

Emission and Propagation of Multi-Dimensional Spin Waves in Anisotropic Spin Textures

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Spin waves offer intriguing novel perspectives for computing and signal processing, since their damping can be lower than the Ohmic losses in conventional CMOS circuits. For controlling the spatial extent and propagation of spin waves on the actual chip, magnetic domain walls show considerable potential as magnonic waveguides. However, low-loss guidance of spin waves, in particular around angled tracks, remains to be shown. Here we experimentally demonstrate that such advanced control of propagating spin waves can be obtained using natural features of magnetic order in an interlayer exchange-coupled, anisotropic ferromagnetic bilayer. Using Scanning Transmission X-Ray Microscopy, we image generation of spin waves and their propagation across distances exceeding multiple times the wavelength, in extended planar geometries as well as along one-dimensional domain walls, which can be straight and curved. These results show routes towards practical implementation of magnonic waveguides employing domain walls in future spin wave logic and computational circuits.

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Spin waves are the elementary excitations of the order parameter in ferromagnetic materials [Fig. 1a)] [1-3]. Also referred to as magnons, they can be used similarly to electrons in CMOS circuitry, but with lower losses, to transmit information, and, therefore, are currently attracting a lot of interest as possible information carriers in alternative computing schemes [4-7]. One of the most pressing issues in present-day high-performance computing are the high power requirements and the necessary heat removal associated with the Ohmic losses in conventional electronic CMOS circuits - latest generation supercomputers easily consume power in the order of ten Megawatts. On a wider societal scale, the reduction of signal-processing losses, in particular in personal mobile communication devices may create substantial benefits due to reduced power consumption, resulting in extended battery life and improved environmental sustainability. Another substantial advantage of spin-wave technology is the fact, that in the GHz range, magnon wavelengths are several orders of magnitude shorter than those of electromagnetic waves [8]. Thus, a significant device miniaturisation can be achieved for applications where the wavelength imposes a critical constraint on the device footprint.

Two of the most challenging aspects of building a magnonic computer remain the generation of short-wavelength magnons and the construction of suitable waveguides for spin wave transport. Several recent works focus on these two issues ([9-24] and [7,24-35], respectively). In [16] the emission of nanoscale spin waves from a pair of stacked vortex cores [36], driven by an alternating magnetic field [37,38] was demonstrated. However, in the geometry [16], where a point-like vortex core source is radiating spin waves into a two-dimensional propagation medium, spin waves originating from a vortex core and traveling outwards radially experience not only Gilbert damping, but also a purely geometric reduction of amplitude proportional to the inverse square root of the distance from the source, as shown schematically in Fig. 1b). Further, it has been suggested that magnetic domain walls could be harnessed to guide spin waves across the magnonic chip [7,24-31]. In particular, it has been

shown that domain walls can host localized modes, excited by alternating magnetic fields [26]. While in Ref. 26, the lateral position of the excited magnetisation amplitudes could be well controlled by tuning the lateral domain wall position, these modes however quickly decayed along the domain wall coordinate with increasing distance from the microwave antenna within subwavelength length scales.

These key issues – short wavelength-spin wave generation and spin wave guidance - are the points we address in this work, where we make use of naturally formed anisotropic spin textures. First, we demonstrate the excitation and propagation of two-dimensional planar spin-waves [Fig. 1c)] excited by the oscillation of straight domain walls. We observe that these excitations can travel distances spanning multiples of the wavelength. Second, we observe excitation and propagation of spin wave modes confined to quasi-one-dimensional natural waveguides (straight or curved) formed by domain walls embedded in a two-dimensional host medium [Fig. 1d)].

Our samples are $\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}/\text{Ru}/\text{Ni}_{81}\text{Fe}_{19}$ multilayers with (46.6/0.8/44.9) nm thickness, patterned into disc- and square-shaped elements, having lateral sizes of several microns [Fig. 2a)]. Each ferromagnetic layer exhibits an in-plane uniaxial anisotropy. The Ru interlayer causes antiferromagnetic coupling between the two ferromagnetic layers [39] (see methods part for further details).

The magnetic ground state configuration stabilized in this system is a pair of stacked vortices, with opposite vorticity due to the antiferromagnetic interlayer exchange coupling. The influence of the CoFeB uniaxial anisotropy leads to a significant distortion of the vortex magnetization distribution in both magnetic layers. The result in each layer is a state of two homogeneously in-plane magnetized domains with opposite magnetizations. These domains are separated by a narrow, partially perpendicularly oriented, 180 degree domain wall that contains the vortex cores and spans the lateral extension of the discs. These magnetic configurations are shown in Figures 2b) and 2c), which are Scanning Transmission X-ray Microscopy images

displaying magnetic information about the in-plane (b) and the out-of plane component (c) of the individual layers. As Fig. 2c) indicates, the out-of-plane magnetization components of the respective layers couple ferromagnetically to each other by their stray field. In particular, this is true for the polarizations of the vortex cores. Micromagnetic simulations confirm this and reveal that the domain wall formed in the sample is, in fact, a mixture between Néel and Bloch types of domain walls [40], where the in-plane components couple antiferromagnetically across the Ru interlayer, as in the domains. The complex ground state magnetic pattern is illustrated in panels d) and e) of Fig. 2. Figure 2d) displays a schematic top view of the domain wall structure in the CoFeB layer, showing the mixed Bloch and Néel components. In Fig. 2e) a cross-section of the bilayer system is shown, which can be imagined as resulting from a cut along the blue lines in panel c) of the Figure, revealing the out-of-plane magnetization components in the domain wall to follow a flux-closing distribution between the two layers.

Spin waves can be excited in such anisotropic spin textures by applying an alternating magnetic field, as shown in Figure 3. Figure 3 (a) is a snapshot of the magnetic excitations at an Oersted field frequency of 1.11 GHz, taken at the Ni absorption edge, displaying the out-of-plane contrast. Plane spin waves are visible, with wave fronts parallel to the domain wall, and propagating away from the domain wall towards the rim of the elliptical element, as indicated by the green arrow. The oscillating Oersted field is dominated by its in-plane component, which is oriented along the minor axis of the ellipse, perpendicular to the domain wall. The main effect of the Oersted field is to excite dynamics of the domain wall, and that the excited domain wall acts as a confined perpendicular source for the observed spin waves [22-24]. The periodic-in-time nature of the waves allows capturing the wave motion at discrete, equispaced phases in each scanned pixel, and composing the recorded data into movie-like arrangements, which impressively show the propagation of these spin-excitations [see movies in the Supplementary Information (SI)]. A comparison of the absorption data taken along the green arrow in Fig. 3a) at different time slices yields the wavelength of the wave, and in particular its speed of

propagation. Three of these time slices are shown in Fig. 3b). Notably, the spin wave amplitude does not visibly decrease across the distance of two micrometers, corresponding to about 7.5 times the wavelength. Increasing the excitation frequency to 1.46 GHz results in a similar wave pattern, but with shorter wavelength [Fig. 3c)]. Around the vortex center, as shown in the magnified image Fig. 3d), in addition to the plane waves generated by the oscillating wall, there exist radial wave fronts which arise from the motion of the vortex core, which acts as a point source [16]. In comparison to the plane waves excited by the domain wall, these radially symmetric waves must decay faster in power density, with a factor of $1/r$ in addition to the exponential decay induced by the Gilbert damping, r corresponding to the distance from the vortex center. This difference can be regarded as a consequence of the fact that the plane waves are excited by a one-dimensional source (the domain wall), while in the case of the radial waves, the source is zero-dimensional (the vortex core). As these two wave forms are excited simultaneously, patterns of interference arise which are also visible in Fig. 3d).

In this manner, we can excite planar spin waves for a broad range of frequencies up to 5 GHz. Remarkable effects, however, appear when going to rather low excitation frequencies, as shown in Fig. 4, displaying excitations at 0.52 GHz and 0.26 GHz [panel a) and b), respectively]. At these low frequencies, no visible excitations exist in the domains, yet the data clearly shows spin waves propagating confined to the domain wall in the directions away from the vortex cores. The wavelength of these waves can be controlled in the same way as in the previous cases, *i.e.* by tuning the excitation frequency. Again, the wave amplitude is still significant even after a propagation distance extending from the vortex core to the rim of the ellipse. This is made possible in a way that is analogue to the above described case of planar waves in a two-dimensional medium excited by the one dimensional domain wall: For the waves propagating along the domain wall, the source is of dimension zero; however, due to the confinement to the domain wall, the propagation medium is effectively one-dimensional. As a result, geometrical decay of the amplitude is avoided, making the domain wall act as a low-loss

waveguide (c.f. the supplemental material for movies of the propagating spin waves in the domain walls).

In order to shed light on the physics underlying these observations, we followed a twofold strategy: First, both observed phenomena - the excitation and propagation of planar spin waves in the domain, and one-dimensional waves confined to the domain wall – were investigated and qualitatively confirmed with micromagnetic simulations. For that purpose, the experimental static magnetization distribution was reproduced prior to excitation by an ac magnetic field. In order to obtain the details of the dispersion relation for the planar waves in the domains within reasonable computation time, the system was modeled by two continuous, homogeneously magnetized coupled layers (further details can be found in the methods section). The experimental plane spin-wave dispersion was quantitatively reproduced by these simulations.

In addition to the simulations, we developed a theory (see SI for in-depth technical details) for the propagation of spin waves in two exchange-coupled extended ferromagnetic films. The core of the theory considers spin wave modes in thin magnetic films, where the magnetization along the coordinate perpendicular to the film plane can be considered homogeneous. The case of thicker films as in the experiment is accounted for by splitting each ferromagnetic layer into a number N of thin films of equal thickness, so that for each of these films the thin-film approximation holds. The N thin films of each layer are then coupled to each other by an effective ferromagnetic intralayer exchange coupling, whose strength is determined by estimating the energy of a magnetization distribution subject to homogeneous torsion and by requiring consistency with the continuum limit. The theory thus enables us to quickly compute dispersion relations for spin waves in the interlayer exchange-coupled bilayer system with ferromagnetic layers whose thicknesses exceed the exchange lengths of the respective material. In Fig. 5, the measured spin wave dispersion relations $f(k = 2\pi/\lambda)$ (f denoting the frequency, k the wave number and λ the wavelength, respectively) for waves in the domains

and in the domain walls are combined with the analytical and micromagnetic simulation results. We first consider the planar waves propagating through the domains. The open circles represent the results extracted from the STXM measurements. The blue continuous line displays the theoretical result, which is found to depend sensitively on the CoFeB in-plane uniaxial anisotropy and the interlayer exchange coupling. For $J = -0.1 \text{ mJ/m}^2$ and $K_u(\text{CoFeB}) = 3 \text{ kJ/m}^3$, we find good agreement with the experimental data. The elevated value of $K_u(\text{CoFeB})$ is reasonable, since we expect the CoFeB to react sensitively to strain exerted by the patterned waveguide microstructure onto the elliptical element [41]. Using the same parameters as in the theory, we also compute the dispersion using micromagnetic simulations [grey dots in Fig. 5]. A striking feature of the plane wave dispersion is the existence of a local minimum at low k around $5 \text{ rad}/\mu\text{m}$, and accordingly, a frequency gap, below which no spin wave excitations are possible. The local minimum at some finite value of the wave vector in Fig. 5 can be understood due to a combination of the non-reciprocity induced by the dipolar coupling between the two antiferromagnetically coupled magnetic layers [16,42] and the uniaxial magnetic anisotropy. Namely, when the anisotropy is null, the collective dispersion in Damon-Eshbach geometry ($\mathbf{k} \perp \mathbf{M}_0$) [43] has a minimum of zero frequency at $k = 0$, while at finite anisotropies, this minimum is shifted to finite values of both wave vector and frequency. Such a k -shifting of the dispersion minimum is somewhat analogous to that induced by the Dzyaloshinskii-Moriya interaction on ferromagnetic/heavy-metal alloys, where the minimum of the dispersion is also shifted. [44]. Our experimental observations of selective excitation and propagation of spin waves in the domain wall can actually be explained based on the existence of this frequency gap: The red circles in Fig. 5 display the dispersion relation of the measured spin waves in the domain wall. In sharp contrast to the planar waves in the domains, the waves confined to the wall exhibit an almost linear dispersion, which runs below its plane wave counterpart and, when extrapolated towards zero, intercepts the y-axis close to $f = 0$. Thus, when tuning the excitation frequency to values inside the gap, no propagating magnons are excited in the domains; only the

energetically lower modes existing in the wall are populated. The existence or, respectively, absence of the gaps in the domain and domain wall can be explained by the Goldstone theorem [45], which states that a system exhibiting a continuous symmetry spontaneously broken by the ground state has a gapless mode. In case of the spin waves in the domains, the corresponding system comprises the two coupled discs. Here, the continuous symmetry is compromised by the uniaxial anisotropy and accordingly, the planar spin wave dispersion relation exhibits a gap. In case of the waves confined to the domain wall, there exists a continuous translational symmetry that gives rise to a gapless mode. The presence of defects and the finite size of the sample, in principle, break this symmetry, but the resulting gap is too small to change the quality of the observed effects.

The idea of using domain walls as waveguides is intriguing, and Fig. 6 shows that the above described phenomenon indeed extends to cases where the walls are curved, i.e., lead ‘around the corner’. Neither is the concept restricted to continuous wave excitation. Figure 6a) displays the static magnetization configuration (out-of-plane contrast) of a domain wall, apparently of the same type as in the aforementioned cases, but curved towards the right-hand rim of the magnetic element. The regions marked in orange and yellow inside the domain wall indicate positions in front of and behind the curve, respectively, when following the domain wall from the vortex core towards the rim. Panels (b)-(d) display the snapshots of the excitation following a field pulse: Due to the width of the spectral composition of the pulse, spin waves are excited inside and above the frequency gap. The resulting plane wave packet traverses the domains in the direction away from the wall and makes it easy to optically distinguish the domain wall wave from the rest of the excitations. Fig. 6b) displays the time slice just before the field pulse. 11.1 ns after the pulse, the wall wave packet has reached the orange region in front of the turn [Fig. 6c)]; 2.5 ns later the wave packet has traveled around the corner. Remarkably, even after the turn, the wave packet maintains a considerable amplitude.

To summarize, the work presented here addresses several key aspects of magnonic computing by exploiting magnetic anisotropy. The first aspect is related to energy and signal range. We demonstrated that textures in a magnetization distribution, like domain walls and vortex cores, can serve as sources for the generation of spin waves of directional nature, that is, planar waves in magnetic domains and waves confined to domain walls, which due to their geometry, are not subject to the reduction of amplitude due to divergence in energy flow. This is an important result, since such waves minimize the losses occurring during propagation. Indeed, we found that the resulting excitations can travel distances easily spanning several microns, *i.e.*, significantly exceeding multiples of the wavelength. The second aspect is to identify possible waveguides for magnonic chips. Here, we showed that domain walls can serve as such waveguides, combining several useful properties. First, due to their inherent symmetry, and consequently their near-gapless dispersion relation, spin waves can selectively be excited in these structures. In addition, we showed that spin wave packets can travel along angled domain walls while largely maintaining their amplitude. Such possibility of angled signal guidance is vital for chip design, and therefore our result may enable new solutions to the development of magnonic circuits.

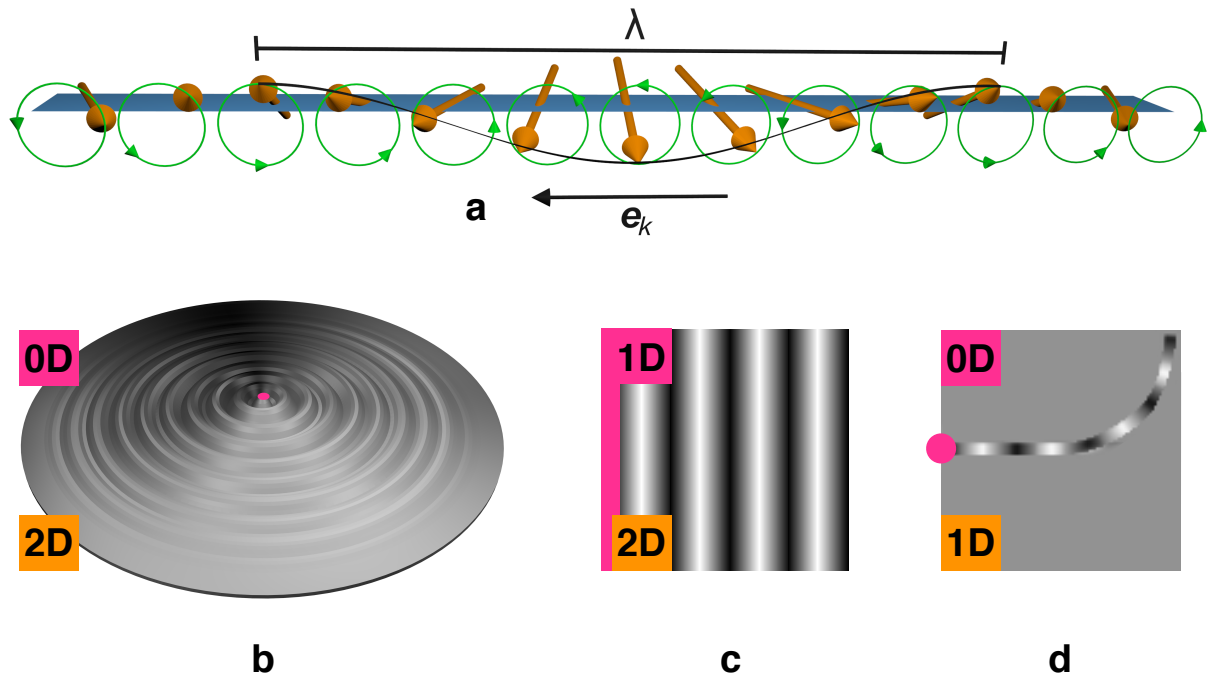


Figure 1: Spin waves in different geometries. (a) Schematics of a spin wave propagating along e_k . Magnetic moments (orange arrows) precess with a spatial phase difference, determining the wavelength λ . (b-d) Three different geometries of spin wave propagation explored in this paper. The magenta and orange fields denote the geometric dimensions of source and propagation medium, respectively. (b) Spin wave emission from a point source. In this case, the dimensions of medium and source differ by two. As a result, in addition to the exponential decay caused by the Gilbert damping, there is a geometric decay of the spin wave amplitude. (c) Plane-wave-like spin wave propagation. Similarly to (b), the waveguide medium is two dimensional, however the source has dimension one in this case. Thus, in (c) the dimensions of source and medium differ by one. This is also the case in panel (d), where a zero-dimensional source excites a one dimensional medium (a domain wall). The situations depicted in (c) and (d) are of special interest from the viewpoint of engineering magnonic waveguides, since in these cases the losses are largely limited to the Gilbert damping.

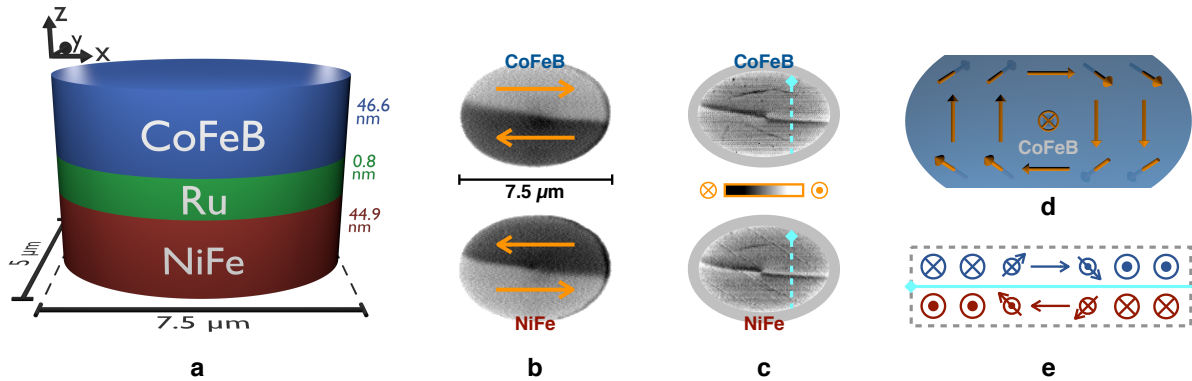


Figure 2: Sample layout and magnetic configuration. (a): The ferromagnetic element is patterned out of an interlayer-exchange-coupled bilayer system, consisting of a NiFe and a CoFeB layer, coupled antiferromagnetically by a Ru interlayer. The coupling leads to the magnetic states shown in (b), where the contrast represents the in-plane component along the long axis of the elliptic element, and (c), where the out-of-plane magnetic contrast is displayed. High-resolution XMCD scans show that the magnetic configuration is a pair of stacked vortices, with antiferromagnetically coupled in-plane magnetizations. We find that an additional anisotropy with easy axis along the long axis of the elliptic element leads to an anisotropic deformation of the vortex patterns, resulting in the formation of a domain wall, which is also visible both in the in-plane and out-of-plane contrast images. Micromagnetic simulations reveal that this domain wall has both Neel and Bloch character, as shown in (d). A cross-section of the domain wall profile is shown in (e), which can be imagined as taken along the blue lines in panel (c), illustrating the in- and out-of-plane components of the layer magnetizations in and around the domain wall.

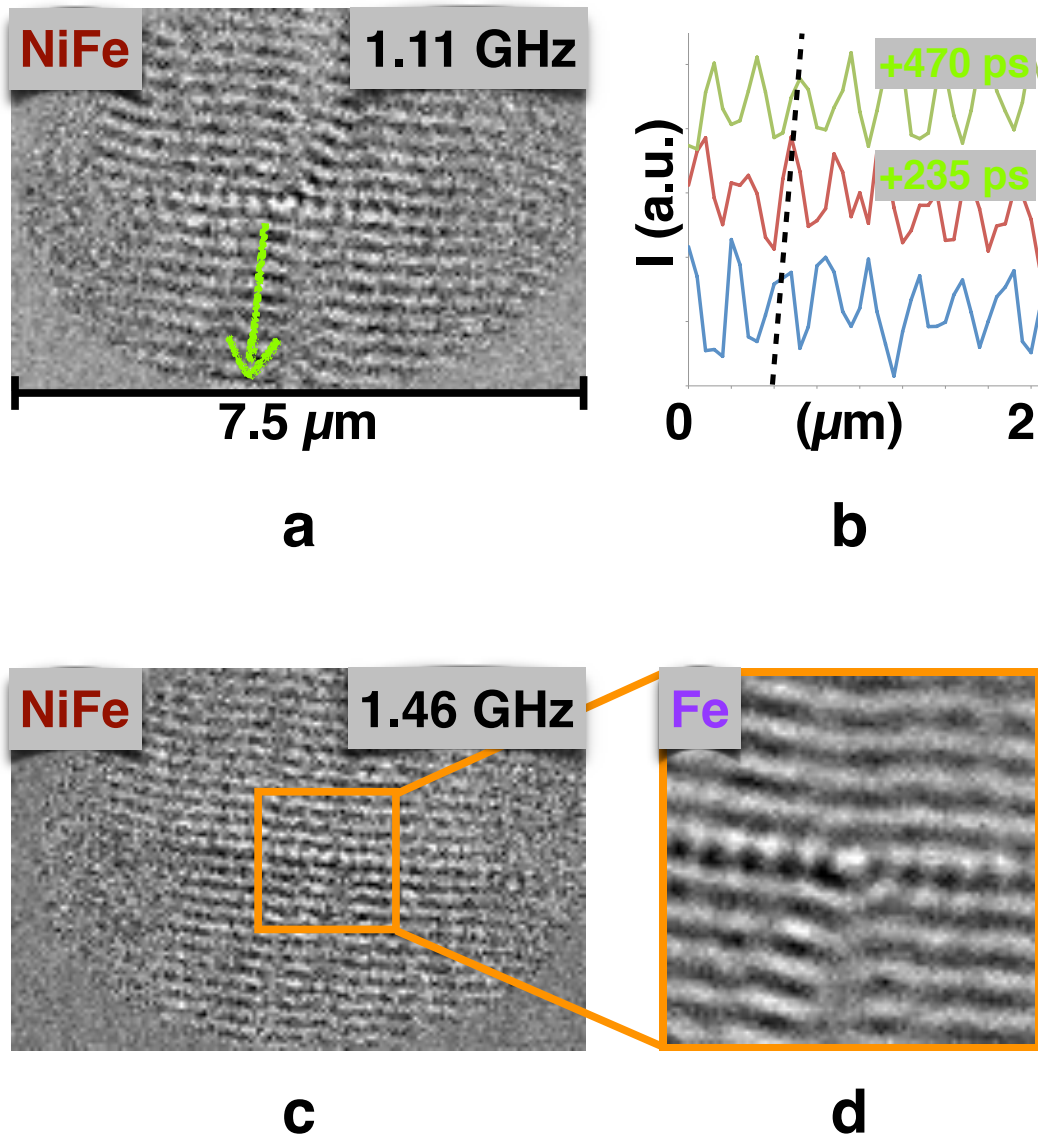


Figure 3: Excitation of spin waves. Snapshots of spin waves (NiFe layer out-of-plane magnetization component), excited using ac magnetic fields at different frequencies. **(a)** At an excitation frequency of 1.11 GHz, spin waves are generated that originate from the domain wall spanning the elliptically shaped magnetic element along the long axis through the vortex core. These plane waves travel from the wall to the rim of the disc, as indicated by the green arrow. Three time slices of the signal amplitude along that arrow taken at equidistant time intervals of 235 ps are shown in panel **(b)**. The time slices allow to determine the wavelength or wave vector, respectively. Furthermore, they show that the wave amplitude does not change significantly across the traveled distance of 2 microns, which clearly exceeds the wavelength. Panel **(c)** shows the corresponding image of a spin wave excited at 1.46 GHz, panel **(d)** displays

an enlarged image of the center region. In addition to the plane waves originating from the domain wall, spin waves with circular wave fronts can be seen. The latter are emitted from the vortex core (c.f. [16]). Using such images, we obtain the dispersion relation for the various types of waves.

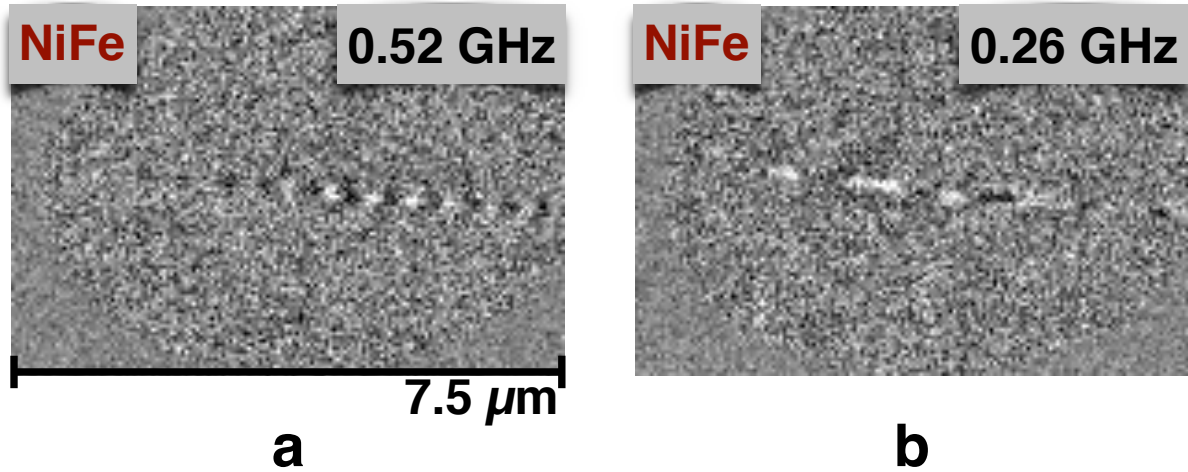


Figure 4: Spin waves in the domain wall. At excitation frequencies below a certain threshold, no spin waves are present in the domain regions. However, spin waves confined to the domain wall are observed that originate from the vortex core and travel towards the rim of the disc. Panel (a) and (b) display such waves (NiFe layer magnetization out-of-plane component) excited at 0.52 and 0.26 GHz, respectively, with accordingly changing wavelengths.

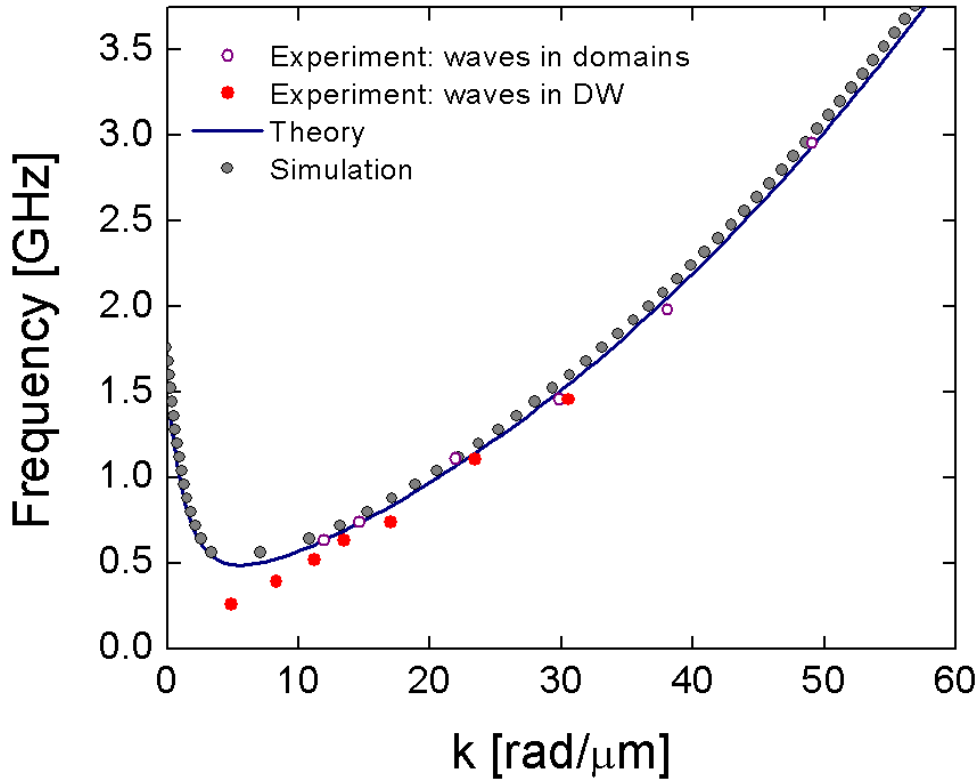


Figure 5: Spin waves dispersion relations. From the experiment, we obtain the dispersion relations for spin waves propagating in the domains (empty purple dots) and waves confined to the domain wall (full red dots). In addition, we show the plane wave dispersions calculated using our model (blue continuous line) and micromagnetic simulations (grey dots), which are in good agreement. Assuming an interlayer exchange coupling of -0.1 J/m^2 and a CoFeB uniaxial anisotropy of 3 kJ/m^3 , we obtain a reasonable agreement between the numeric results and the measured plane wave dispersion. The key difference of the plane waves and the waves confined to and propagating through the domain walls is the existence of a frequency gap in the plane wave dispersion, while for the wall waves, such a gap is absent, or too small to play a role here. These results explain why it is possible to selectively excite spin waves in the domain wall.

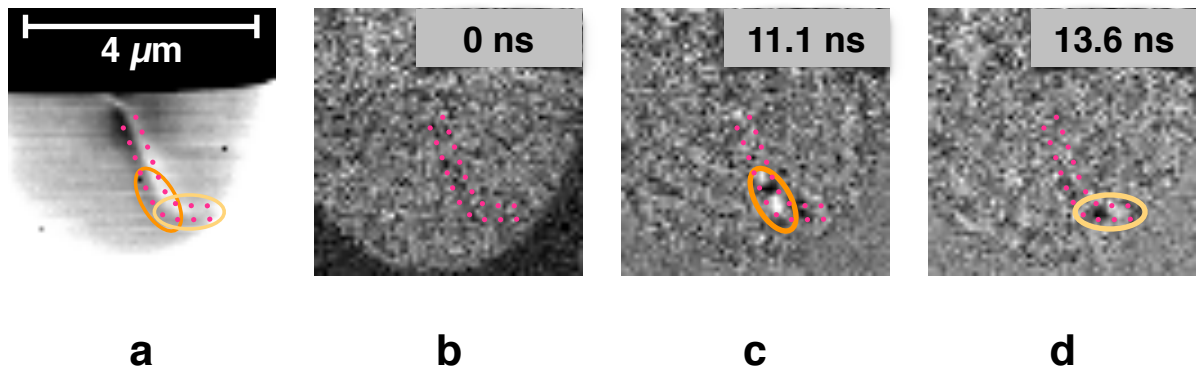


Figure 6: Domain walls as waveguides. We demonstrate the possibility of harnessing domain walls as waveguides for magnonic excitations by sending a spin wave packet around a domain wall curving around a corner. Panel (a) displays an in-plane magnetic contrast image of the domain wall, where the orange and yellow ellipses mark two regions in front and behind the curve, respectively. Panels (b) to (d) show snapshots of a spin wave packet excited by a magnetic field pulse, which are taken at different instances of time after the pulse. At 11.1 ns after the pulse (c), the wave packet has reached the region in front of the curve, as indicated by the orange ellipse. 2.5 ns later, the wave packet has traveled around the corner (d).

Methods

Sample fabrication

The samples were prepared on x-ray transparent silicon-nitride membrane substrates with a thickness of 200 nm. Multilayer films of Ni₈₁Fe₁₉/Ru/Co₄₀Fe₄₀B₂₀/Al were deposited by magnetron sputtering onto these, where Al (5 nm) is serving as a capping layer for oxidation protection. The thicknesses of the ferromagnetic layers, NiFe and CoFeB, were determined by transmission electron microscopy to be 44.9 nm and 46.6 nm, respectively. The Ru spacer (0.8 nm nominal) between them mediates an antiferromagnetic interlayer exchange coupling [39] according to the hard axis magnetization reversal of extended multilayer stacks, which was measured by magneto-optic Kerr effect (MOKE) [46]. Additional MOKE measurements on corresponding single layer films revealed collinear uniaxial magnetic anisotropies of 0.2 kJ/m³ for NiFe and 1.1 kJ/m³ for CoFeB. However, in order to reproduce the experimentally found static magnetic configuration in the micromagnetic simulations, a significantly larger value around 3 kJ/m³ is required for CoFeB. This elevated value for the in-plane uniaxial anisotropy in CoFeB can be attributed to strain, which in our case is caused by the contact with the waveguide. In fact, CoFeB is known for its sensitivity to strain and the orientation of the experimentally observed magnetic pattern with respect to the waveguide is consistent with this interpretation [41]. The patterning of the microelements was realized by electron beam lithography (EBL) and consecutive ion beam etching. Upon an initial oxygen plasma treatment for adhesive purposes, a negative resist (MA-N 2910) was spun onto the multilayer films. In a second step, the microelements were exposed by EBL. The samples were then developed for 300 s in MA-D 525 and rinsed in de-ionized water. Finally, the samples were exposed to an argon ion beam at two different angles (85° and 5°) for physically etching the magnetic microelements out of the continuous films. Remaining resist was removed by acetone and a second oxygen plasma treating. For magnetic field excitation, a copper strip of 200 nm thickness was fabricated on top of the microelements by means of EBL, electron beam

evaporation deposition, and lift-off processing [16]. The patterned microstrip has a width of 5 μm , hence the resulting magnetic Oersted field from a flowing electric current of one mA can be estimated to $\mu_0 H = 4\pi * 10^{-2}$ mT.

Time-resolved STXM.

The magnetic orientation in the multilayer microelement investigated was imaged by means of synchrotron based scanning transmission x-ray microscopy (STXM) [47]. Here, a Fresnel zone plate is used to focus a monochromatic x-ray beam onto the sample. The locally transmitted x-ray intensity is then measured by a single pixel detector, hence raster scanning the sample yields a two-dimensional absorption image with approximately 25 nm lateral resolution. Using furthermore circularly polarized x-rays allows for exploiting x-ray magnetic circular dichroism (XMCD) [48] leading to a magnetic contrast. As XMCD only occurs at the element specific resonant absorption edges, the magnetic signal from both ferromagnetic layers, NiFe and CoFeB, can be separated by tuning the incident x-rays to the corresponding L_3 energies, Ni L_3 ~ 853 eV and Co L_3 ~ 778 eV, respectively. On the other hand, a collective signal from both layers can be collected from the Fe L_3 edge at ~ 708 eV since both layers contain Fe. The magnetic contrast acquired is proportional to the projection of the magnetic orientation $\mathbf{m} = \mathbf{M}/M$ on the x-ray propagation direction \mathbf{e}_k . Therefore, in normal incidence, the STXM setup is sensitive to the perpendicular magnetization component, while an inclined sample mounting also allows for detecting in-plane magnetization components.

The magnetization dynamics of the multilayer microelements was imaged stroboscopically by means of time-resolved STXM. This method utilizes the specific time structure of the incident x-ray pulses, i.e. 2 ns repetition rate at ~ 100 ps effective pulse length. Each incoming signal (photon or no photon transmitted) is routed after every pulse to a periodic counting register of a field programmable gate array. Here the number of registers (Q) sets the

maximum non-stroboscopic observation period ($Q \cdot 2$ ns), while the number of excitation repetitions in this period (J) sets the nominal time resolution as well as the excitation frequency in case of a continuous sinusoidal excitation. The excitation current was measured both in front of and behind the sample by means of -20 dB pick-off tees through an oscilloscope.

Micromagnetic simulations.

Micromagnetic simulations based on the time integration of the Landau-Lifshitz-Gilbert [49,50] equation were carried out using the code MuMax³ [51]. The simulations were performed to compute the spin wave dispersion relations in the coupled layer system. The ferromagnetic layers are homogeneously magnetized and the dispersion relations are calculated in a thin film approach. Therefore, the system was discretized into 4096 x 16 x 115 cells and periodic boundary conditions were applied along the y – direction, which corresponds to the direction of the applied ac magnetic field. The thickness of the individual layers and the spacer were chosen according to TEM measurements. This results in a cell size along the z – axis of 0.8 nm. The material parameter used in the micromagnetic simulations are as follows: For NiFe, the respective values of saturation magnetization, exchange stiffness and uniaxial in-plane anisotropy are: $M_s^{\text{Py}} = 800$ kA/m, $A_{xc}^{\text{Py}} = 7.5$ pJ/m [52] and $K_U^{\text{Py}} = 200$ J/m³. For the CoFeB layer, we used $M_s^{\text{CoFeB}} = 1250$ kA/m, $A_{xc}^{\text{CoFeB}} = 12$ pJ/m [53] and $K_U^{\text{CoFeB}} = 3000$ J/m³. The interlayer exchange coupling is $J = -0.1$ mJ/m². The Gilbert damping constant α for CoFeB and NiFe is chosen to 0.008 and 0.01, respectively. To prevent reflection of spin waves from the edges the damping was increased linearly to 0.065 for both layers.

An out-of-plane sinusoidal excitation field with a fixed frequency was applied in a 100 nm wide region in the center of the system. After the system reached the dynamic equilibrium the magnetization configuration was stored. To extract the wave number for each frequency a spatial fast-Fourier transform along x – direction of the system was performed. The corresponding dispersion relations are shown in Fig. 5 as grey full dots and are in good

agreement with the result from the model calculations. Additional simulations were performed in order to compare the effects of oscillatory magnetic fields applied in- and out-of-plane, in each case perpendicular to the magnetization. The simulations clearly show that the bilayer system is more susceptible to out-of-plane field perturbations. This result can be understood taking into account the fact that the excited collective mode exhibits an in-phase oscillation of the perpendicular, yet anti-phase oscillation of the in-plane magnetization component, and thus couples more efficiently to driving fields oriented perpendicular to the sample plane. There exists another type of collective mode in the system, which exhibits an in-phase oscillation of the in-plane component, however this mode resides at higher frequency values than the measured ones.

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Author contributions

V.S., M.W., and S.W. performed the STXM measurements. T.S., T.W., A.K., and S.W. did the micromagnetic simulations. R.A.G, A.R.M, and P.L calculated the spin wave dispersion relation. R.M. and S.W. supervised the sample preparation. V.S. and S.W. wrote the manuscript. All authors contributed to the discussion of the results and commented on the manuscript.