Coherent spin-wave transport in an antiferromagnet

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Magnonics is a research field complementary to spintronics, in which the quanta of spin waves (magnons) replace electrons as information carriers, promising lower dissipation. The development of ultrafast, nanoscale magnonic logic circuits calls for new tools and materials to generate coherent spin waves with frequencies as high and wavelengths as short as possible. Antiferromagnets can host spin waves at terahertz frequencies and are therefore seen as a future platform for the fastest and least dissipative transfer of information. However, the generation of short-wavelength coherent propagating magnons in antiferromagnets has so far remained elusive. Here we report the efficient emission and detection of a nanometre-scale wavepacket of coherent propagating magnons in the antiferromagnetic oxide dysprosium orthoferrite using ultrashort pulses of light. The subwavelength confinement of the laser field due to large absorption creates a strongly non-uniform spin excitation profile, enabling the propagation of a broadband continuum of coherent terahertz spin waves. The wavepacket contains magnons with a shortest detected wavelength of 125 nm that propagate into the material with supersonic velocities of more than 13 km s⁻¹. This source of coherent short-wavelength spin carriers opens up new prospects for terahertz antiferromagnetic magnonics and coherence-mediated logic devices at terahertz frequencies.

Antiferromagnetic (AFM) insulators are prime candidates to replace ferromagnets as active media in applications involving high-speed spin transport and large spectral bandwidth operation. Integration of AFMs in future wave-based technologies requires the realization of coherent (ballistic) transport of AFM spin waves over large distances. In this regard, non-uniform spin-wave modes with short wavelengths (λ ≤ 100 nm) are of particular importance: they can operate at terahertz (THz) clock rates, exhibit high propagation velocities and enable the miniaturization of devices down to the nanoscale. Phase-coherent ballistic spin transport in AFMs is also interesting from a fundamental point of view, as it is anticipated to be a prerequisite for the occurrence of exotic phenomena such as magnetic solitons, Bose–Einstein condensates and spin superfluidity. Such prospects motivate the search for efficient methods for the excitation, manipulation and detection of short-wavelength coherent AFM magnons.

Conventional methods of linear spin-wave excitation use spatially varying oscillating magnetic fields. However, the high frequency of THz resonances inherent to AFM dynamics make traditional field sources exploiting microstrip lines or coplanar waveguides impractical to be used in AFM media. As a result, recent demonstrations of magnon-mediated spin transport in antiferromagnets were limited to either diffusive propagation of incoherent magnons or evanescent spin-wave modes. The experimental generation of coherent propagating short-wavelength magnons, which enables phase-coherent high-speed spin transport in an antiferromagnet, has so far not been achieved.

Ultrafast pulses of light have been routinely used to generate and to control large-amplitude THz spin precession in antiferromagnets. The small photon momentum, however, poses a problem: it gives rise to a large momentum mismatch with short-wavelength spin waves. Consequently, optical techniques have so far been restricted to the generation of k=0 uniform AFM magnons and/or pairs of mutually coherent magnons at the edges of the Brillouin zone, for which group velocities are (near) zero and no spatial transport of energy and angular momentum takes place. Here we overcome this problem and present an all-optical method to excite and detect a broadband wavepacket of short-wavelength coherent propagating magnons in an insulating antiferromagnet. Optical excitation of intense charge-transfer (CT) electronic transitions in the prototypical antiferromagnet dysprosium orthoferrite (DyFeO₃) with ultrashort pulses of light provides strong confinement of the light field, which creates a narrow exponential profile of deflected spins near the sample surface. This nanoscale magnetic non-uniformity serves as a source of short-wavelength coherent spin waves propagating into the sample bulk, as illustrated in Fig. 1a. Using k-selective magneto-optical Bragg detection, we map out spectral components of the magnon wavepacket and reveal magnon modes with nanoscale wavelengths, supersonic group velocities and an estimated propagation length of more than 1 μm.

DyFeO₃ is a CT AFM with Néel temperature Tᵥ = 645 K, exhibiting one of the strongest observed interactions between spins and ultrashort laser pulses. The optical spectrum of DyFeO₃ is dominated by a set of intense electronic O–Fe (2p–3d) CT transitions. The absorption due to these transitions sets in above 2 eV, and promptly brings the absorption coefficient α to values as high as 5×10⁷ cm⁻¹ (Fig. 1a, inset), corresponding to penetration depths (δ) of less than 50 nm.

In our experiments, we study a 60-μm-thick slab of z-cut DyFeO₃. The sample is excited with 100 fs pump pulses that have photon energy tunable in the spectral range of 1.5–3.1 eV, covering the lowest-energy A₁g → T₁g CT electronic transition. We use time-delayed probe pulses at various photon energies below the CT gap (hv < 2 eV) to detect the photo-induced magnetic dynamics.
(Extended Data Fig. 1). The probing is simultaneously performed in two complementary transmission and reflection geometries (Fig. 1b). In both geometries, the pump-induced rotation of the probe polarization plane, originating from the Faraday effect ($\theta_F$) or the magneto-optical Kerr effect (MOKE) ($\theta_K$), is tracked as a function of the pump–probe delay time. Note that while the Faraday transmission geometry is routinely used in pump–probe experiments for detecting uniform ($k = 0$) spin precession in antiferromagnets\textsuperscript{19}, the reflection geometry has been shown to enable the detection of finite-$k$ coherent excitations such as propagating acoustic wavefronts\textsuperscript{26,27}. As shown below, we demonstrate that the reflection geometry can also be used to probe the dynamics of short-wavelength propagating coherent spin waves.

Following the optical pumping in the regime of strong absorption ($h\nu = 3.1 \text{ eV}$), the time-resolved dynamics reveal high-frequency oscillations in the range of hundreds of gigahertz (Fig. 1c). The frequencies $f_0$ and $f_k$ of the oscillations observed in the transmission and reflection geometry, respectively, are substantially different: $f_k > f_0$ (Fig. 1c, inset). The decay time of the oscillations also differs by nearly an order of magnitude.

To identify the origin of the oscillations, we track their central frequency as a function of temperature. The AFM state in DyFeO$_3$ adopts two distinct spin configurations, sharply separated by a first-order phase transition at the so-called Morin temperature $T_M \approx 50 \text{ K}$ (ref. 28). At $T < T_M$, the antiparallel iron spins are oriented along the $y$ axis and arranged in a compensated collinear AFM pattern. Above $T_M$, the spins experience a reorientation towards the $x$ axis accompanied by mutual canting and the stabilization of a canted AFM phase (Fig. 2a). The temperature dependence of the oscillation frequency exhibits a characteristic cusp-like softening...
with a minimum at \( T_{\text{M}} \) (Fig. 2b and Extended Data Fig. 2). This frequency softening is a hallmark of the quasi-antiferromagnetic (q-AFM) magnon branch in DyFeO\(_3\) and is caused by strong temperature variations in the magneto-crystalline anisotropy in the vicinity of \( T_{\text{M}} \) (ref. 29). Indeed, the frequencies \( f_0 \) observed in the transmission geometry match the values reported in the literature for the zone-centre (\( k = 0 \)) q-AFM magnon31.

To explain the physical origin of the oscillation at frequency \( f_0 \) seen in the MOKE experiment, we refer to the dispersion relation for magnons. In both magnetic phases, below and above \( T_{\text{M}} \), the magnon spectrum \( \omega_0 \) in DyFeO\(_3\) is given by29

\[
\omega_k = \sqrt{\omega_0^2 + (\nu_0 k)^2},
\]

where \( \nu_0 \approx 20 \text{km s}^{-1} \) is the limiting group velocity of the spin waves29. This dispersion relation is shown in Fig. 2b, inset. At small wavenumbers (\( \nu_0 k \ll \omega_0 \)), it has a quadratic form due to the magnon gap \( \omega_0 = 2\pi f_0 \) arising from magneto-crystalline anisotropy. At larger wavenumbers (\( \nu_0 k \gg \omega_0 \)), the dispersion relation becomes dominated by the exchange interaction (exchange regime) and thus takes a linear form typical for antiferromagnets29. Based on the form and properties of the dispersion relation, we identify the MOKE signal at \( f_0 \) as a finite-\( k \) magnon on the q-AFM branch: A spin wave with a propagation vector along the \( z \) axis causes a perturbation of the magnetic order and a corresponding periodic modulation of the off-diagonal components of the dielectric tensor\(^{-1}\), resembling the magneto-optical analogue of a dynamic volume phase grating. The polarization state of the reflected probe beam is explained by the Bragg reflection of light from this grating, an approach similar to the one used in Brillouin light scattering studies on spin waves\(^{31}\). As a result, the polarization rotation of the reflected probe beam with wavenumber \( k_\text{m} \) becomes subject to a Bragg condition:

\[
k_\text{m} = 2k_0 n(\lambda_0) \cos \gamma', \tag{2}
\]

where \( n(\lambda_0) \) is the optical refractive index of the medium at probe wavelength \( \lambda_0 \), \( \gamma' \) is the refracted angle of incidence of the probe and \( k_\text{m} \) is the normal projection of the \( k \) vector of the magnon. Using equation (2), we find that a probe pulse at a central wavelength of 680 nm (\( n \approx 2.39 \)) and normal incidence (\( \gamma' = 0 \)) is sensitive to propagating magnons with wavenumber \( k_\text{m} \approx 4.2 \times 10^5 \text{cm}^{-1} \). Note that this independent estimation agrees with the magnon wavenumber retrieved using the measured frequency and the known dispersion relation (equation (1)).

The generation of finite-\( k \) coherent magnons is anticipated to strongly rely on the confinement provided by the optical penetration depth \( \delta \), which is highly dispersive near the CT band. In particular, changing the pump photon energy between 2.4 and 3.1 eV provides a variation in the penetration depth between 300 and 50 nm, while the real part of the refractive index (influencing the pump wavelength) changes by only 5% (Extended Data Fig. 3). Therefore, the amplitude of the finite-\( k \) magnon is expected to vary strongly as a function of the pump photon energy. The time-resolved MOKE signals obtained in the reflection geometry for different photon energies...
I close to the wavelength $\lambda$ is nearly absent for penetration depths larger than 150 nm, a value (Fig. 3c). The obtained dependence shows that the finite-$k$ magnon amplitudes increase (that is, decreasing penetration depth), proportionally to the light penetration depth (Supplementary Section 2). The evolution of the spin dynamics is described by

$$\varphi(z,t) = \int_{-\infty}^{\infty} dk \left[A_k \cos(\kappa z) \cos(\omega_k t)\right]$$

and is shown in Fig. 4a and Extended Data Fig. 4. The strong dispersion promptly smears out the initial exponential profile of the spin excitation, simultaneously forming a spin-wave front that propagates into the bulk, already after around 10 ps. This front is composed of short-wavelength magnons with $k > 20 \times 10^5$ cm$^{-1}$ propagating with the limiting group velocity $v_g$.

Applying the Bragg condition of equation (2), we can experimentally map out the spectral components of the magnon wavepacket, as well as extract the group velocity and propagation length of individual magnon modes. First, we vary the incidence angle $\gamma$ of the probe pulse (Fig. 4b, inset) and find that the central frequency of the oscillations is reduced on increasing $\gamma$ (Fig. 4b), in perfect agreement with equation (2) and magnon dispersion of equation (1). Next, on decreasing the probe wavelength, we observe a

![Diagram](image1.png)

**Fig. 3** Confinement of light as a necessary condition for the generation of finite-$k$ spin waves. 

- **a**. Time-resolved polarization rotation after excitation with pump pulses of increasing photon energy as measured in the reflection geometry. 
- **b**. Fourier amplitude spectra of the time-resolved signals from a. 
- **c**. Amplitude of the AFM propagating spin wave, as extracted from sine fits to the data from a versus the penetration depth of the excitation pulse (colour markers correspond to a). 

Amplitude markers correspond to $k_m = 3.7 \times 10^5$ cm$^{-1}$. The excited spin-wave continuum forms a broadband magnon wavepacket, in which individual spectral components propagate independently, each adhering to the dispersion relation $\omega_k = 2\pi f_k$ (equation (1)). To visualize the time evolution of the wavepacket, we use the linearized sine–Gordon equation for the space ($z$-) and time ($t$-) dependent amplitude of the spin deflections $\varphi(z,t)$ (ref. 80) (Supplementary Section 2). The evolution of the spin dynamics is described by

$$\varphi(z,t) = \int_{-\infty}^{\infty} dk \left[A_k \cos(\kappa z) \cos(\omega_k t)\right]$$

and is shown in Fig. 4a and Extended Data Fig. 4. The strong dispersion promptly smears out the initial exponential profile of the spin excitation, simultaneously forming a spin-wave front that propagates into the bulk, already after around 10 ps. This front is composed of short-wavelength magnons with $k > 20 \times 10^5$ cm$^{-1}$ propagating with the limiting group velocity $v_g$.

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![Diagram](image2.png)
systematic increase in the magnon frequency (Fig. 4c), once again in accordance with the Bragg condition.

To summarize our observations, we plot the extracted central frequencies as a function of the corresponding wavenumbers $k_m$ (Fig. 4d). These points—fit to the dispersion relation $\omega_k$ given by equation (1)—yield a limiting group velocity $v_g = 19.7 \pm 0.1 \text{ km s}^{-1}$, in good agreement with the literature values. Using this extracted value, we evaluate the group velocities $v_g = \frac{\partial \omega_k}{\partial k_m}$ of the optically detected magnons given by $\omega_k = v_0 \frac{\lambda_0}{2}$. These values, shown in Fig. 4e, indicate that while the zone-centre magnons do not support propagation, the shortest-wavelength components of the magnon wavepacket detected in our experiment propagate at a supersonic velocity ($v_s = 6.2 \text{ km s}^{-1}$; Supplementary Section 3) of nearly 13 km s$^{-1}$. We note that the velocities of these magnons already approach the exchange-wave regime characterized by the limiting group velocity $v_g$. This feature—inherent to antiferromagnets—stands in contrast with the situation in ferromagnets, where the quadratic dispersion relation dictates that the exchange value of the group velocity is reached only for magnons with $k \lesssim 10$ nm. Although the shortest magnon wavelength detected in our experiments is 125 nm, magnons at even shorter wavelengths—down to the penetration depth limit of 50 nm—are anticipated, and could be detected using probe pulses at higher photon energies or other means to measure non-local ultrafast spin excitations. Using the extracted lifetime of the oscillations $\tau = 85 \text{ ps}$ (Extended Data Fig. 5), we estimate the coherence length $l_c$ of the spin-wave transport $l_c = v_0 \tau = 1.1 \text{ nm}$. We note that this length scale, which is large compared with metallic antiferromagnets, also agrees with the studies of diffusive spin transport in other insulating antiferromagnets. One can anticipate even longer propagation lengths for the coherent (ballistic) regime reported here: our estimate of the coherence length is only a lower limit, as the propagating spin wave is likely to escape from the region that is probed efficiently by the reflected probe light (of the order of $\lambda_0/2$). These observations make AFM insulators such as DyFeO$_3$ a promising platform for the realization of high-speed wave-based magnonic devices.

Through optical pumping of above-bandgap electronic transitions, we have explored an efficient and virtually universal route for exciting coherent propagating spin waves in insulating antiferromagnets. The strong optical absorption provides an opportunity to spatially confine the light to a subwavelength scale, inaccessible by any other means such as focusing, enabling the emission...
of a broadband continuum of short-wavelength AFM magnons. The universal mechanism opens up prospects for THz coherent AFM magnonics and opto-spintronics’, providing a long-sought source of coherent high-velocity spin waves. We anticipate even higher propagation velocities to be observed in the broad class of easy-plane antiferromagnets (for example, haematite\textsuperscript{37} and FeBO\textsubscript{3}), in which the spin-wave gap $\omega_0$ is reduced and the high-velocity exchange-wave regime can be achieved at considerably smaller wavenumbers $k$. The demonstrated approach holds promise for a wide range of fundamental studies exploiting the excitation and propagation of nonlinear spin waves such as magnetic solitons\textsuperscript{32,41}, as well as the investigation of the giant magneto-elastic coupling between AFM magnons and acoustic phonons\textsuperscript{42} directly in the time domain.

**Online content**

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**References**

1. Kruglyak, V. V. & Hicken, R. J. Magnonics: experiment to prove the concept. *J. Magn. Magn. Mater.* **306**, 191–194 (2006).

2. Kruglyak, V. V., Demokritov, S. & Grundler, D. Magnonics. *J. Phys. D* **43**, 264001 (2010).

3. Lenk, B., Ulrichs, H., Garbs, F. & Münzenberg, M. The building blocks of magnonics. *Phys. Rep.* **507**, 107–136 (2011).

4. Chumak, A. V., Vasyuchka, V. I., Serga, A. A. & Hillebrands, B. Magnon spintronics. *Nat. Phys.* **11**, 453–461 (2015).

5. Sander, D. et al. The 2017 magnetism roadmap. *J. Phys. D* **50**, 363001 (2017).

6. Jungwirth, T., Marti, X., Wadley, P. & Wunderlich, J. Antiferromagnetic spintronics. *Nat. Nanotechnol.* **11**, 231–241 (2016).

7. Némec, P., Fiebig, M., Kampfrath, T. & Kimel, A. V. Antiferromagnetic opto-spintronics. *Nat. Phys.* **14**, 229–241 (2018).

8. Baltz, V. et al. Antiferromagnetic spintronics. *Rev. Mod. Phys.* **90**, 015005 (2018).

9. Lebrun, R. et al. Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide. *Nature* **561**, 222–225 (2018).

10. Li, J. et al. Spin current from sub-thermally-generated antiferromagnetic magnons. *Nature Phys.* **578**, 70–74 (2020).

11. Vaidya, P. et al. Subthermally spin pumping from an insulating antiferromagnet. *Science* **366**, 160–165 (2020).

12. Galkina, E. & Ivanov, B. Dynamic solitons in antiferromagnets. *Low. Temp. Phys.* **44**, 618–633 (2018).

13. Giamarchi, T., Rüegg, C. & Therychmyshov, O. Bose–Einstein condensation in magnetic insulators. *Nat. Phys.* **4**, 198–204 (2008).

14. Johansen, O., Kamra, A., Ulloa, C., Brataas, A. & Duine, R. A. Magnon-mediated indirect exciton condensation through antiferromagnetic insulators. *Phys. Rev. Lett.* **123**, 167203 (2019).

15. Bukov, Y. M. et al. High-$T_c$ spin superfluidity in antiferromagnets. *Phys. Rev. Lett.* **108**, 177002 (2012).

16. Takeda, S., Halperin, B. I., Yacoby, A. & Tserkovnyak, Y. Superfluid spin transport through antiferromagnetic insulators. *Phys. Rev. B* **90**, 094408 (2014).

17. Qaimzadeh, A., Skarsvåg, H., Holmqvist, C. & Brataas, A. Spin superfluidity in biaxial antiferromagnetic insulators. *Phys. Rev. Lett.* **118**, 137201 (2017).

18. Dąbrowski, M. et al. Coherent transfer of spin angular momentum by evanescent spin waves within antiferromagnetic NiO. *Phys. Rev. Lett.* **124**, 217201 (2020).

19. Kimel, A. et al. Ultrafast non-thermal control of magnetization by instantaneous photomagnetic pulses. *Nature* **435**, 655–657 (2005).

20. Duong, N., Satoh, T. & Fiebig, M. Ultrafast manipulation of antiferromagnetism of NiO. *Phys. Rev. Lett.* **93**, 117402 (2004).

21. Kampfrath, T. et al. Coherent terahertz control of antiferromagnetic spin waves. *Nat. Photon.* **5**, 31–34 (2011).

22. Bossini, D. et al. Macrospin dynamics in antiferromagnets triggered by sub-20 femtosecond injection of nanomagnons. *Nat. Commun.* **7**, 10645 (2016).

23. Afanasiev, D. et al. Ultrafast control of magnetic interactions via light-driven phonons. *Nat. Mater.* **20**, 607–611 (2021).

24. Afanasiev, D. et al. Control of the ultrafast photoinduced magnetization across the Morin transition in DyFeO\textsubscript{3}. *Phys. Rev. Lett.* **116**, 097401 (2016).

25. Usachev, P. et al. Optical properties of thulium orthoferrite TmFe\textsubscript{2}O\textsubscript{4}. *Phys. Solid State* **47**, 2292–2298 (2005).

26. Thomsen, C., Grahn, H. T., Maris, H. J. & Tauc, J. Surface generation and detection of phonons by picosecond light pulses. *Phys. Rev. B* **34**, 4129–4138 (1986).

27. Holtensius, J. R., Afanasiev, D., Sasani, A., Bousquet, E. & Caviglial, A. D. Ultrafast strain engineering and coherent structural dynamics from resonantly driven optical phonons in LaAIO\textsubscript{3}. *npj Quantum Mater.* **5**, 9 (2020).

28. Afanasiev, D., Zvezdin, A. & Kimel, A. Laser-induced shift of the Morin point in antiferromagnetic DyFe\textsubscript{0.5}O\textsubscript{1.5}. *Opt. Express* **23**, 23978–23984 (2015).

29. Balbashov, A., Volkov, A., Lebedev, S., Mukhin, A. & Prokhhorov, A. High-frequency magnetic properties of dysprosium orthoferrite. Zh. Eksp. Teor. Fiz. [Sov. Phys. JETP] **88**, 974–987 (1985).

30. Bar’yakhkta, V. G., Ivanov, B. & Chetkin, M. V. Dynamics of domain walls in weak ferromagnets. *Soz. Phys. Usp.* **28**, 563–588 (1985).

31. Zvezdin, A. K. & Kotov, V. A. Modern Magnetooptics and Magnetooptical Materials (CRC Press, 1997).

32. Demokritov, S. O., Hillebrands, B. & Slavin, A. N. Brillouin light scattering studies of confined spin waves: linear and nonlinear confinement. *Phys. Rep.* **348**, 441–489 (2001).

33. Qiu, H. et al. Ultrafast spin current generated from an antiferromagnet. *Nat. Phys.* **17**, 388–394 (2021).

34. Radaudoki, I. et al. Nanoscale interface confinement of ultrafast spin transfer torque driving non-uniform spin dynamics. *Nat. Commun.* **8**, 15007 (2017).

35. Melnikov, A. et al. Ultrafast transport of laser-excited spin-polarized carriers in Au/Fe/MgO (001). *Phys. Rev. Lett.* **107**, 076601 (2011).

36. Siddiqui, S. A. et al. Metallic antiferromagnets. *J. Appl. Phys.* **128**, 040904 (2020).

37. Lebrun, R. et al. Long-distance spin-transport across the Morin phase transition up to room temperature in the ultra-low damping single crystals of the antiferromagnet $\alpha$-Fe\textsubscript{2}O\textsubscript{3}. *Nat. Commun.* **11**, 6332 (2020).

38. Hashimoto, Y. et al. All-optical observation and reconstruction of spin wave dispersion. *Nat. Commun.* **8**, 15859 (2015).

39. Satoh, T. et al. Directional control of spin-wave emission by spatially shaped light. *Nat. Photon.* **6**, 662–666 (2012).

40. Au, Y. et al. Direct excitation of propagating spin waves by focused ultrashort optical pulses. *Phys. Rev. Lett.* **110**, 097201 (2013).

41. Bonetti, S. et al. Direct observation and imaging of a spin-wave soliton with p-like symmetry. *Nat. Commun.* **6**, 8889 (2015).

42. Ozogin, V. & Preeobrazhenskii, V. Anharmonicity of mixed modes and giant acoustic nonlinearity of antiferromagnetics. *Sov. Phys. Usp.* **31**, 713–729 (1988).

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Methods

Sample. A single crystal of DyFeO$_3$, 60 $\mu$m thick, grown by a floating zone melting technique was used in this work. The sample is cut perpendicular to the crystallographic z axis.

Time-resolved experiment. The experimental setup is schematically shown in Extended Data Fig. 1.

An amplified 1 kHz Ti:sapphire laser system (Astrella, Coherent; central wavelength, 800 nm; pulse energy, 7 mJ; pulse duration, 100 fs) forms the basis of the experimental setup. A large fraction of this output is used to pump a dual optical parametric amplifier (TOPAS-TWINS, LIGHT CONVERSION). The optical parametric amplifier delivers linearly polarized 100 fs output pulses with photon energies $h\nu$ in the range of 0.45–1.00 eV ($\lambda_0 = 2.7$–1.4 $\mu$m). The photon energy of these output pulses was doubled or tripled using a $\beta$-barium borate single crystal to obtain tunable excitation pulses that cover photon energies in the optical range of 1.55–3.10 eV (corresponding wavelength, 400–800 nm). A small portion of the amplifier pulses was sent through a mechanical delay line and used as a probe of the spin dynamics in the reflection and transmission geometries.

Pump and probe pulses were focused onto the DyFeO$_3$ sample (pump spot diameter, 300 $\mu$m; typical fluence, 2 mJ cm$^{-2}$; probe spot diameter, 80 $\mu$m), which was kept in a dry-cycle cryostat (Montana Instruments) that allowed to cool it down to 10 K and vary the temperature with high stability in a wide temperature range (10–250 K). The pump-induced changes in the polarization $\theta_K,F$ of the reflected or transmitted probe pulse were measured using an optical polarization bridge (Wollaston prism) and a pair of balanced Si photodetectors.

Experimental determination of the absorption coefficient. The unpolarised absorption spectrum of DyFeO$_3$ was directly obtained with light propagating along the crystal z axis in the spectral region of 1.0–2.2 eV. The resulting absorption is shown in Fig. 1a, inset. In addition, we performed spectroscopic ellipsometry measurements using a Woollam M5000 ellipsometer over a wide energy range to obtain the real and imaginary parts of the refractive index. In the photon energy region of 2.5–4.0 eV, where the transmission measurements are not possible for thick samples, we estimated the absorption using the acquired complex refractive index. These values are shown in Fig. 1a, inset.

Data availability

Source data for figures are publicly available at https://doi.org/10.5281/zenodo.4716539. All other data that support the findings of this paper are available from the corresponding authors upon request.

Code availability

The code used to simulate the magnon dynamics is available upon reasonable request.

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Author contributions

D.A. and A.D.C. conceived the project. J.R.H., D.A. and M.M. performed the experiments and analysed the data. B.A.I. developed the general theoretical framework describing the spin-wave propagation. R.L. and R.V.M. developed the theoretical formalism of the spin-wave detection. B.A.I., R.C., R.V.M. and A.V.K. contributed to discussion and theoretical interpretation of the results. A.D.C. supervised the project. The manuscript was written by J.R.H., D.A. and A.D.C., with feedback and input from all the co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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**Extended Data Fig. 1 | Experimental setup.** RR: gold retroreflector mounted on a motorized mechanical precision delay stage, OPA: optical parametric amplifier, BBO: β-barium borate crystal, WP: Wollaston Prism, D1, D2: a pair of balanced silicon photodetectors.
Extended Data Fig. 2 | Time-resolved spin-wave detection at different temperatures. a, b. Time resolved polarization rotation in the transmission (a) and reflection geometry (b) following excitation at $h\nu = 3.1 \text{eV}$ for different temperatures. The probe incidence angle is near-normal, with $\lambda_0 = 700 \text{nm}$. 
Extended Data Fig. 3 | Real part of the refractive index as a function of the pump photon energy. Real part $n$ of the refractive index, as extracted using spectroscopic ellipsometry measurements.
Extended Data Fig. 4 | Simulations of the light-induced spin wave dynamics. Real-space distribution of the magnon spin deflection at different times $t$, after optical excitation at $h\nu = 3.1$ eV with a penetration depth of 50 nm, as determined by equation (3).
Extended Data Fig. 5 | Extracting the magnon propagation distance. Time-resolved polarization rotation originating from a propagating magnon, as obtained in the reflection geometry. The solid line represents a best fit of a damped sine, giving a lifetime of about 85 ps. With the largest estimated group velocities $v_g$ of the measured magnons of about 13 km/s, this gives a propagation distance $l = v_g \tau = 1.1 \mu m$. 

\[ l = v_g \tau = 1.1 \mu m. \]