Long-distance propagation of high-velocity antiferromagnetic spin waves

Hanchen Wang,1,2,3 Rundong Yuan,1,∗ Yongjian Zhou,4† Yuelin Zhang,1 Jilei Chen,5,2 Song Liu,2,5 Hao Jia,2,5 Dapeng Yu,2,5 Jean-Philippe Ansermet,6,5 Cheng Song,4 † and Haiming Yu1,2,†

1Fert Beijing Institute, MIIT Key Laboratory of Spintronics, School of Integrated Circuit Science and Engineering, Beihang University, Beijing 100191, China
2International Quantum Academy, Shenzhen 518048, China
3Department of Materials, ETH Zurich, Zurich 8093, Switzerland
4Key Laboratory of Advanced Materials (MOE), School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China
5Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
6Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015, Lausanne, Switzerland
(Dated: November 22, 2022)

We report on coherent propagation of antiferromagnetic (AFM) spin waves over a long distance (∼10 µm) at room temperature in a canted AFM α-Fe2O3 with the Dzyaloshinskii-Moriya interaction (DMI). Unprecedented high group velocities (up to 22.5 km/s) are characterized by microwave transmission using all-electrical spin wave spectroscopy. We derive analytically AFM spin-wave dispersion in the presence of the DMI which accounts for our experimental results. The AFM spin waves excited by nanometric coplanar waveguides with large wavevectors enter the exchange regime and follow a quasi-linear dispersion relation. Fitting of experimental data with our theoretical model yields an AFM exchange stiffness length of 1.7 Å. Our results provide key insights on AFM spin dynamics and demonstrate high-speed functionality for AFM magnonics.

Spin waves or magnons1–4 as collective spin excitations can transport coherent spin information in a magnetic media over long distances5–7 without suffering from Ohmic loss, and are therefore promising for magnon-based computing with low-power consumption8,9. So far, an overwhelming majority of magnonic research are conducted in ferro-(ferri-)magnetic material systems, such as yttrium iron garnet (YIG)10–14, permalloy15–18 and magnetic multilayers19–21. In ferromagnetic (FM) materials, long wavelength spin waves are predominantly affected by dipolar interactions, resulting in Damon-Eshbach (DE) and Backward-volume (BV) modes with distinct configurations of the magnetization (m) and wavevector (k) and non-degenerate dispersions [Fig. 1(a)]. This anisotropy hinders spin waves from propagating through a curved circuit22 and leads to vulnerability to external field disturbances. Thus, it is desirable to excite high-k exchange spin waves in ferromagnets with short wavelengths that are substantially less anisotropic. Exchange spin waves in ferromagnets23 follows a parabolic dispersion relation suggesting an increasing group velocity for higher k. It is extremely challenging to excite exchange spin waves with a record high velocity around 1 km/s and a wavelength below 100 nm24,25.

In antiferromagnetic (AFM) materials, these challenges and obstacles are inherently neutralized because spin waves are insensitive to disturbing magnetic fields26 and can propagate with higher velocities27. However, new challenges arise as antiferromagnets have zero net moment28. In addition, antiferromagnetic spin waves fall typically in the THz or sub-THz frequency regime29,30 and are so far mostly excited with an optical method27,31 that is difficult to integrate with on-chip magnonic devices. All-electrical excitation and detection of coherent AFM spin waves32 are highly desired for magnonics, but remain challenging. Recently, advanced microwave technology based on solid-state extenders enabled frequency multiplication of conventional GHz source into sub-THz generators for all-electrical AFM magnon excitation33–34. Until now, coherent AFM spin waves are electrically excited only with k = 0, i.e., antiferromagnetic resonance (AFMR)31,33,35 (e.g. black arrow in Fig. 1(b)), which has zero group velocity in a canted AFM36. High-velocity propagating AFM exchange spin waves with electrical excitation has not been realized so far.

In this Letter, we experimentally demonstrate coherent propagation of AFM exchange spin waves over a long distance (10 µm) in α-Fe2O3 with a high group velocity (22.5 km/s) at room temperature. The velocity is approximately one order of magnitude higher than that of FM exchange spin waves36,24,25. α-Fe2O3 also known as hematite is an insulating antiferromagnet37–39 with ultra-low magnetic damping (∼10−5)40 and high Néel temperature (∼960 K)41. At room temperature (above its Morin temperature TM ∼ 260 K), α-Fe2O3 is in an easy-plane antiferromagnetic phase, where its Néel vector n lies in the plane [Fig. 1(b)] normal to the corundum crystal c axis42. The bulk Dzyaloshinskii-Moriya interaction (DMI) in α-Fe2O3 induces a small canted moment43 as shown in the inset of Fig. 1(b). The weak canted moment (∼1.2 emu/cm3) existing in the easy plane is measured by vibrating sample magnetometer as shown in the Section I in
Supplementary Material (SM) [48]. Although the canted moment is negligibly weak as a net magnetic moment (~1% of YIG magnetic moment), it facilitates AFMR excitation with conventional microwave antennas [46, 47]. As the easy-plane anisotropy is remarkably small ($H_a \sim 0.06$ mT), the AFMR frequency drops to around 20 GHz, which is accessible using conventional microwave techniques. The negligible easy-plane anisotropy also allows the Néel $\mathbf{n}$ to rotate freely in plane with respect to the spin-wave wavevector $\mathbf{k}$, as illustrated in Fig. 1(c) for $\mathbf{k} \perp \mathbf{n}$ and $\mathbf{k} \parallel \mathbf{n}$ as examples. Unlike in ferromagnets where $\mathbf{k} \perp \mathbf{m}$ (DE) and $\mathbf{k} \parallel \mathbf{m}$ (BV) behave differently [Fig. 1(b)], spin waves in antiferromagnets are degenerate for $\mathbf{k} \perp \mathbf{n}$ and $\mathbf{k} \parallel \mathbf{n}$ [Fig. 1(c)] and any intermediate angle because the AFM spin-wave dispersion is not affected by dipolar interaction but fully determined by exchange interaction. Recently, Boventer et al. [47] have theoretically derived the AFMR ($k = 0$) formula for α-Fe$_2$O$_3$. However, literature on the spin-wave dispersion for an easy-plane antiferromagnet with DMI remains elusive.

Let us first derive and discuss the spin-wave dispersion for an antiferromagnet with DMI-induced canting and easy-plane anisotropy like that of α-Fe$_2$O$_3$ [Fig. 1(b)]. We consider a one-dimensional spin chain with two sublattices $\mathbf{m}_1$ and $\mathbf{m}_2$ that are antiferromagnetically coupled and confined in the easy plane. In the AFM system, the exchange energy, Zeeman energy, anisotropy energy and Dzyaloshinskii-Moriya (DM) energy constitute the total free energy, from which we obtain the equations of motion describing the dynamics of two spin sublattices in a mean-field approximation (see Sec. II in SM [48]),

\[
\begin{align*}
\frac{d\mathbf{m}_1}{dt} &= -\gamma \mu_0 \mathbf{m}_1 \times \left[ H_0 - H_{ex} \mathbf{m}_2 - \frac{1}{2} H_{ex} a_{ex}^2 \nabla^2 \mathbf{m}_2 - H_A (\mathbf{m}_1 \cdot \hat{z}) \hat{z} - H_a (\mathbf{m}_1 \cdot \hat{y}) \hat{y} + H_{DM} (\mathbf{m}_2 \times \hat{z}) \right], \\
\frac{d\mathbf{m}_2}{dt} &= -\gamma \mu_0 \mathbf{m}_2 \times \left[ H_0 - H_{ex} \mathbf{m}_1 - \frac{1}{2} H_{ex} a_{ex}^2 \nabla^2 \mathbf{m}_1 - H_A (\mathbf{m}_1 \cdot \hat{z}) \hat{z} - H_a (\mathbf{m}_2 \cdot \hat{y}) \hat{y} - H_{DM} (\mathbf{m}_1 \times \hat{z}) \right].
\end{align*}
\]  

where $H_0$ is the external magnetic field, $H_{ex}$ is the strength of the exchange field, $a_{ex}$ is the exchange stiffness length (see Sec. II in SM [48]), $H_A$ ($H_a$) is the out-of-plane (in-plane) anisotropy and $H_{DM}$ is the DM effective field. The exchange stiffness term consisting of the $H_{ex}$ and $a_{ex}$ is discussed in the SM Table I [48] with a comparison between ferromagnetic (ferri-)magnetic [51] and antiferromagnetic models [52]. Coordinate axes are defined in the inset of Fig. 1(b). Considering a small canting angle $\theta$ induced by the DMI, the cartesian coordinate defined with $\mathbf{n}$ and $\mathbf{m}$ is subsequently transformed to align with $\mathbf{m}_1$ or $\mathbf{m}_2$ in order to deduce the dynamics of the sublattices. By extracting the eigenfrequencies of Eq. (1) one derives the dispersion relations for both acoustic (low-frequency) and optical (high-frequency) AFM magnon modes (see Sec. II in SM [48]). Since only the low-frequency one is relevant for our experiments, we present its spin-wave dispersion here as

\[
f = \frac{\gamma \mu_0}{2\pi} \sqrt{H_0 (H_0 + H_{DM}) + 2H_a H_{ex} + H_{ex}^2 a_{ex}^2 k^2},
\]

where $\gamma$ is the gyromagnetic ratio and $\mu_0$ is the vacuum permeability. If on the one dd we take $k = 0$, the last term underneath the square root vanishes and thereby it reduces to the uniform AFMR of a canted antiferromagnet as studied by Boventer et al. [47]. On
FIG. 2. (a) A global scanning electron microscopic (SEM) image of two coplanar waveguide (CPW) antennas integrated on \(\alpha\text{-Fe}_2\text{O}_3\) with a ground-signal-ground (GSG) design. The pitch of the contact pad is 250 \(\mu\text{m}\), compatible with microwave probes. The gray background represents \(\alpha\text{-Fe}_2\text{O}_3\) substrate. (b) SEM image within the black dashed square area in (a). (c) SEM-resolved image of a CPW. The center-to-center distance \(s\) between CPW1 and CPW2 for this device is 8 \(\mu\text{m}\). The blue arrow indicate the spin-wave wavevector \(k\). The yellow-rendered parts are the gold conducting lines whose width \(w\) = 200 \(\text{nm}\) is characterized by the further close-up image in (d). (e)-(g) Spin-wave transmission spectra \(S_{12}\) measured by a vector network analyzer (imaginary parameter) and plotted as a function of applied magnetic field for three devices with different propagation distances \(s\) = 5, 8, 10 \(\mu\text{m}\). (h) Lineplots extracted at 45 mT for propagation distances \(s\). Spectra are shifted for clarity. Orange arrows highlight the peak positions.

In the following, we present experimental demonstration of high-velocity propagation of spin waves in \(\alpha\text{-Fe}_2\text{O}_3\) crystal with e-beam lithography and connected to a vector network analyzer (VNA) to excite and detect spin waves. Transmission spectra \(S_{21}\) (excitation at CPW1 and detection at CPW2) are measured by the VNA as a function of magnetic field, sweeping from negative to positive values and shown in Figs. 2(e-g) for different propagation distances \(s\) of 5 \(\mu\text{m}\), 8 \(\mu\text{m}\) and 10 \(\mu\text{m}\). Single spectra extracted at 45 mT are plotted together for three different propagation distances in Fig. 2(h). The transmission signal amplitude decays due to spin-wave damping. With increasing \(s\), the observed signal oscillation becomes denser and the number of peaks (marked by orange arrows) increases, for the following reason. The VNA is sensitive to the phase delay between both antennas and the interval between two neighboring peaks corresponds to a phase difference \(\Delta\phi = 2\pi\). Over a certain propagation distance \(s\), the phase change is given by \(\Delta\phi = \Delta k \cdot s\), where \(\Delta k\) represents a broad wavevector excitation generated by the nanoscale CPW antennas, as shown in Fig. 3(a) and (b). When \(\Delta\phi = \Delta k \cdot s\) reaches \(2\pi\), the second peak appears and the corresponding frequency interval \(\Delta f\) is observed [Fig. 3(d)]. Therefore, the spin-wave group
The frequency intervals $\Delta f$ project into different frequency spans $\Delta f_1$, $\Delta f_2$ and $\Delta f_3$ in accordance with the dispersion. The frequency spans manifest themselves as peak-to-peak separation in the measured transmission spectrum $S_{21}$ in (d). These frequency spans correspond to a phase change of $2\pi$ after propagation over a certain distance $s$. The orange dashed curve in (d) defines effective excitation envelope corresponding to the wavevector distribution of CPW in (a). Horizontal and vertical black dashed lines are guide for the eyes.

The slope of the fitted red line yields a group velocity of about 14.2 km/s. Following this method, we extract group velocities at different frequency bands and plot them in Fig. 4 as the red open squares. The data acquisition from linear fittings of $\Delta f$ versus $1/s$ for frequencies of 15.9 GHz, 18.8 GHz and 20.7 GHz are presented in the Sec. IV and V in SM [48]. Two additional devices with slightly modified CPWs (Type 2 and Type 3) were also measured (see Sec. IV and V in SM [48]) and group velocities obtained from these two samples are plotted as the orange circle and blue open triangle in Fig. 4. From the distance-dependent measurements, we extract a decay length of about 10 $\mu m$ for coherent AFM spin waves (see Sec. VI in SM [48]).

![Diagram](image)
10 pJ/m and a saturated velocity of 30.2 km/s (see Sec. II in SM [18]). To approach the saturated velocity, we fabricate even smaller CPW antennas with larger wavevector $k$ ($\sim5.2$ rad/$\mu$m, see Sec. VII in SM [18]). However, we do not observe clear signal oscillations in transmission spectra, which we attribute to the impedance mismatch as further down-scaling the microwave antennas [53][56]. For micrometer-scale CPW antennas with small wavevectors ($\sim1.0$ rad/$\mu$m, see Sec. VII in SM [18]), we again do not observe oscillating transmission signals owing to a low group velocity at the low-$k$ limit.

In summary, we experimentally observed the coherent propagating AFM spin waves at room temperature in a single-crystal $\alpha$-Fe$_2$O$_3$ film. Over a long distance of 10 $\mu$m, the coherence of AFM spin waves can still be detected with a high group velocity of up to 22.5 km/s. With measurements using CPW antennas of different propagation distances, the AFM spin-wave dispersion could be indirectly characterized via the relationship between group velocities and frequencies. These data could be accounted for with a theoretical model that takes into account exchange, DM, Zeeman and anisotropy energy. The AFM exchange stiffness length is estimated to be about 1.7 Å. Additional measurements under different configurations between the canted moments and wavevector directions present almost the same frequencies and group velocities, verifying the degenerate AFM spin-wave dispersion shown in Fig. 1 (see Sec. VIII in SM [48]). High-velocity coherent propagating AFM spin waves is suggestive of great prospects for coherent AFM magnonics.

The authors thank M. Elyasi, P. Gambardella, K. Yamamoto, and S. Maekawa for their helpful discussions. We wish to acknowledge the support by the National Key Research and Development Program of China Grants No. 2022YFA1402801, NSF China under Grant Nos. 2022YFA1402801, 12074026, 52225106, and U1801661, China Scholarship Council (CSC) under Grant No. 202206020091, and Shenzhen Institute for Quantum Science and Engineering, Southern University of Science and Technology (Grant No. SIQSE202007).

---

* These authors contributed equally to this work.
1 jean-philippe.ansermet@epfl.ch
2 songcheng@mail.tsinghua.edu.cn
3 haiming.yu@buaa.edu.cn

[1] V. Kruglyak, S. Demokritov, and D. Grundler, Magnonic Solitons. J. Phys. D Appl. Phys. 43, 264001 (2010).
[2] A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, Magnon spintronics. Nat. Phys. 11, 453-461 (2015).
[3] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, Advances in coherent magnonics. 6, 1114-1135 (2021).
[4] A. Barman et al., The 2021 magnonics roadmap. J. Phys. Condens. Matter 33, 413001 (2021).
[5] L. J. Cornelissen, J. Liu, R. A. Duine, J. B. Youssef, and B. J. van Wees, Long-distance transport of magnon spin information in a magnetic insulator at room temperature. Nat. Phys. 11, 1022-1026 (2015).
[6] C. Liu, J. Chen, T. Liu, F. Heimbach, H. Yu, Y. Xiao, J. Hu, M. Liu, H. Chang, T. Stueckler et al., Long-distance propagation of short-wavelength spin waves. Nat. Commun. 9, 1–8 (2018).
[7] R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, L. Baldrati, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide. Nature 561, 222-225 (2018).
[8] G. Csaba, A. Papp, and W. Porod, Perspectives of using spin waves for computing and signal processing. Phys. Lett. A 11, 948-953 (2016).
[9] A. V. Chumak et al., Advances in magnetics roadmap on spin-wave computing. IEEE Trans. Magn. 58, 1–72 (2022). IEEE Trans. Magn. 58, 0800172 (2022).
[10] A. Serga, A. Chumak, B. Hillebrands, YIG Magnonicics. J. Phys. D Appl. Phys. 43, 264002 (2010).
[11] H. Chang, P. Li, W. Zhang, T. Liu, A. Hoffmann, L. Deng, and M. Wu, Nanometer-thick yttrium iron garnet films with extremely low damping. IEEE Magn. Lett. 5, 6700 (2014).
[12] H. Qin, G. J. Both, S. J. Hämäläinen, L. van Dijken, Low-loss YIG-based magnonic crystals with large tunable bandgaps. Nat. Commun. 9, 5445 (2018).
[13] Q. Wang et al., Spin pinning and spin-wave dispersion in nanoscopic ferromagnetic waveguides. Phys. Rev. Lett. 122, 247202 (2019).
[14] H. Yu, O. Allivy Kelly, V. Cros, R. Bernard, P. Bortolotti, A. Anane, F. Brandl, R. Huber, I. Stasinopoulos, and D. Grundler, Magnetic thin-film insulator with ultra-low spin wave damping for coherent nanomagnonics. Sci. Rep. 4, 6848 (2014).
[15] V. Vlaminck, and M. Bailleul, Current-induced spin-wave Doppler shift. Science 322, 410 (2008).
[16] S. Neusser, G. Duerr, H. G. Bauer, S. Tiacchi, M. Madami, G. Woltersdorf, G. Gubbiotti, C. H. Back, and D. Grundler, Anisotropic propagation and damping of spin waves in a nanopatterned antidot lattice. Phys. Rev. Lett. 105, 067208 (2010).
[17] A. Haldar, D. Kumar, and A. O. Adeyeye, A reconfigurable waveguide for energy-efficient transmission and local manipulation of information in a nanomagnetic device. Nat. Nanotechnol. 11, 437-443 (2016).
[18] K. Wagner, A. Kádkay, K. Schultheiss, A. Henschke, T. Sebastian, and H. Schultheiss, Magnetic domain walls as reconfigurable spin-wave nanochannels, Nat. Nanotechnol. 11, 432-436 (2016).
[19] J. Han, P. Zhang, J. T. Hou, S. A. Siddiqui, and L. Liu, Mutual control of coherent spin waves and magnetic domain walls in a magnonic device. Science 366, 1121-1125 (2019).
[20] M. Ishibashi, Y. Shiota, T. Li, S. Funada, T. Moriyama, and T. Oto, Switchable giant nonreciprocal frequency shift of propagating spin waves in synthetic antiferromagnets. Sci. Adv. 6, eaaz6931 (2020).
[21] Y. Liu, Z. Xu, L. Liu, K. Zhang, Y. Meng, Y. Sun, P. Gao, H.-W. Zhao, Q. Niu, and J. Li, Switching magnon chirality in artificial ferrimagnet. Nat. Commun. 13, 1264 (2022).
[22] K. Vogt, H. Schulheiss, S. Jain, J. E. Pearson, A. Hoffmann, S. D. Bader, and B. Hillebrands, Spin waves turning a corner. Appl. Phys. Lett. 101, 042410 (2012).
[23] B. Kalinikos, and A. Slavin, Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions. J. Phys. C Solid State Phys. 19, 7013 (1986).
[24] V. Sluka et al., Emission and propagation of 1D and 2D spin waves with nanoscale wavelengths in anisotropic spin textures. Nat. Nanotechnol. 14, 328-333 (2019).
[25] P. Che, K. Baumgaertl, A. Kikutová, C. Dubs, and D. Grundler, Efficient wavelength conversion of exchange magnons below 100 nm by magnetic coplanar waveguides. Nat. Commun. 11, 1445 (2020).
[26] V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, and Y. Tserkovnyak, Antiferromagnetic spintronics. Rev. Mod. Phys. 90, 015005 (2018).
[27] J. R. Hortensius, D. Afanasiev, M. Matthiesen, R. V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, S. Rezende, A. Azevedo, and R. L. Rodríguez-Suárez, et al., P. J. Besser, A. H. Morrish, and C. W. Searle, Magnetic spin textures. Nat. Nanotechnol. 17, 590 (2022).
[28] R. Lebrun, A. Ross, O. Gomonay, V. Baltz, U. Ebels, A.-L. Barra, A. Quinzadeh, A. Brataas, J. Brataas, and M. Kläui, Long-distance spin-transport across the Morin phase transition up to room temperature in ultralow damping single crystals of the antiferromagnet α-Fe₂O₃. Nat. Phys. 17, 1001-1006 (2021).
[29] T. Jungwirth, X. Marti, P. Waldey, and J. Wunderlich, Antiferromagnetic spintronics. Nat. Nanotechnol. 11, 231-241 (2016).
[30] O. Gomonay, V. Baltz, A. Brataas, and Y. Tserkovnyak, Antiferromagnetic spin textures and dynamics. Nat. Phys. 14, 213-216 (2018).
[31] H. Qiu et al., Manipulating Thz spin current dynamics by the Dzyaloshinskii-Moriya interaction in antiferromagnetic hematite. arXiv:2209.10175.
[32] T. Kampfrath, A. Sell, G. Klatt, A. Pashkin, S. Mährlein, T. Dekorsy, M. Wolf, M. Fiebig, A. Leitenstorfer, and R. Huber, Coherent terahertz control of antiferromagnetic spin waves. Nat. Photon. 5, 31-34 (2011).
[33] M. Dąbrowski, T. Nakano, D. M. Burn, A. Frisk, D. G. Newman, C. Klewe, Q. Li, M. Yang, P. Shafer, E. Arenholz, T. Hesjedal, G. van der Laan, Z. Q. Qiu, and R. J. Hicken, Coherent transfer of spin angular momentum by evanescent spin waves within antiferromagnetic NiO. Phys. Rev. Lett. 124, 217201 (2020).
[34] C. Caspers, V. P. Gandhi, A. Magrez, E. de Rijk, and J.-Ph. Ansermet, Sub-terahertz spectroscopy of magnetic resonance in BiFeO₃ using a vector network analyzer. Appl. Phys. Lett. 108, 241109 (2016).
[35] J. Li et al., Spin current from sub-terahertz-generated antiferromagnetic magnons. Nature 578, 70-74 (2020).
[36] I. Boventer, H. Simensen, B. Brekke, M. Weides, A. Anane, M. Kläui, A. Brataas, and R. Lebrun, Antiferromagnetic cavity magnon polaritons in collinear and canted phases of hematite. arXiv:2203.10924.
[37] S. Rezende, A. Azevedo, and R. L. Rodríguez-Suárez, Introduction to antiferromagnetic magnons. J. Appl. Phys. 126, 151101 (2019).
[38] F. J. Morin, Electrical properties of α-Fe₂O₃ containing titanium. Phys. Rev. 83, 1005 (1951).
[39] H. Jani, J.-C. Lin, J. Chen, J. Harrison, F. Maccherozzi, J. Schad, S. Prakash, C.-B. Eom, A. Ariando, T. Venkatesan, and P. G. Radaelli, Antiferromagnetic half-skyrmions and bimerons at room temperature. Nature 590, 74-79 (2021).
[40] F. P. Chmiel et al., Observation of magnetic vortex pairs at room temperature in a planar α-Fe₂O₃/Co heterostructure. Nat. Mater. 17, 581-585 (2018).
[41] A. Wittmann et al., Role of substrate clamping on anisotropy and domain structure in the canted antiferromagnet α-Fe₂O₃. arXiv:2210.16411.
[42] F. J. dos Santos, M. dos Santos Dias, and S. Lounis, Modeling spin waves in noncollinear antiferromagnets: Spin-flop states, spin spirals, skyrmions, and antiskyrmions. Phys. Rev. B 102, 104436 (2020).
[43] P. X. Zhang, C.-T. Chou, H. Yun, B. C. McGoldrick, J. T. Hou, K. A. Mkhowan, L. Liu, Control of Néel vector with spin-orbit torques in an antiferromagnetic insulator with tilted easy plane. Phys. Rev. Lett. 129, 017203 (2022).
[44] R. Lebrun, A. Ross, O. Gomonay, V. Baltz, U. Ebels, A.-L. Barra, A. Quiñzadeh, A. Brataas, J. Brataas, and M. Kläui, Long-distance spin-transport across the Morin phase transition up to room temperature in ultralow damping single crystals of the antiferromagnet α-Fe₂O₃. Nat. Commun. 11, 6332 (2020).
[45] M. Białek, J. Zhang, H. Yu, and J.-Ph. Ansermet, Antiferromagnetic resonance in α-Fe₂O₃ up to its Néel temperature. Appl. Phys. Lett. 121, 032401 (2022).
[46] H. Wang, Y. Xiao, M. Guo, E. Lee-Wong, G. Q. Yan, R. Cheng, and C. R. Du, Spin pumping of an easy-plane antiferromagnet enhanced by Dzyaloshinskii-Moriya interaction. Phys. Rev. Lett. 127, 117202 (2021).
[47] I. Boventer, H. T. Simensen, A. Anane, M. Kläui, A. Brataas, and R. Lebrun, Room-temperature antiferromagnetic resonance and inverse spin-Hall voltage in canted antiferromagnets. Phys. Rev. Lett. 126, 187201 (2021).
[48] See Supplementary Material for magnetic hysteresis loop of α-Fe₂O₃ spin-chain model for easy-plane antiferromagnetic spin waves with Dzyaloshinskii-Moriya interaction, magnetic parameters extracted from the field-dependent reflection spectra, different types of CPW antennas and their AFM spin-wave transmission spectra, group velocities extracted from experimental results, decay length estimated by experimental results, spin-wave transmission spectra measured on the CPW antennas with higher and lower wavevectors, propagating AFM spin-wave transmission measurements at different angles between wavevector k and Néel vector n, which includes Refs. [49, 50].
[49] J.-Ph. Ansermet, and S. D. Brechet, Principles of thermodynamics. (Cambridge University Press, 2019).
[50] R. M. Cornell, and U. Schwertmann, The Iron Oxides: Structure, Properties, Reactions, Occurrences, and Uses. (Wiley-vch Weinheim, 2003), Chap. 2.
[51] E. H. Turner, Interaction of phonons and spin waves in yttrium iron garnet. Phys. Rev. Lett. 5, 100 (1960).
[52] S. M. Rezende, R. L. Rodríguez-Suárez, and A. Azevedo, Diffusive magnonic spin transport in antiferromagnetic insulators. Phys. Rev. B 93, 054412 (2016).
[53] A. Scholl, M. Liberati, E. Arenholz, H. Ohldag, and J. Stöhr, Creation of an antiferromagnetic exchange spring. Phys. Rev. Lett. 92, 247201 (2004).
[54] E. J. Samuelsen, and G. Shirane, Inelastic neutron scattering investigation of spin waves and magnetic interactions in α-Fe₂O₃. Phys. Stat. Sol. 42, 241-256 (1970).

[55] F. Ciubotaru, T. Devolder, M. Manfrini, C. Adelmann, and I. Radu, All electrical propagating spin wave spectroscopy with broadband wavevector capability. Appl. Phys. Lett. 109, 012403 (2016).

[56] J. Lucassen, C. F. Schippers, L. Rutten, R. A. Duine, H. J. Swagten, B. Koopmans, and R. Lavrijsen, Optimizing propagating spin wave spectroscopy. Appl. Phys. Lett. 115, 012403 (2019).