Nonreciprocal nano-optics with spin-waves

Edoardo Albisetti\textsuperscript{1,2,*}, Silvia Tacchi\textsuperscript{3}, Raffaele Silvani\textsuperscript{3,4}, Giuseppe Scaramuzzi\textsuperscript{1}, Simone Finizio\textsuperscript{5}, Sebastian Wintz\textsuperscript{5}, Jörg Raabe\textsuperscript{5}, Giovanni Carlotti\textsuperscript{3}, Riccardo Bertacco\textsuperscript{1}, Elisa Riedo\textsuperscript{6,2,*} and Daniela Petti\textsuperscript{1,*}

\textsuperscript{1}Dipartimento di Fisica, Politecnico di Milano, 20133 Milano, Italy.
\textsuperscript{2}Advanced Science Research Center, CUNY Graduate Center, 85 St. Nicholas Terrace, New York, New York 10031, USA.
\textsuperscript{3}Istituto Officina dei Materiali del CNR (CNR-IOM), Unità di Perugia, c/o Dipartimento di Fisica e Geologia, Perugia, Italy.
\textsuperscript{4}Dipartimento di Fisica e Geologia, Università di Perugia, Via A. Pascoli, Perugia, I-06123, Italy
\textsuperscript{5}Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
\textsuperscript{6}Tandon School of Engineering, New York University, New York NY 11201, USA

*Correspondence to: edoardo.albisetti@polimi.it, elisa.riedo@nyu.edu, daniela.petti@polimi.it;

Abstract

Integrated optically-inspired analog computing based on the interference of coherent wavefronts is envisioned to outperform digital processing in many tasks, such as image processing and speech recognition. Nanoscale integration, however, represents a major challenge, due to the centimeter-long wavelength of electromagnetic radiation in the GHz frequency range used for processing. Here, we realize a versatile optically-inspired platform using spin-waves, demonstrating the wavefront engineering, focusing, and robust interference of spin-waves with nanoscale wavelength. In particular, we use magnonic nanoantennas based on tailored spin-textures for launching spatially shaped coherent wavefronts, diffraction-limited spin-wave beams, and generating robust multi-beam interference patterns, which spatially extend for several times the spin-wave wavelength. Furthermore, we show that intriguing features such as one-way propagation naturally arise from the spin-wave non-reciprocity, preserving the high quality of the interference patterns from spurious counterpropagating modes. This work represents a fundamental step towards the realization of nanoscale optically-inspired computing devices based on spin-waves.
**Introduction**

Optically-inspired wave-based analog computing (WBAC) is envisioned to outperform conventional digital processing in a set of specific tasks, such as image processing, recognition and filtering.\(^1\)-\(^3\) In such systems, computation is performed via analog interference of coherent wavefronts propagating in a specifically designed medium, with huge advantages in terms of energy efficiency and multiplexing capability. However, the scalability of WBAC systems using electromagnetic waves is severely limited by their wavelength, which is centimeters long in the GHz frequency range used for signal transmission and processing, and therefore not compatible with nanoscale integration. The use of engineered (meta)materials for controlling the propagating wavefronts\(^4\)-\(^6\), or coupling electromagnetic waves with plasmons in nano-optical platforms\(^7\) represent promising avenues. Surface (SAW) and bulk (BAW) acoustic waves, generated by piezoelectric materials, despite representing reference technologies in wireless communications, are still limited by their poor scalability and integrability.\(^8\)

Another intriguing route consists in coupling microwave signals with spin-waves (SWs) in magnetic materials. Spin-waves\(^9\)-\(^11\) combine nanometric wavelength,\(^12\) a great degree of tunability via the engineering of the magnetic properties\(^13\)-\(^25\), and a rich phenomenology\(^26\)-\(^33\), constituting an extremely promising path towards integrated analog signal processing.\(^34\)

So far, however, the development of nanoscale optically-inspired spin-wave platforms was hindered by the absence of efficient ways for manipulating spin-wave wavefronts at the nanoscale,\(^35\) in analogy to what is done in the field of nano-optics, where tailored plasmonic wavefronts are emitted by coupling light with engineered plasmonic nanoantennas.

Here, we experimentally realize such a platform, by generating and shaping nanoscale spin-wave wavefronts, propagating in a magnetic multilayer. This is done by coupling radiofrequency signals with engineered magnonic nanoantennas, directly patterned in the spin-texture of the multilayer via thermally assisted magnetic scanning probe lithography (tam-SPL)\(^36\),\(^37\).

In such a platform, we demonstrate the generation of spin-waves with planar, radial, convex and concave wavefronts, the directional emission of spin-wave beams, and their diffraction-limited focusing into dimensions comparable to their nanoscale wavelength. Furthermore, by combining the emission of multiple nanoantennas, we generate robust interference patterns, which span for more than 15 times the spin-wave wavelength. Then, we show that the non-reciprocity of spin-waves in our SAF system\(^38\) leads to one-way SW propagation, and guarantees immunity from back-scattering at defects and spurious reflections, therefore preserving an extremely high quality of the interference patterns. The demonstration of such a rich phenomenology opens up intriguing possibilities for the realization of integrated analog processing nanodevices using spin-waves.

**Discussion**

In Figure 1, we present the concept of magnonic nanoantennas, based on the patterning of magnetic domain walls shaped with nanoscale precision. The multilayer structure, grown by magnetron sputtering (see Methods) is sketched in Fig. 1A. It consists of two 45 nm CoFeB ferromagnetic layers
aligned antiferromagnetically via bilinear coupling through a thin non-magnetic Ru 0.6 nm spacer (synthetic antiferromagnet, SAF). The magnetization direction of the top CoFeB layer is set via exchange bias with a 10 nm IrMn antiferromagnetic layer. The hysteresis loop, shown in the Supplementary Information (Fig. S1), features two well defined and separate lobes, related to the two ferromagnetic layers, and the characteristic flat region around zero external field, indicating the robustness of the antiferromagnetic coupling.

For writing the spin-texture of the SAF, a nanoscale field cooling is performed via thermally assisted scanning probe lithography (tam-SPL), by sweeping a heated scanning probe on the surface of the sample in an applied external field (see Methods). As a result, two-dimensional magnetic domains, mono-dimensional domain walls and zero-dimensional topological magnetic quasiparticles with deterministically tailored spin configuration can be directly patterned in the continuous film. Fig. 1A shows a sketch of a straight 180° domain wall (see also Fig. S2 and related discussion in the Supplementary Information). Fig. 1B, C shows magnetic force microscopy (MFM) images of straight (B) and curved (C) magnetic domain walls, patterned via tam-SPL by writing domains with oppositely oriented magnetization direction. In each image, the equilibrium magnetization direction of the top CoFeB layer is indicated by violet arrows.

In the following, we show that spin-textures can be used as magnonic nanoantennas, for spatially shaping at the nanoscale and manipulating spin-wave wavefronts propagating in the film. Panel D shows a micromagnetic simulation sketching this concept, where a curved domain wall, indicated by the thick magenta line, driven into oscillation by a microwave field, directionally emits spin-waves with wavelength \( \lambda \) along the direction \( \mathbf{u} \). Below, the orientation of the spins in the top CoFeB layer within a single spin-wave wavelength is sketched.

In order to show the versatility and potential of this platform, we provide the proof-of-concept of different functionalities. In Figure 2, we demonstrate the generation of spatially shaped wavefronts and directional emission of spin-wave beams by using curved nanoantennas. The spin-wave excitation and propagation is visualized stroboscopically with high spatial and temporal resolution via Scanning Transmission X-Ray Microscopy (STXM) (see Methods). The black/white color corresponds to the oscillation of the out-of-plane component of the magnetization \( M_z \) associated to the propagation of spin-waves, with respect to the average value over one period of oscillation. The oscillation of the domain wall is driven by an external magnetic field \( H_{RF} \), provided by a stripline run by radio-frequency current, patterned on top of the multilayer in close proximity to the wall (see Methods).

Panels A and B show the experimental STXM image (left, see also Supplementary Movie 1) and micromagnetic simulation (right) of the emission of spin-waves from an extended curved domain wall, indicated by the thick magenta line. Subsequent convex wavefronts are indicated by alternated red/blue lines, and white arrows indicate the direction of the equilibrium magnetization in the top layer. Noteworthy, the wavefronts retain the shape of the emitter, so that a straightforward wavefront engineering is enabled, by tuning the curvature of the domain wall. The obliquity factor of the
The Huygens-Fresnel principle in optics is naturally contained in the physics of the nonreciprocal SW modes in SAFs, so that the same principle can be directly applied in our context to the propagation of wavefronts generated by oscillating DWs. Each portion of a wavefront acts as a point source of almost circular waves propagating only in the forward direction (see Figure 4 below) and the wavefront propagation can be easily predicted by exploiting the analogy with diffraction optics. Panel C, D show the experimental spatial and temporal profiles extracted from the dashed line and blue dot in panel A, respectively, featuring a spin-wave wavelength of $\lambda \sim 300$ nm for an excitation frequency $f = 1.57$ GHz. Importantly, a strong spin-wave signal is clearly visible after more than 15 periods of propagation, limited by the STXM acquisition window. The combination of short-wavelength spin-wave modes, wavefront engineering, and propagation length exceeding several times their wavelength is essential for building analog nanodevices based on spin-wave interference. Another appealing feature in wave-based processing is the possibility of focusing the wave energy in specific and controlled directions. In panels E, F, we demonstrate the directional emission and focusing of spin-wave beams. The left panel shows the STXM image (see also Supplementary Movie 2) of propagating spin-waves emitted by the curved portion of a domain wall nanoantenna, in magenta. The wavefront shape is highlighted in red (trough) and blue (crest). The right panel shows the corresponding micromagnetic simulation, and the direction of the equilibrium magnetization in the top layer (white arrows). The wall locally excites a converging spin-wave beam which is focused at a distance $d_f \sim 2.5 \mu m$ from the emitter. Consistently with a focusing effect, the concavity of the wavefront changes from concave to convex after the focal point. Panel H shows the spatial profile extracted in correspondence of the yellow dashed line in panel E, at the focal point. The full width at half maximum (FWHM) of the beam amplitude at the focal point is $w_f \sim 340 \pm 50$ nm. Noteworthy, this picture is in good agreement with a description analogue to diffractive optics for the emission from a source of finite size, as shown in panel G. The focusing is determined by the numerical aperture of the object, in our case the finite wall source, so that the minimum beam width can be estimated as $w_f = \lambda /[2 \sin(\alpha)] = 363$ nm, where $\lambda = 330$ nm is the experimental spin-wave wavelength at $f = 1.43$ GHz and $\alpha = 27^\circ$ is determined by the wall geometry.

The generation of controlled wavefronts is one of the crucial requirements for analog based computation. In the following, we show that by combining multiple spin-wave sources, we are able to generate robust spin-wave interference patterns which span for several times their wavelength. For demonstrating the generality of the approach, we use planar wavefronts emitted by straight domain walls, and radial wavefronts emitted by vortices (see Supplementary Note 4 and Supplementary Movies 3, 4) as building blocks for generating interference patterns.

In Figure 3A (experiment, see also Supplementary Movie 5) and B (simulations), a straight domain wall (magenta line) and a vortex located within the domain wall itself (magenta circle) are used for generating simultaneously linear and radial wavefronts, respectively, which spatially superimpose during propagation. The curved and straight red/blue lines identify the separate wavefronts with radial and linear symmetry, respectively. In the STXM images and simulations, the black/white contrast represents $\Delta M_z$ component at a specific time. Destructive interference fringes, where the spin-waves
sum in anti-phase are clearly visible as low intensity, grey regions, while constructive interference is visualized as high intensity black/white regions. For better visualizing the interference pattern, in panel C we show the spatial map of the spin-wave amplitude, obtained by evaluating the amplitude of the experimental oscillation of $\Delta M_z$ point-by-point. The characteristic alternated interference minima and maxima are visible as yellow and blue regions, respectively, and are numbered in the figure. Panel D shows the experimental spatial profile extracted from the red dashed line in panel C (red line), showing the first 5 interference maxima spaced by ~ 450 nm, in excellent agreement with the simulation (gray line). In panels E (experiment, see also Supplementary Movie 6), F (simulations), a domain wall comprising two straight branches forming a $\beta = 135^\circ$ angle with each other is used for directionally emitting two angled wavefronts with planar symmetry, indicated by the red/blue lines. The emission of the planar wavefronts and the interference figure are clearly visible both in the STXM image and simulation. Noteworthy, the interference patterns are still clearly visible after more than 15 oscillation periods, limited by the experimental acquisition window. These results demonstrate the generation of robust multi-beam interference patterns at the nanoscale, i.e. the basic element for integrated wave-based computing.

The high quality and robustness of the interference patterns are determined by the peculiar properties of the spin-wave dispersion in SAFs. For better clarifying these aspects, in Figure 4, we show the results of micromagnetic simulations of the spin-wave propagation in extended exchange biased antiferromagnetically coupled bilayers (see methods and Supplementary Note 5), focusing on the in-plane angular dependence of the dispersion. In Figure 4A, the spin-wave dispersion curves calculated for different values of the angle $\varphi$ between the magnetization of the top CoFeB film ($M_{\text{top}}$) and the wavevector $k$ are shown. Black filled dots show the experimental dispersion of spin-waves emitted by a straight domain wall, confirming the possibility of tuning the spin-wave wavelength by varying the microwave excitation frequency. Two fundamental features are evident from the dispersion. First, the strong nonreciprocity causes the two branches ($\pm k$) to have significantly different dispersion and localization across the film thickness (see also Supplementary Note 5). In fact, spin-waves propagating in opposite directions have different group velocity ($\partial \omega / \partial k$) and wavelength, for a fixed frequency, and will be referred to as “short-wavelength” (+$k$, the focus of our experiments) and “long-wavelength” (-$k$) modes. Noteworthy, below the threshold frequency value corresponding to the crossing point of the different curves at $k = 0$ ($f = 1.57$ GHz), spin-wave propagation occurs only in the positive direction (+$k$), for the “short-wavelength” modes.

Second, “short wavelength” modes are characterized by a roughly isotropic in-plane propagation on a wide angular range, i.e. its wavelength and group velocity vary weakly with the propagation direction in a wide range of angles (from 90°, corresponding to the “Damon-Eshbach” configuration, dark blue curve, down to 15°, orange curve).

The effect of the combination of these two properties is evident in Fig. 4B, where we show the simulated one-way propagation of wavefronts emitted by a point source (see also Supplementary
Note 5) oscillating at 1.57 GHz. One can see that spin-waves, with highly regular radial wavefronts, are exclusively emitted on the right side of the source, reflecting the above discussed nonreciprocity. A deeper understanding can be achieved by analyzing the calculated isofrequency curves in the reciprocal space (also known as slowness curves), plotted in Fig. 4C. For negative $k_x$ the isofrequency curves are characterized by a strongly anisotropic behavior, typical of dipole-dominated spin-waves. On the contrary, for positive $k_x$, the contours show an elliptical shape reflecting the almost isotropic character of the “short wavelength” mode.

The peculiar combination of roughly isotropic and one-way propagation guaranteed by the SAF system is at the origin of the features we observe experimentally, i.e. highly regular wavefronts which are maintained for distances of several times the wavelength, and the absence of back-reflections by boundaries or defects, which preserve the spin-wave interference patterns from the contamination of counter-propagating modes. Noteworthy, this provides the opportunity to realize the natural spin-wave analogue to the optical isolation used e.g. in optical diodes, where time-reversal symmetry breaking leads to one-way light propagation.

Crucially, we highlight that the spatial control of the magnetization direction, which is a prerogative of tam-SPL, allows to straightforwardly exploit nonreciprocity as an additional design rule for the control of the emission and propagation of spin-waves.

Conclusion

In this work, we realized a versatile optically-inspired platform for controlling the generation, propagation and interference of nanoscale spin-waves. We demonstrated the spatial engineering of spin-wave wavefronts via tailored magnonic nanoantennas, the focusing of spin-wave beams down to the nanoscale and the controlled generation of robust multibeam interference patterns which span multiple times the spin-wave wavelength. Crucially, with respect to light and plasmons, spin-waves offers the unique opportunity to exploit phenomena naturally arising from the spin-wave non-reciprocity, such as one-way propagation, back-reflection immunity, and resilience to defects. In view of applications, we point out that our platform is based on conventional CMOS compatible magnetic thin films grown via sputtering, does not require bulky electromagnets for applying uniform external fields, and allows for the full reconfigurability of the magnonic nanoantennas, e.g. via laser writing. The unique combination of these features gives rise to a versatile playground for studying the physics of nonreciprocal spin-wave propagation, and represents a fundamental step towards optically-inspired processing. A plethora of applications can be envisioned, including reconfigurable microwave filters, and devices for pattern and speech recognition based on the emission, manipulation and interference of coherent spin-wave wavefronts at the nanoscale.
**Figure 1. Magnonic nanoantennas based on patterned spin-textures.** A, Sample structure of the exchange biased synthetic antiferromagnet (SAF), consisting of a sputtered IrMn / CoFeB / Ru / CoFeB magnetic multilayer. The orientation of the spins of a magnetic domain wall (DW) is sketched. Spin-waves are launched by driving the oscillation of the domain wall with a radiofrequency (RF) external magnetic field $H_{rf}$. B, C, Magnetic force microscopy images of patterned spin-textures. Straight, angled (B) and curved (C) domain walls with precisely controlled geometry and spin configuration are written in the spin-texture via thermally assisted magnetic scanning probe lithography (tam-SPL). Purple arrows indicate the direction of the equilibrium magnetization in the top CoFeB layer. Scale bars: 3 μm. D, Simulation of spatially shaped spin-wave wavefronts generated by a curved nanoantenna. $u_k$ marks the spin-wave propagation direction. Below, the precession of the spins along a single spin-wave wavelength $\lambda$. 
Figure 2. Spin-wave wavefront engineering. A, B, Experimental STXM image (A) and micromagnetic simulation (B) of the directional emission of convex spin-wave wavefronts by a curved domain wall (red line). Wavefronts are indicated by thin red and blue lines. C, D, Spatial and temporal profiles extracted from the yellow dashed line and blue dot in panel A, and corresponding Supplementary Movie 1, respectively. Strong spin-wave intensity is measured after more than 15 periods of propagation. E, F, Experimental image (E) and simulation (F) of the emission and focusing of spin-wave beams with concave wavefronts. G, Diffractive-optics analogue of spin-wave focusing by a magnonic nanoantenna with angular aperture 2α. H, Spatial profile of the spin-wave amplitude along the dashed line in panel E. At the beam waist, located 2.5 μm away from the emitter, spin-waves are localized in a region comparable to the spin-wave wavelength ~ 340 nm. White arrows indicate the direction of the equilibrium magnetization in the top CoFeB film. Scale bars: 500 nm.
Figure 3. Generation of multi-beam interference patterns. A, B Experimental STXM image (A) and simulations (B) of the interference from radial wavefronts emitted by a vortex and planar wavefronts emitted from a straight domain wall. The domain wall and vortex are indicated by magenta lines and dot. C, Spatial map of the spin-wave amplitude related to panel A. Constructive and destructive interference fringes are visible as alternated minima (blue) and maxima (yellow). The region of the first interference maximum is indicated by white lines in panels A-C. D, Experimental (red) spatial profile of the spin-wave amplitude extracted from the red dashed line in panel C, and corresponding simulation (grey). The numbers refer to the first 5 interference maxima. E, F, Experimental (E) and simulated (F) interference pattern generated by the spin-wave wavefronts emitted by two angled domain wall nanoantennas, indicated in magenta. The two linear wavefronts are indicated by thin red and blue lines. White arrows indicate the equilibrium magnetization direction of the top layer. Scale bars: 500 nm.
Figure 4. Characteristics of low-anisotropy nonreciprocal spin-wave modes in a SAF. A, Color-coded lines show the simulated spin-wave dispersion in the SAF multilayer, as a function of the angle $\varphi$ between the wavevector $k$ and the equilibrium magnetization $M_{\text{top}}$ in the top layer. Black dots show the experimental points. On the right side (positive wavevectors), the dispersion features short-wavelength spin-waves characterized by low anisotropy. B, Simulated spin-wave wavefronts, in the real space, emitted by a point excitation (white dot) at $f = 1.57$ GHz. The direction of the magnetization of the top layer $M_{\text{top}}$ is indicated by the purple arrow. Scale bar: 500 nm. C, Simulated isofrequency curves, in the reciprocal space, for the spin-wave modes propagating in the SAF. The equilibrium magnetization of the top layer $M_{\text{top}}$ is directed along $y$. The dashed line indicates the curve for $f = 1.57$ GHz.
Acknowledgements

The authors thank A. Melloni, F. Morichetti, P. Laporta, for fruitful discussions and Guido Gentili for the simulations of the electrical behavior of the striplines. The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements no. 705326, project SWING, and no. 730872, project CALIPSOplus. This work was partially performed at Polifab, the micro- and nano-technology center of the Politecnico di Milano. Part of this work was performed at the PolLux (X07DA) endstation of the Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland. The PolLux endstation was financed by the German Minister für Bildung und Forschung (BMBF) through contracts 05KS4WE1/6 and 05KS7WE1.

References

1. Ulmann, B. Analog computing. (Oldenbourg Wissenschaftsverlag, 2013).
2. Goodman, J. W. Introduction to Fourier optics. (Roberts & Co, 2005).
3. Solli, D. R. & Jalali, B. Analog optical computing. Nature Photonics 9, 704–706 (2015).
4. Silva, A. et al. Performing mathematical operations with metamaterials. Science 343, 160–163 (2014).
5. del Hougne, P. & Lerosey, G. Leveraging Chaos for Wave-Based Analog Computation: Demonstration with Indoor Wireless Communication Signals. Physical Review X 8, 1–20 (2018).
6. Sihvola, A. Enabling Optical Analog Computing with Metamaterials. Science 343, 144–145 (2014).
7. Nikitin, a. Y. et al. Controlling graphene plasmons with resonant metal antennas and spatial conductivity patterns. Science 344, 1369–1373 (2014).
8. Aigner, R. SAW and BAW technologies for RF filter applications: A review of the relative strengths and weaknesses. in 2008 IEEE Ultrasonics Symposium 582–589 (IEEE, 2008). doi:10.1109/ULTSYM.2008.0140
9. Kruglyak, V. V, Demokritov, S. O. & Grundler, D. Magnonics. Journal of Physics D: Applied Physics 43, 264001 (2010).
10. Chumak, A. V., Vasyuchka, V. I., Serga, A. A. & Hillebrands, B. Magnon spintronics. Nature Physics 11, 453–461 (2015).
11. Lenk, B., Ulrichs, H., Garbs, F. & Münzenberg, M. The building blocks of magnonics. Physics Reports 507, 107–136 (2011).
12. Yu, H. et al. Approaching soft X-ray wavelengths in nanomagnet-based microwave technology. Nature Communications 7, 11255 (2016).
13. Hämäläinen, S. J., Madami, M., Qin, H., Gubbiotti, G. & van Dijken, S. Control of spin-
wave transmission by a programmable domain wall. *Nature Communications* **9**, 4853 (2018).

14. Wintz, S. *et al.* Magnetic vortex cores as tunable spin-wave emitters. *Nature Nanotechnology* **11**, 948–953 (2016).

15. Garcia-Sanchez, F. *et al.* Narrow Magnonic Waveguides Based on Domain Walls. *Physical Review Letters* **114**, 247206 (2015).

16. Haldar, A., Kumar, D. & Adeyeye, A. O. A reconfigurable waveguide for energy-efficient transmission and local manipulation of information in a nanomagnetic device. *Nature Nanotechnology* **11**, 437–443 (2016).

17. Krawczyk, M. & Grundler, D. Review and prospects of magnonic crystals and devices with reprogrammable band structure. *Journal of physics. Condensed matter : an Institute of Physics journal* **26**, 123202 (2014).

18. Behncke, C. *et al.* Spin-wave interference in magnetic vortex stacks. *Communications Physics* **1**, 50 (2018).

19. Davies, C. S. *et al.* Towards graded-index magnonics: Steering spin waves in magnonic networks. *Physical Review B* **92**, 20408 (2015).

20. Vogt, K. *et al.* Realization of a spin-wave multiplexer. *Nature Communications* **5**, 3727 (2014).

21. Albisetti, E. *et al.* Nanoscale spin-wave circuits based on engineered reconfigurable spin-textures. *Communications Physics* **1**, 56 (2018).

22. Van de Wiele, B., Hämäläinen, S. J., Baláž, P., Montoncello, F. & van Dijken, S. Tunable short-wavelength spin wave excitation from pinned magnetic domain walls. *Scientific Reports* **6**, 21330 (2016).

23. Sluka, V. *et al.* Emission and Propagation of Multi-Dimensional Spin Waves in Anisotropic Spin Textures. *arXiv preprint* (2018).

24. Liu, C. *et al.* Long-distance propagation of short-wavelength spin waves. *Nature Communications* **9**, 4–11 (2018).

25. Lan, J., Yu, W., Wu, R. & Xiao, J. Spin-Wave Diode. *Physical Review X* **5**, 41049 (2015).

26. Stigloher, J. *et al.* Snell’s Law for Spin Waves. *Physical Review Letters* **117**, 37204 (2016).

27. Loayza, N., Jungfleisch, M. B., Hoffmann, A., Bailleul, M. & Vlaminck, V. Fresnel diffraction of spin waves. *Physical Review B* **94**, 1–7 (2018).

28. Bonetti, S. *et al.* Direct observation and imaging of a spin-wave soliton with p-like symmetry. *Nature Communications* **6**, 1–6 (2015).

29. Henry, Y., Stoeffler, D., Kim, J.-V. & Bailleul, M. Unidirectional spin-wave channeling along magnetic domain walls of Bloch type. *arXiv preprint* (2018).

30. Schneider, T. *et al.* Nondiffractive subwavelength wave beams in a medium with externally controlled anisotropy. *Physical Review Letters* **104**, 1–4 (2010).

31. Kwon, J. H. *et al.* Giant nonreciprocal emission of spin waves in Ta/Py bilayers. *Science Advances* **2**, 6–13 (2016).

32. Kim, J. Von, Stamps, R. L. & Camley, R. E. Spin Wave Power Flow and Caustics in Ultrathin Ferromagnets with the Dzyaloshinskii-Moriya Interaction. *Physical Review Letters*
Chiral protection of dipole-exchange spin-waves. *arXiv preprint* (2018).

34. Csaba, G., Papp, Á. & Porod, W. Perspectives of using spin waves for computing and signal processing. *Physics Letters A* **381**, 1471–1476 (2017).

35. Papp, A. *et al.* Waveguides as sources of short-wavelength spin waves for low-energy ICT applications. *The European Physical Journal B* **91**, 107 (2018).

36. Albisetti, E. *et al.* Nanopatterning reconfigurable magnetic landscapes via thermally assisted scanning probe lithography. *Nature Nanotechnology* **11**, 545–551 (2016).

37. Albisetti, E. *et al.* Stabilization and control of topological magnetic solitons via magnetic nanopatterning of exchange bias systems. *Applied Physics Letters* **113**, 162401 (2018).

38. Grünberg, P. A. Nobel Lecture: From spin waves to giant magnetoresistance and beyond. *Reviews of Modern Physics* **80**, 1531–1540 (2008).
Nonreciprocal nano-optics with spin-waves

SUPPLEMENTARY INFORMATION

Supplementary Note 1. Methods

Sample fabrication
Co$_{40}$Fe$_{40}$B$_{20}$ 45 nm / Ru 0.6 nm / Co$_{40}$Fe$_{40}$B$_{20}$ 45 nm / Ir$_{22}$Mn$_{78}$ 10 nm / Ru 2 nm stacks were deposited on 200 nm thick Si$_3$N$_4$ membranes by DC magnetron sputtering using an AJA Orion8 system with a base pressure below $1 \times 10^{-8}$ Torr. During the deposition, a 30 mT magnetic field was applied in the sample plane for setting the exchange bias direction in the as-grown sample. Then, the samples underwent an annealing in vacuum at 250 °C for 5 minutes, in a 400 mT magnetic field oriented in the same direction as the field applied during the growth.

Thermally assisted magnetic Scanning Probe Lithography (tam-SPL) was performed via NanoFrazor Explore (SwissLitho AG). Spin-textures were patterned by sweeping in a raster-scan fashion the scanning probe, heated above the blocking temperature of the exchange bias system $T_B \approx 300$ °C, in presence of an external magnetic field. Two rotatable permanent magnets were employed for generating a uniform external magnetic field applied in the sample plane during patterning.

Microstrip antennas were then fabricated via optical lithography using a Heidelberg MLA100 Maskless Aligner and lift-off, after depositing a 50 nm thick SiO$_2$ insulating layer via magnetron sputtering. A Cr 7 nm / Cu 200 nm bilayer was deposited by means of thermal evaporation with an Evatec Bak 640 system.

Scanning trasmission X-ray microscopy
The magnetic configuration of the samples was investigated with time-resolved scanning transmission X-ray microscopy at the PolLux (X07DA) endstation of the Swiss Light Source$^1$. In this technique, monochromatic X-rays, tuned to the Co L$_3$ absorption edge (photon energy of about 781 eV), are focused using an Au Fresnel zone plate with an outermost zone width of 25 nm onto a spot on the sample, and the transmitted photons are recorded using an avalanche photodiode as detector. To form an image, the sample is scanned using a piezoelectric stage, and the transmitted X-ray intensity is recorded for each pixel in the image. The typical images we employed for the investigation of the spin-wave propagation in our samples were acquired with a point resolution between 50 nm and 100 nm.
Magnetic contrast in the images is achieved through the X-ray magnetic circular dichroism (XMCD) effect, by illuminating the sample with circularly polarized X-rays. As the XMCD effect probes the component of the magnetization parallel to the wave vector of the circularly polarized X-rays, the samples were mounted to achieve perpendicular orientation of the surface with respect to the X-ray beam, allowing us to probe the out-of-plane component of the magnetization in the SAF.

The time-resolved images were acquired in a pump-probe scheme, using an RF magnetic field, generated by injecting an RF current in a microstrip antenna as pumping signal and the X-ray flashes generated by the synchrotron light source as probing signal. The pumping signal was synchronized to the 500 MHz master clock of the synchrotron light source (i.e. to the X-ray flashes generated by the light source) through a field-programmable gate array (FPGA) setup. Due to the specific requirements of the FPGA-based pump-probe setup installed at the PolLux endstation, RF frequencies of \( f_{\text{exc}} = 500 \times \frac{M}{N} \text{ MHz} \), being \( N \) a prime number and \( M \) a positive integer, were accessible. For the measurements presented in this work, \( N \) was typically selected to be equal to 7, giving a phase resolution of about 50° in the time-resolved images. Depending on the RF frequency, the temporal resolution of the time-resolved images is given by \( \frac{2}{M} \text{ ns} \), with its lower limit given by the width of the X-ray pulses generated by the light source (i.e. about 70 ps FWHM).

For extracting the spatial map of the spin-wave amplitude from the STXM video, the time-trace of each pixel was fitted with a sinusoidal function, whose amplitude was extracted.

**Magnetic Force Microscopy**

Magnetic force microscopy of the patterned magnetic spin-textures was performed via a Bruker Multimode 8 scanning probe characterization system, equipped with a Nanosensors PPP-MFMR AFM magnetic probe. MFM imaging was performed in tapping lift-mode.

**Micromagnetic Simulations**

Micromagnetic simulations of the magnetization dynamics were carried out by solving the Landau–Lifshitz–Gilbert equation of motion, using the open-source, GPU-accelerated software MuMax³. The simulated material parameters were set to the following values: saturation magnetization \( M_s=1000 \text{ kA}\cdot\text{m}^{-1} \), exchange constant \( A_{\text{ex}}=1.2\cdot10^{-11} \text{ J}\cdot\text{m}^{-1} \), interlayer exchange coupling constants \( J=-0.6 \text{ mJ}\cdot\text{m}^{-2} \). The Gilbert damping parameter was set to \( \alpha = 0.001 \).

To compute the spin wave dispersion relation in the extended antiferromagnetically coupled bilayer, a stripe geometry with a length of 12.6 \( \mu \text{m} \) (along x), a width of 40 nm (along y) and a total thickness of 2×45 nm for the two CoFeB films was modeled. The total simulated volume was discretized into 2048×4×16 number of cells and periodic boundary conditions were applied in the x and y directions.
The exchange bias field was modeled applying in the uppermost layer of cells of the top CoFeB film an external magnetic field of 30 mT parallel to the magnetization of the CoFeB film itself. To simulate the spin wave dispersion for different configurations, the magnetization of the two CoFeB films was initialized to be pointing in opposite direction at remanence, following the relation $M_s(\cos \theta, -\sin \theta, 0) [M_s(\cos(\theta + \pi), -\sin(\theta + \pi), 0)]$ in the top (bottom) one, where $\theta$ is the angle between the $x$-axis and the magnetization of the top film. In order to excite spin-waves, a sinc-shaped field pulse $b(t) = b_0 \frac{\sin(2\pi f_0(t-t_0))}{2\pi f_0(t-t_0)}$, directed along the $z$-axis, with amplitude $b_0 = 10$ mT and frequency $f_0 = 30$ GHz, was applied in the center of the simulated area in a region having a size of 6 nm and 40 nm along the $x$ and $y$ directions, respectively. The dispersion relation was calculated by performing a Fourier-transform of the $z$-component of the magnetization both in space and time in the whole simulated area.

To simulate the spatial profile of the spin-wave modes emitted by the spin-textures, the total simulated volume was discretized into cells having dimensions of $10 \times 10 \times 11.25$ nm$^3$. Periodic boundary conditions in the $y$ direction were used. In order to stabilize the domain wall, the exchange bias field, modeled as an external magnetic field of 30 mT, was applied in opposite direction inside and outside the patterned area in the uppermost layer of cells of the top CoFeB film. First, the system was relaxed to the ground state for stabilizing the spin-texture and then the magnetization dynamics was excited applying a 0.1 mT time-varying sinusoidal magnetic field to the whole system. The Gilbert damping parameter was set to $\alpha = 0.008$.

**Supplementary Note 2. Magnetic characterization of exchange biased SAF samples**

Figure S1 (top panel) shows the hysteresis loop of the CoFeB 45 / Ru 0.6 / CoFeB 45 / IrMn 10 nm / Ru 2 nm synthetic antiferromagnet (SAF) measured at room temperature via vibrating sample magnetometry (VSM). The sample measurement was performed after initialization, i.e. after undergoing a field cooling in vacuum in a 400 mT magnetic field oriented in the $+x$ direction within the plane of the film. This process sets a uniform exchange bias direction in the system, which pins the magnetization of the top CoFeB layer (purple arrows) along $+x$.

The VSM loop shows the $x$-component of the magnetization, normalized to its maximum value, as a function of the external magnetic field applied along $x$ in the $-100$ mT $-$ $100$ mT range. Purple and orange arrows show the direction of the magnetization of the top layer and bottom layer, respectively. For strong, negative fields, the magnetization of both layers is saturated in the $-x$ direction. By decreasing the field, the RKKY-mediated coupling forces the canting of the magnetization towards antiparallel alignment. At the same time, the exchange bias in the top layer (which is set along $+x$), forces the orientation of the top layer magnetization along $+x$. The combination of these two
interactions makes sure that at remanence the magnetizations of the two layers are aligned antiferromagnetically, and that, importantly, the in-plane orientation of the magnetizations is determined by the direction of the exchange bias in the top layer. The robustness of the antiferromagnetic coupling is confirmed by the characteristic plateau observed at low fields. Finally, by applying strong external magnetic field in the $+x$ direction, the antiferromagnetic coupling is overcome, and the magnetization of both layers saturate along $+x$.

The bottom panel shows the simulated hysteresis loop of the SAF system, which is in excellent agreement with the experimental one.

Figure S1. **Experimental and simulated magnetic hysteresis loops of SAF.** The top panel shows the normalized $x$-component of the magnetization of the SAF samples used in the experiments, measured via Vibrating Sample Magnetometry. Purple and orange arrows shows the direction of the magnetizations in the top and bottom layer, respectively. The bottom panel shows the corresponding micromagnetic simulation.
Supplementary Note 3: Spin-configuration of patterned domain walls in SAF

Figure S2 shows static micromagnetic simulations of the spin-configuration of domain walls in SAF. The direction of the magnetization in the two layers is kept antiparallel point-by-point by the RKKY interaction, both in the domains and within the domain wall. The right panel shows the direction of the magnetization in the top (purple rectangle) and bottom (orange rectangle) CoFeB layer. The color-code is referred to the out-of-plane component of the magnetization ($M_z$), where positive (negative) $M_z$ is marked by red (blue) color. An increase in the color contrast approaching the central part of the DW is observed, and the change from red to blue contrast across the domain wall. This is consistent with a partial canting of the magnetization out-of-plane in correspondence of the domain wall, which is towards the positive (negative) $z$ direction in the left (right) part of the wall. The direction of the out-of-plane canting is determined by the chirality of the wall, i.e. by the direction of the spins at the center of the domain wall. The bottom panel shows the section of the domain wall ($xz$ plane), in which the orientation of the magnetization in both layers is visible, together with the color-coded $M_z$. Black arrows indicate the direction of the magnetization in the top (purple) and bottom (orange) layer.

Figure S2. Spin-configuration of domain walls in SAF. The left panel shows the sketch of the spin-texture of the domain wall patterned in the exchange biased synthetic antiferromagnet (SAF). The
right panel shows the spin-configuration in the top (purple) and bottom (orange) CoFeB layers, respectively. The bottom panel shows the section of the sample, where the top and bottom layers are highlighted by purple and orange rectangles. The black arrows mark the direction of the magnetization, while the color code marks the out-of-plane component of the magnetization ($M_z$), where red (blue) indicates $+z$($-z$). Scale bars: 200 nm.

**Supplementary Note 4. Generation of linear and radial wavefronts**

Figure S3 shows the generation of planar (panel A) and radial (panel B) spin-wave wavefronts by straight domain walls and vortex-Bloch lines, respectively. In particular, panel A shows the STXM image of spin-waves excited by a straight domain wall, propagating away from the wall (see also Supplementary Movie 3). The black/white color corresponds to the oscillation of the out-of-plane component of the magnetization $M_z$ associated to the propagation of spin-waves, with respect to the average value across one cycle of excitation. The oscillation of the domain wall is driven by an external magnetic field $H_{RF}$, provided by a stripline run by radiofrequency current, patterned on top of the multilayer and in close proximity to the wall (see Methods). The magenta line indicates the domain wall and the white arrow indicates the direction of the magnetization in the top layer. The inset shows the spatial Fourier transform of the image. The high localization of the bright dots associated with the propagating mode demonstrates the highly directional emission from the wall.

Panel B shows the excitation and propagation of spin-waves with radial symmetry, emitted from a vortex Bloch line located within a domain wall (see also Supplementary Movie 4). The radial symmetry of the spin-wave wavefronts is confirmed by the characteristic bright ring in the Fourier image in the inset. The brighter dots on the ring are related to the excitation of linear wavefronts from the domain wall. Noteworthy, the ring features a remarkably low ellipticity, which is the signature of the fact that the spin-wave wavelength is weakly dependent on the propagation direction (see detailed discussion in the main text).
Figure S3. Generation of linear and radial wavefronts. A. Linear wavefronts generated by a straight wall. B. Radial wavefronts generated by a vortex Bloch line.

Supplementary Note 5. Additional micromagnetic simulations of spin-wave modes in SAF
The extended antiferromagnetically coupled bilayer can support both acoustic and optic SW modes\(^2\), depending on whether the magnetization of the two CoFeB films precess in-phase or out-of-phase, respectively. Figure S4 shows the dispersion relation calculated at remanence for the configuration where the angle between \(k\) and the magnetization of the top CoFeB film is 90°. Micromagnetic simulations have been performed using the same parameters and the procedure described in the Methods. To put in evidence the presence of both the acoustic and optic modes, the magnetization dynamics has been excited using a sinc-shaped field pulse resulting from the superposition of a uniform spatial profile and one with a nodal plane through the film thickness. As it can be seen both the acoustic and the optic mode are present and are characterized by a non-reciprocal propagation.
Figure S4. Dispersion relation for spin waves in an extended bilayer system with antiparallel alignment of the CoFeB films. Spin wave dispersion relation for acoustic (red line) and optic (blue line) modes. Filled black points represent the experimental dispersion.

Moreover, we performed additional simulations to calculate the modes spatial profiles at $k=0$. Micromagnetic simulations have been carried out using a simulated area having width 40 nm, length 40 nm, thickness $2 \times 45$ nm, and divided in $4 \times 4 \times 64$ number of cells. Periodic boundary condition was applied both in $x$ and $y$ direction. The exchange bias field was modeled applying in the uppermost layer of cells of the top CoFeB film an external magnetic field of 30 mT parallel to the magnetization of the CoFeB film itself. The magnetization of the two CoFeB films was initialized to be pointing in opposite direction at remanence. The magnetization dynamics was excited applying in the entire area an external field sinc-pulse, $b(t) = b_0 \frac{\sin(2\pi f_0(t-t_0))}{2\pi f_0(t-t_0)}$ oriented along the $z$-axis with an amplitude of $h_0 = 10$ mT and a frequency of $f_0 = 30$ GHz.

Figure S5 reports the calculated amplitude (left panels) and the phase (right panel) of the $M_z$ component of the dynamic magnetization of the mode excited using a pulse with (a) a uniform spatial profile and (b) a pulse with a nodal plane through the film thickness. As it can be seen, depending on the pulse spatial profile, a mode characterized by an in-phase (out-of-phase) precession in the top and bottom CoFeB layers, is excited at about 1.5 (5.4) GHz. These results confirm the acoustic and optic character of the modes observed in the relation dispersion at lower and higher frequencies, respectively.
Figure S5. Mode spatial profiles. Amplitude (left panels) and phase (right panels) of the $M_z$ component of the dynamic magnetization of (A) the acoustic and (B) the optic modes calculated for $k=0$, using a pulse with a uniform spatial profile and a pulse with a nodal plane through the film thickness, respectively.

Note that in our experiment only the acoustic mode has been observed, for the following reasons. First, the frequency of the optic mode is out of the frequency range experimentally investigated. Second, the total $M_z$ over the whole film is zero in the case of optic modes, therefore it would not be possible to observe it in our experimental STXM configuration.

As discussed in the main text, the acoustic mode is characterized by a strong non-reciprocal propagation, and as a consequence a “short-wavelength” and a “long-wavelength” branches, propagating along negative and positive $k$, respectively, can be identified. Moreover, we found that the two branches of the acoustic mode are characterized by a different spatial localization, in agreement with the theoretical calculations of Grünberg\textsuperscript{3}. Figure S6 shows the simulated dispersion relation of the acoustic mode, calculated at remanence for the configuration where the angle between $k$ and the magnetization of the top CoFeB film is 90°, probing the dynamic component of the magnetization perpendicular to the film surface ($M_z$) in different regions of the sample.

Micromagnetic simulations have been performed using the same parameters and the procedure described in the Methods. The dispersions reported in panels (a) and (b) have been obtained recording $M_z$ only in the uppermost layer of cells of the top CoFeB film, and in the lowermost layer of cells of the bottom CoFeB film, respectively. The dispersion showed in panel (c) has been achieved recording $M_z$ only in the layer of cells at the interface between the two CoFeB films. One can see that the short-wavelength mode, propagating for positive $k$, has the maximum spin wave amplitude in the region at the interface between the two CoFeB films. On the contrary, the oscillation amplitude of the long-
wavelength mode, propagating for negative k, is mainly concentrated at the top and bottom surfaces of the system.

Figure S6. Dispersion relation for the acoustic mode in an extended bilayer system with antiparallel alignment of the CoFeB films. Spin wave dispersion relation for the acoustic mode. In panels (a) and (b) the dispersion is related to the modes in the uppermost layer of cells of the top CoFeB film, and in the lowermost layer of cells of the bottom CoFeB film, respectively. In panel (c) the dispersion refers to the modes in the layer of cells at the interface between the two CoFeB films.

Supplementary Note 6. Scanning transmission X-ray microscopy movies
The temporal evolution of the spin-wave emission and propagation can be better appreciated in the time-resolved STXM movies. Each frame of the movies is a time-resolved image acquired stroboscopically via STXM and shows the normalized $M_z$ contrast calculated as the magnetic deviation $\Delta M_z(t)$ from the time-averaged $<M_z(t)>$ state. The excitation of the spin-waves was applied through a sinusoidal function with frequency $f$. The time resolution of each movie was $\Delta t = 1/(7f)$, as reported in the Methods. The complete sequence corresponds to a period of sinusoidal excitation of the microstrip.
| File name                | Functionality         | Freq.      | Notes            | Size (nm²)    |
|-------------------------|-----------------------|------------|------------------|---------------|
| Supplementary Movie 1   | Convex Wavefronts     | 1.57 GHz   | See Fig. 2a      | 3800x5000     |
| Supplementary Movie 2   | Spin-wave Focusing    | 1.43 GHz   | See Fig. 2e      | 4200x4600     |
| Supplementary Movie 3   | Linear Wavefronts     | 1.43 GHz   | See Fig. S3a     | 2650x2250     |
| Supplementary Movie 4   | Radial Wavefronts     | 1.57 GHz   | See Fig. S3b     | 2700x2700     |
| Supplementary Movie 5   | Interference 1        | 1.29 GHz   | See Fig. 4a      | 4500x3600     |
| Supplementary Movie 6   | Interference 2        | 1.57 GHz   | See Fig. 4e      | 3950x3900     |

References

1. Raabe, J. et al. PolLux: A new facility for soft x-ray spectromicroscopy at the swiss light source. *Rev. Sci. Instrum.* **79**, 1–10 (2008).
2. Grünberg, P. A. Nobel lecture: From spin waves to giant magnetoresistance and beyond: The 2007 Nobel Prize for Physics was shared by Albert Fert and Peter Grünberg. This paper is the text of the address given in conjunction with the award. *Rev. Mod. Phys.* **80**, 1531–1540 (2008).
3. Grünberg, P. Magnetostatic spin-wave modes of a heterogeneous ferromagnetic double layer. *J. Appl. Phys.* **52**, 6824–6829 (1981).