phase fronts which needs to be taken into account when interpreting the measurements and designing potential devices. Moreover, we show, by means of micromagnetic simulations, that an external magnetic field can be used to move the circular Bloch line within the DW and to manipulate spin-wave propagation.

Magnonics offers a new promising concept for devices with the potential to go beyond CMOS technology in cases when low power computing is desired as Joule losses are effectively circumvented by the nature of the operation of magnonic devices. It was shown that it is possible to fabricate an all magnon transistor and spin-wave logic gates based on a Mach–Zehnder interferometer [1, 2]. These gates rely on a controlled phase shift of spin waves, which might be achieved, e.g., by magnetic domain walls [3–5].

For this reason, the propagation of spin waves through domain walls (DW) is of high interest. Recently, it has been shown that domain walls can serve as a spin-wave valve depending on its magnetic state (head-to-head and tail-to-tail spin configurations) [6]. In samples with perpendicular magnetic anisotropy, it was demonstrated, that DWs can affect both spin-wave amplitude and phase and that spin waves can move the DW by spin torque phenomena [7, 8]. Moreover, DWs may also serve as a source and probe of spin waves with short wavelengths [9, 10]. However, there was no experimental study on the spatial evolution of spin waves transmitted through a DW in a magnonic waveguide. A thorough understanding of the behavior of spin waves in magnonic waveguides hosting DWs is necessary for designing future integrated magnonic circuits as they present the most elementary building block of magnonic circuitry.

In this study, we focused on spatial imaging of spin-wave propagation through a Néel domain wall confined in an in-plane magnetized magnonic waveguide. To prepare a sample suitable for this study, we used a metastable fcc Fe79Ni22 thin film with a nominal thickness of 16nm, grown under UHV conditions on a Cu(001) single crystal substrate using the procedure described in [11]. The bcc Fe79Ni22 magnetic waveguides with dimensions 3 × 20 μm² were written into the non-magnetic fcc layer by inducing the fcc → bcc phase transformation with a focused ion beam (Tescan Lyra3 FIB/SEM), using the procedure described in [12]. The produced waveguides had an effective anisotropy field of 40 mT with an in-plane easy axis perpendicular to the waveguide’s long axis. This configuration allows for spin wave propagation in Damon–Eshbach (DE) geometry in zero external magnetic field and for stabilization of a domain wall in the vicinity of a spin-wave source. Spin waves were excited by a stripline antenna placed on top of the waveguide [see Fig. 1(a)]. The 1 μm wide antenna, made of a multilayer structure consisting of a 20nm SiO₂ insulating layer, 5nm Ti, 85nm Cu and a 10nm Au capping layer was patterned by electron beam lithography using PMMA resist, followed by e-beam evaporation of the layers and subsequent lift-off process. The desired two-domain state of the waveguide was stabilized by applying an external magnetic field in +y direction while observing the magnetization by a Kerr microscope (evico magnetics GmbH). The DW was positioned at a distance of approximately 3 μm from the antenna in order to obtain a sufficient BLS signal on both sides of the domain wall. The position of the domain wall was stable in zero external magnetic field with a depinning field of 1.0 ± 0.1 mT (obtained by Kerr microscopy experiments).

To further reveal the internal structure of the DW, we performed magnetic force microscopy measurements (Bruker Dimension Icon, ASMFMMLM probe tip), supplemented by mi-
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Spin-waves propagation was studied using micro-focused Brillouin light scattering (μBLS)\(^\text{29}\). In order to get better insight into internal magnetic field structure, we measured thermally excited spin waves while scanning the μBLS spot (300nm in diameter) in the center of the waveguide, across the DW [Fig. 1(d)]. The total length of the line scan was 2µm, with the spatial step of 50nm. We observe an increase of spin-wave frequencies by approximately 2GHz in the DW region (the DW is located at \(x = 0\mu m\)) in comparison to the uniformly magnetized area. This increase can be attributed to approximately 15mT increase in the local effective magnetic field. The effective magnetic field obtained from micromagnetic simulation is plotted together with the thermal spectra [Fig. 1(d), red curve]. Note, that at the exact position of the DW, the effective field exceeds 600mT but this peak is spatially restricted only to a region of approximately 10nm (an order of magnitude below the μBLS spatial resolution), and its contribution is not present in the acquired spectra.

In the second experiment, we excited spin waves by passing a RF signal (5dBm, 7–10GHz, frequency step 50MHz) through the microwave antenna. The spin-wave intensity for each excitation frequency was acquired at two positions: the first position was \(x = -0.5\mu m\) (before the DW) and the second position was \(x = 0.5\mu m\) (after the DW). The resulting spectra are shown in Fig. 1(e). Based on these measurements we selected two frequencies (7.15GHz and 9.00GHz, indicated by red arrows), where we observed an increased spin-wave intensity at both positions, before and after the DW.

For the selected frequencies we performed intensity- and phase-resolved μBLS experiments. The measurements were done for the magnonic waveguide in a single domain state (SD) and in the DW state (here, DW state means two-domain state separated by the Néel domain wall). For the SD state, we observe only the central waveguide mode [Fig. 2(a)]. The corresponding spin-wave phase (\(\Phi\)), obtained by the technique described in\(^\text{29,28}\), shows a linear increase in the region -1µm \(< x < 1\mu m\) [Fig. 2(d), blue region] as expected for a propagating wave. Outside of this region the phase could not be reconstructed due to either nonlinear spin-wave behavior

FIG. 1. (a) Scheme of the experimental geometry. The ocher wire represents the excitation antenna producing the RF magnetic field. The uniaxial anisotropy (easy axis) created by the FIB irradiation is shown as a blue double arrow. The domain wall is positioned 3µm from the edge of the antenna. (b) Micromagnetic simulation of the DW state. (c) Magnetic force microscopy image of the DW. (d) Plot of the BLS thermal spectra acquired while scanning the laser spot across the DW (located at \(x = 0\mu m\)). The color code represents the spin-wave intensity and the red curve (right axis) represents the magnitude of the local effective field. (e) Frequency sweeps for positions \(x = -0.5\mu m\) (before the DW) and \(x = 0.5\mu m\) (after the DW). The red arrows indicate prominent frequencies used in following experiments.
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FIG. 2. Spin-wave intensity maps for excitation frequency of 7.15 GHz (a) in single domain (SD) state and (b) in two-domain state separated by the Néel domain wall (DW state) and (c) for excitation frequency of 9.00 GHz in DW state. The white dashed lines indicate the positions of measured phase. (d) Evolution of the spin-wave phase along the white dashed line at the frequency of 7.15 GHz in SD state and (e) DW state. (f) Spin-wave phase for excitation frequency of 9.00 GHz in DW state. The blue region in (d) indicates a region of detectable linear phase evolution. The red line represents the linear fit of this data and the spin-wave wavelength is calculated from the slope of the fitted line.

FIG. 3. (a)-(c) Simulated 2D maps of the squared out-of-plane magnetization component averaged over two periods of excitation. (a) SD state, (b) DW state excited at 7.15 GHz and (c) DW state excited at 9.00 GHz. (d)-(f) Phase maps corresponding to the respective intensity maps. (d) SD state, (e) DW state excited at 7.15 GHz and (f) DW state excited at 9.00 GHz. The white dashed lines indicate the positions where the phase was experimentally measured. The blue region in (d) indicates a region of detectable linear phase evolution. The green dots represent µBLS spots at which the simulated relative phase is evaluated in panel (g).

closer to the antenna) or insufficient spin-wave signal (farther from the antenna). We determine the wavelength of the excited spin waves from the slope of the fitted line [Fig. 2(d), red line], \( \lambda = 4.5 \pm 0.2 \mu m \), which is in agreement with the calculated dispersion relation \(^{[3]}\). The propagation of the spin waves excited at 7.15 GHz through the DW is shown in Fig. 2(b). The spin-wave propagation pattern before the DW resembles closely the one seen in Fig. 2(a). After passing the DW, the spin waves are split into two beams. A similar effect of splitting into two beams was observed in a different system by Demidov \(^{[5,30]}\). The phase evolution in the lower spin-wave beam [Fig. 2(e)] exhibits a clear discontinuity; a phase shift of approximately 0.6π at the DW position. For the second measured frequency of 9.00 GHz, the 2D spin-wave intensity map looks remarkably different. In this case, the transmitted spin wave is confined to the middle of the waveguide. The corresponding spin-wave phase, shown in Fig. 2(f), exhibits a phase shift of approximately 0.5π at the position of the DW (\( x = 0 \mu m \)).

To further understand this frequency-dependent behavior and phase evolution, we conducted dynamic micromagnetic simulations, using the same material parameters as for the calculation of the static magnetization configuration. Spin waves were excited by a spatially varying field (the field from the rectangular antenna was calculated by FEMM \(^{[1]}\)). To prevent reflections at the ends of the simulated waveguide, we im-
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implemented regions with increasing damping at both ends of the waveguide. A continuous RF excitation was applied during the initial 20 periods. Then the spatial distribution of the magnetization was sampled for two periods with a time step of 2 ps. The magnetization was transformed to in-plane and out-of-plane components and the spin-wave phase was calculated using the procedure described in. The results of these simulations are shown in Fig. 3(a-c) in the form of the time-averaged squared out-of-plane component of the magnetization. Panel (a) shows the spin-wave propagation in the SD state. Panel (b) shows the spin wave-propagation through the DW at the excitation frequency of 7.15 GHz and panel (c) at the frequency of 9.00 GHz. We can observe qualitatively the same behavior as in the experiment.

Simulated phase maps corresponding to the previously described intensity maps are shown in Fig. 3(d-f). For the waveguide in the SD state we can observe that the phase is almost constant across the y coordinate of the µBLS spot [see green dot in Fig. 3(d) and black line in Fig. 3(g)]. On the other hand, the phase after passing the DW is much more distorted across relatively small distance [for 7.15 GHz see green dot in Fig. 3(e) and red line in Fig. 3(g)] and the same applies to 9.00 GHz spin wave [see Fig. 3(f), green dot and Fig. 3(g), blue line]. This distortion explains why we were not able to see the linear phase evolution in our experiments. We were probing the spin waves with a 300 nm µBLS spot, and the phase is changing by more than 0.5 rad within the spot size.

To check if a change in the internal configuration of the domain wall can be used to modify the spin-wave propagation, we performed a simulation where we applied a small external magnetic field of 5 mT along the x direction. This moves the circular Bloch line in y-direction towards the edge of the waveguide [see Fig. 4(a)]. The field dependence of the Bloch line position along the y axis is shown in Fig. 4(b).

This displacement of circular Bloch line changes the transmitted spin-wave profile significantly. In Fig. 4(c) we can observe that for 7.15 GHz, the Bloch line still casts a shadow in the spin-wave intensity; only little space and intensity are left for the lower beam (y < 0.7 μm). At f = 9 GHz, as in Fig. 3(c), a maximum is seen downstream of the Bloch line, but now displaced sideways, and the wave pattern appears bent.

In summary, we stabilized a symmetric Néel DW with a topologically enforced circular Bloch line confined in a magnetic waveguide with imprinted uniaxial anisotropy in the vicinity of a microwave antenna. This configuration allowed us to experimentally observe zero-magnetic-field propagation of DE spin waves through a DW by phase-resolved µBLS. We observed two different regimes of spin-wave propagation appearing at frequencies of 7.15 GHz and 9.00 GHz. In the first regime which was observed at the frequency of 7.15 GHz, spin-wave propagation in the vicinity of the circular Bloch line is suppressed and two spin-wave beams are created. In contrary, at 9.00 GHz spin waves propagate through the circular Bloch line and create a single spin-wave beam. Phase-resolved measurements reveal that spin waves exhibit a phase shift of approximately 0.6π upon transmission through the DW. We observed that the DW spatially distorts the phase of the spin wave. This effect needs to be taken in account when designing DW-based phase shifters or other devices relying on spin-wave phase manipulation. The other point, which needs to be taken into consideration, is the occurrence of topologically enforced spin structures which are unavoidable in certain geometries. They can limit the performance or functionality of the DW-based device. On the other hand, they can also be an advantage, as in the case where we propose an interesting technique for spin-wave guidance by manipulating the circular Bloch line position in the DW by external magnetic fields. This technique can be used for dynamical turning or blocking spin waves in future magnonic devices.

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The anisotropy field is called effective as we see only the result of the two competing contributions – crystalline uniaxial magnetic anisotropy coming from the FIB writing process and from the uniaxial shape anisotropy having its origin in the shape of the waveguide (approx. 7 mT for the 1.5 µm wide waveguide). The total anisotropy of the structure is then obtained as the difference of the two contributions.