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 less energy dissipation[1-3]. 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[4,5]. Antiferromagnets can host spin waves at THz frequencies and are therefore seen as a future platform for the fastest and the least dissipative transfer of information[6-11]. 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 nanometer-scale wavepacket of coherent propagating magnons in antiferromagnetic $DyFeO_3$ 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 THz spin waves. The wavepacket features magnons with detected wavelengths down to 125 nm that propagate with supersonic velocities of more than 13 km/s into the material. The long-sought source of coherent short-wavelength spin carriers demonstrated here opens up new prospects for THz antiferromagnetic magnonics and coherence-mediated logic devices at THz frequencies.

Antiferromagnetic insulators (AFMs) are prime candidates to replace ferromagnets (FMs) as active media in the quest towards high-speed spin transport and large spectral bandwidth operation[6-8]. Integration of AFMs in future wave-based technologies[3] crucially requires the realization of coherent (ballistic) transport of antiferromagnetic spin waves over large distances[5]. In this regard, non-uniform spin-wave modes with short wavelengths ($\lambda \lesssim 100$ nm) are of particular importance: they can operate at 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 predicted to be a prerequisite for the occurrence of exotic phenomena such as magnetic solitons[12], Bose-Einstein condensates[13,14] and spin-superfluidity[15-17]. These prospects call for efficient methods for the excitation, manipulation, and detection of short-wavelength coherent antiferromagnetic magnons.

Conventional methods of linear spin-wave excitation use spatially varying oscillating magnetic fields. However, the high-frequency THz resonances inherent to antiferromagnetic dynamics make traditional field sources based on microstrip lines or coplanar waveguides impractical to be used in antiferromagnetic media. As a result, recent demonstrations of magnon-mediated spin transport in antiferromagnets were represented either by diffusive propagation of incoherent magnons[9-11] or by evanescent spin-wave modes[18], and the generation of coherent propagating short-wavelength magnons leading to phase-coherent transport in an antiferromagnet has yet to be experimentally realized.

Ultrashort pulses of light have been routinely used to generate and to control large-amplitude THz spin precession[19-21] 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 antiferromagnetic magnons and/or pairs of mutually coherent magnons at the edges of the Brillouin zone[22], 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 electronic transitions using ultrashort pulses in the prototypical antiferromagnet $DyFeO_3$ provides strong confinement of the optical field, which creates a narrow exponential profile of deflected spins near the sample surface. This magnetic non-uniformity extends over the nanoscale penetration depth of the light and serves as a source of short-wavelength coherent spin waves propagating into the sample bulk, as illustrated in Figure 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.

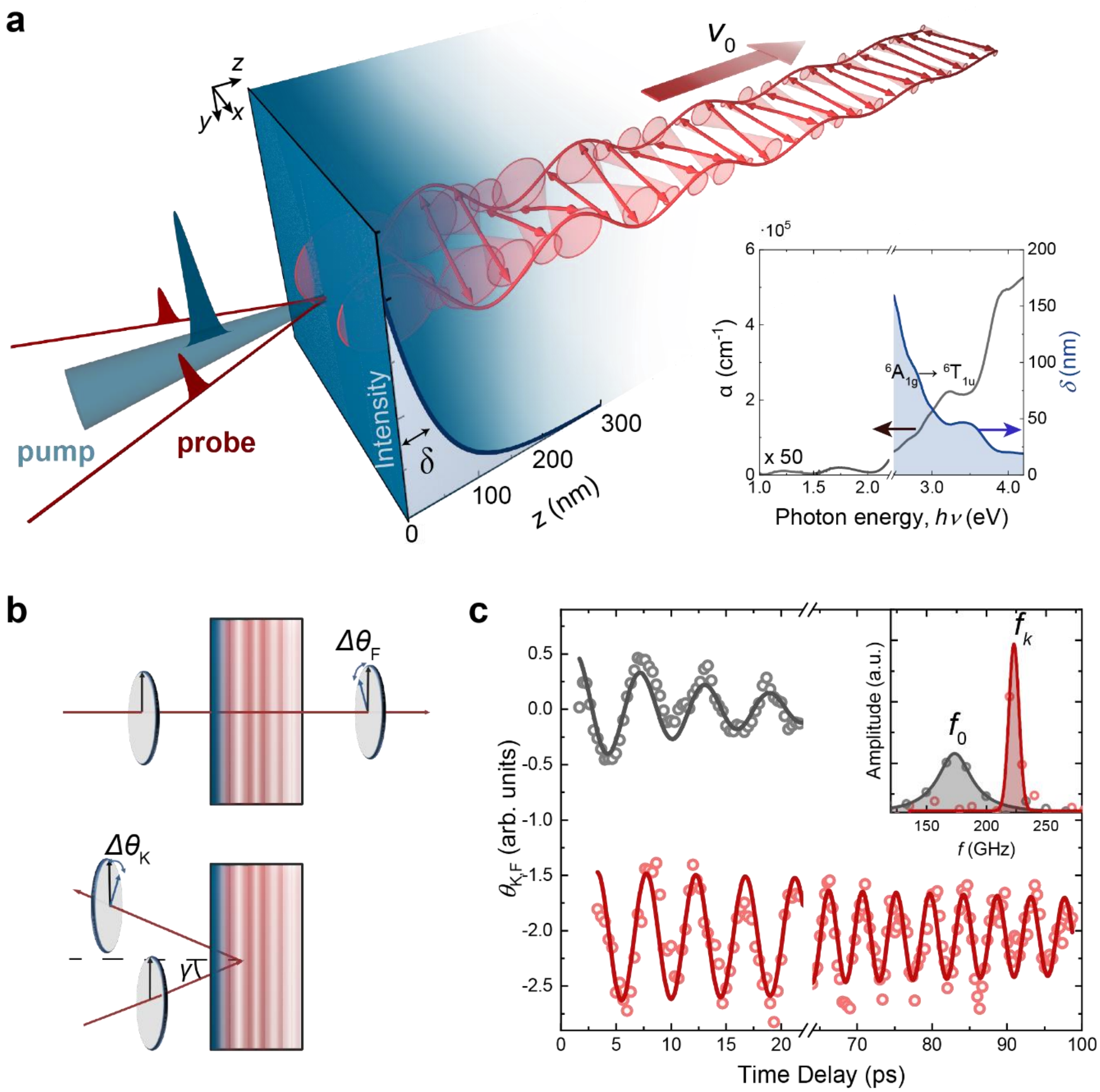

Figure 1: All-optical generation and detection of coherent antiferromagnetic spin waves. (**a**) Schematic illustration of the generation and detection of propagating antiferromagnetic spin waves after excitation of strongly absorbing electronic transitions. The optical penetration depth δ of the light defines the excited region and the width of the magnetic non-uniformity. Inset: Absorption coefficient (left axis) and corresponding penetration depth (right axis) for $DyFeO_3$ as function of photon energy (see methods). $^6A_{1g} \rightarrow {}^6T_{1u}$: the charge-transfer transition of interest. (**b**) Schematics for the optical detection mechanisms of spin waves in transmission (top) and reflection (bottom) geometries, measuring transient changes in the Faraday rotation (θ_F) and Kerr rotation (θ_K) respectively; γ is the angle of incidence. (**c**) Time-resolved measurements of the polarization rotation of a near-infrared probe pulse after excitation with pump pulses with a photon energy of 3.1 eV in the detection geometries shown in (b). The thick solid

lines are exponentially damped sine fits. Inset: Fourier spectra of the oscillations with Lorentzian fits (thick solid lines), with central frequencies f_0 (transmission geometry) and f_k (reflection geometry). a.u.: arbitrary units.

Dysprosium orthoferrite ($DyFeO_3$) is a charge-transfer antiferromagnetic insulator with the Néel temperature T_N = 645 K, exhibiting one of the strongest observed interactions between spins and laser pulses[19,23,24]. The optical spectrum of $DyFeO_3$ is dominated by a set of intense electronic O-Fe (2*p*-3*d*) charge-transfer (CT) transitions. The absorption due to these transitions sets in above 2 eV, and promptly brings the absorption coefficient to values as high as 5×10^5 cm^{-1} (see inset Fig. 1a)[25]. Such strong absorption enables confinement of light down to penetration depths (δ) of less than 50 nm.

In our experiments we study a 60 μm thick slab of *z*-cut $DyFeO_3$. The sample is excited with 100 fs pump pulses which have photon energy tunable in the spectral range of 1.5 - 3.1 eV, covering the lowest energy ${}^6A_{1g}\rightarrow{}^6T_{1u}$ charge-transfer electronic transition[25]. We use time-delayed probe pulses at various photon energies below the fundamental absorption gap ($h\nu < 2$ eV) to detect the photo-induced magnetic dynamics, see Extended Data Fig. 1. The probing is simultaneously performed in two complementary experimental geometries: a transmission geometry using the Faraday effect and a reflection geometry, using the magneto-optical Kerr effect (MOKE) (see Fig. 1b). In both geometries, the pump-induced rotation of the probe polarization plane, originating from the Faraday effect (θ_F) or the MOKE (θ_K), is tracked as a function of the pump-probe time delay. Note that while the Faraday transmission geometry is routinely used in pump-probe experiments for detecting uniform (k = 0) spin precession in antiferromagnets[19], the reflection geometry has been shown to enable detection of finite-*k* coherent excitations such as propagating acoustic wavefronts[26,27]. As shown below we demonstrate that the reflection geometry can be also 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 eV, δ = 50 nm) the time-resolved dynamics of the probe polarization reveal high-frequency oscillations in the hundreds of GHz range (see Fig. 1c). The frequencies f_0 and f_k of the oscillations observed in the transmission and reflection geometry respectively, are substantially different: $f_k > f_0$ (see inset Fig. 1c). Notably, the decay time of the oscillations also differ by nearly an order of magnitude.

To identify the origin of the oscillations, we track their central frequency as a function of temperature. The antiferromagnetic state in $DyFeO_3$ adopts two distinct spin arrangements, sharply separated by a first-order phase transition at the so-called Morin temperature $T_M \simeq 50$ K[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 the mutual canting and stabilization of a canted AFM phase (see Fig. 2a). The experimentally acquired temperature dependence of the oscillation frequency exhibits a characteristic cusp-like softening with a minimum at T_M (see Fig. 2b and Extended Data Fig. 2). This frequency softening is an unambiguous hallmark of the so-called quasi-antiferromagnetic (q-AFM) magnon branch in $DyFeO_3$ and is caused by strong temperature variations of the magneto-crystalline anisotropy in the vicinity of the spin-reorientation phase transition[29]. Indeed, the frequencies f_0 of the oscillations observed in the transmission geometry perfectly match values reported in literature for the zone-centre ($k = 0$) q-AFM magnon[29].

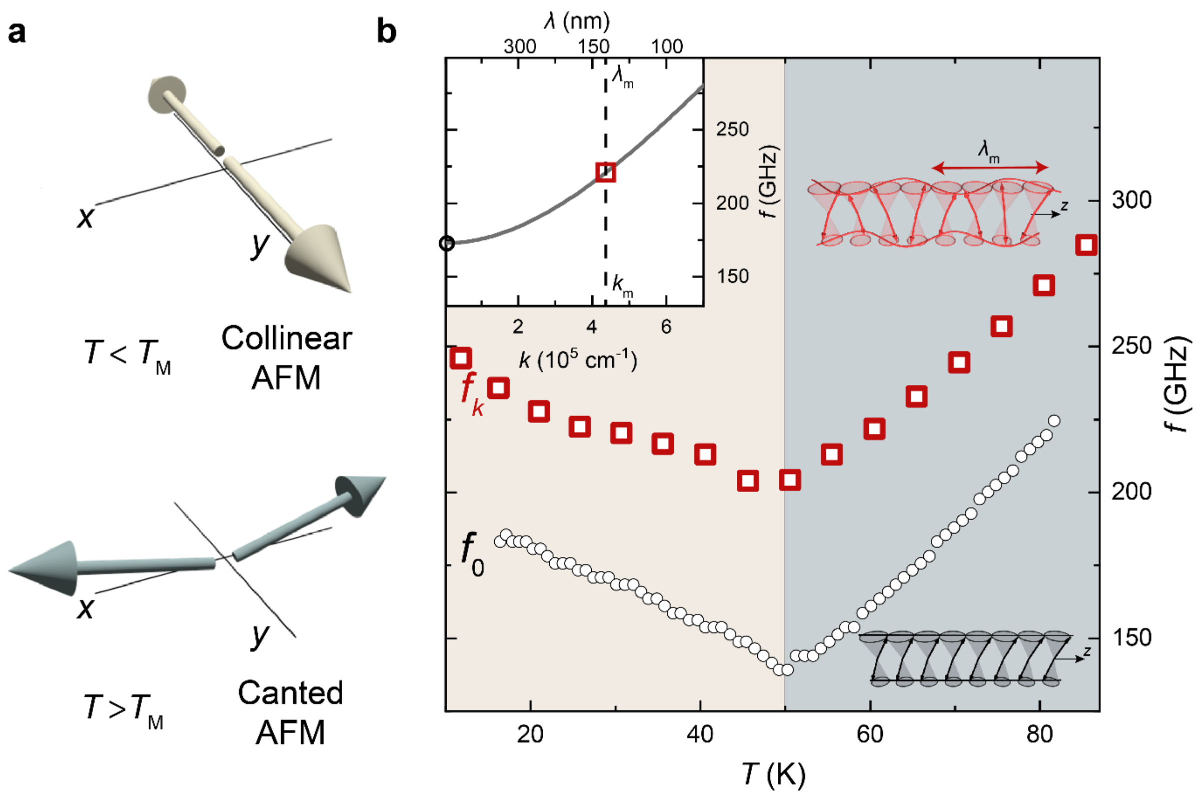

Figure 2: Generation and detection of coherent finite-*k* antiferromagnetic spin waves. (**a**) The spin orientation in the collinear AFM (top panel) and canted AFM phase (bottom panel). (**b**) Temperature (T) dependence of the central frequency of the oscillatory dynamics as measured in the reflection geometry (red square markers) after excitation with strongly absorbed pump pulses ($h\nu = 3.1$ eV, $\delta = 50$ nm) compared with the $k = 0$ magnon T-dependence, as

measured in standard transmission geometry (black circle markers). See also Extended Data Fig. 2. Left top inset: The antiferromagnetic magnon dispersion of $DyFeO_3$ and the wavenumbers of the magnons observed in the reflection and transmission experimental geometries. Right insets: Schematic illustration of the spin wave corresponding to the oscillatory dynamics at the different frequencies.

To explain the physical origin of the oscillation at frequency f_k seen in the MOKE experiment, we refer to the dispersion relation for magnon modes in antiferromagnets. In both magnetic phases, below and above T_M, the magnon spectrum ω_k in $DyFeO_3$, is given by[30]:

$$\omega_k = \sqrt{\omega_0^2 + (v_0 k)^2}, \tag{1}$$

where $v_0 \approx 20$ km/s is the limiting group velocity of the spin waves[30]. This dispersion relation is schematically shown as an inset to Fig. 2b. At small wavenumbers $kv_0 << \omega_0$, it has a quadratic form due to the magnon gap $\omega_0 = 2\pi f_0$, arising from magneto-crystalline anisotropy. At larger wavenumbers ($v_0 k >> \omega_0$), the dispersion relation becomes dominated by the exchange interaction (exchange regime), and thus takes a linear form typical for antiferomagnets[30]. We identify the MOKE signal at f_k as a finite-k magnon on the q-AFM branch: it follows the characteristic temperature dependence of the f_0 zone-center magnon mode and has a nearly temperature-independent blueshift. The detection geometry implies that the magnon wavevector $\mathbf{k}$ is perpendicular to the sample surface, and its magnitude can be deduced from Eq. (1) to be $k = 4.2\times10^5$ cm^{-1} ($\lambda \approx 140$ nm), as marked on the inset to Figure 2b.

By considering the modulation of the material's dielectric tensor due to the propagating coherent spin waves, the attribution of the f_k oscillation to a finite-k magnon on the q-AFM branch can be further supported. A spin wave with a propagation vector along the z-axis results in a perturbation of the magnetic order and a corresponding periodic modulation of the off-diagonal components of the dielectric tensor[31]. In this way the spin waves in the medium produce the magneto-optical analogue of a dynamical volume phase grating for the probe light wave. The polarization state of the reflected probe is explained by the Bragg reflection of light from this diffraction grating, an approach similar to the one used in Brillouin light scattering studies on spin waves[32]. As a result, the polarization rotation of the reflected probe beam with wavenumber k_0 becomes subject to a Bragg condition:

$$k_\mathrm{m} = 2k_0 n(\lambda_0)\cos\gamma', \tag{2}$$

where $n(\lambda_0)$ is the optical refractive index of the medium at the probe wavelength λ_0, γ' is the refracted angle of incidence of the probe, and k_m is the normal projection of the **k**-vector of the magnon to which the probe pulse is sensitive (see Supplementary section S1). Using Eq. (2) we find that a probe pulse at a central wavelength of 680 nm ($n \approx 2.39$)[25] and normal incidence ($\gamma' = 0$) is sensitive to propagating magnons with wavenumber $k \approx 4.2\times10^5$ cm^{-1}. Note that this independent estimation perfectly matches the magnon wavenumber retrieved using the measured frequency and known dispersion relation (Eq. (1)).

The generation and detection of finite-k coherent magnons is anticipated to rely strongly on the confinement provided by the optical penetration depth δ, which is highly dispersive near the charge-transfer band. In particular, changing the pump photon energy between 2.4 eV 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% (see Extended Data Fig. 3). Therefore, we expect that by changing the photon energy of the pump pulses, the amplitude of the finite-k magnon will vary strongly. The time-resolved MOKE signals obtained in the reflection geometry for different photon energies of the pump excitation, are shown in Fig. 3a. The Fourier transforms of the signals (Fig. 3b) show that the spectra are composed of two components, corresponding to the zone-centre and finite-k ($k = 3.7\cdot10^5$ cm^{-1}) magnon modes. We observe that with increasing photon energy (i.e. decreasing penetration depth), the amplitude of the finite-k magnon mode increases dramatically. The magnon amplitude extracted for the pump excitation at different photon energies, as a function of the corresponding penetration length, is shown in Fig. 3c. The obtained dependence shows that the finite-k magnon is nearly absent for penetration depths larger than 150 nm, a value close to the wavelength of the detected magnons, and grows dramatically for shorter penetration lengths.

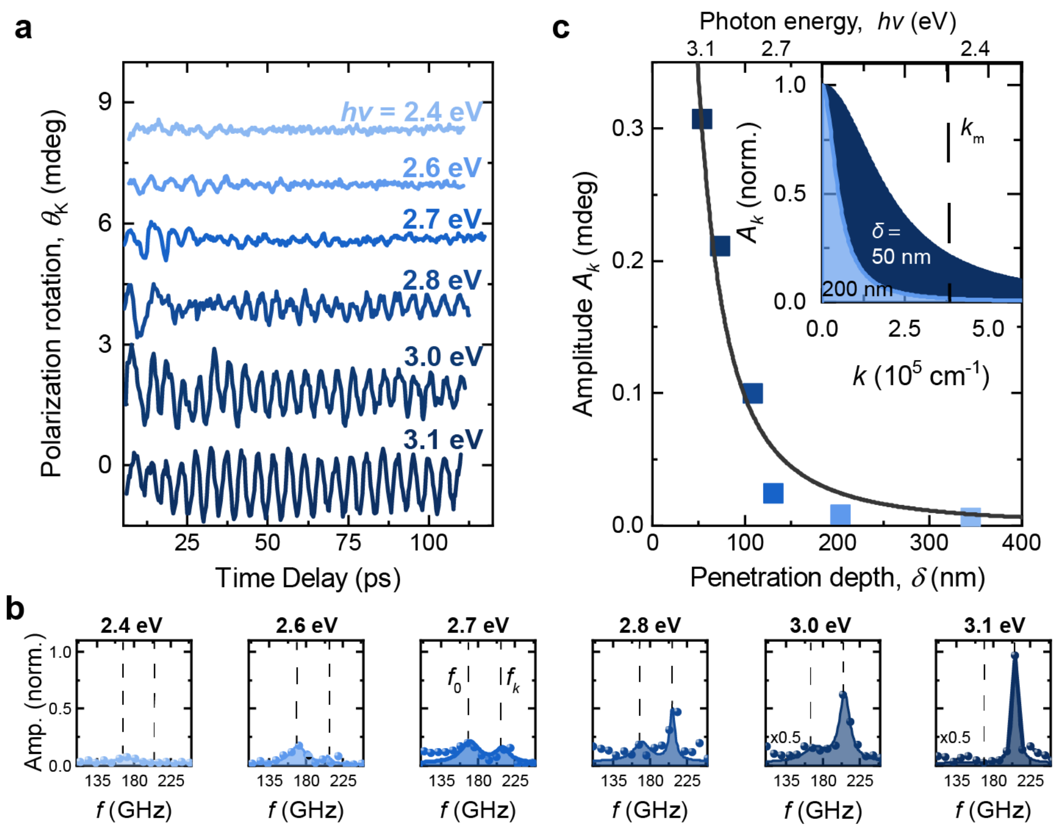

Figure 3: Confinement of the light as a necessary condition for the generation of high-*k* spin waves. (**a**) Time-resolved signals of the polarization rotation of the near-infrared probe pulse after excitation with pump pulses with increasing photon energy in a reflection geometry. (**b**) Fourier amplitude spectra of the time-resolved signals from panel (a). (**c**) Amplitude of sine fit oscillations corresponding to the AFM propagating spin wave to the data from panel (a) vs penetration depth of the excitation pulse (color markers correspond to traces in panel (a)). The solid line is a fit using $I_0/(1 + (k\delta)^2)$. Inset: Magnon frequency distribution after excitation with pump pulses with δ = 50 nm (dark blue, broadband distribution) and 200 nm (light blue, narrowband). The probe is sensitive to $k_m = 3.7\cdot10^5$ cm^{-1}, indicated by the dashed line.

We model this observation using a simple assumption: the ultrashort light pulse promotes a spin excitation that is strongly non-uniform along the direction of incidence z. The excitation leads to a nearly instantaneous deflection of spins by an angle $\varphi(z)$ with the spatial distribution following the optical absorption profile given by the Beer-Lambert law: $\varphi(z,t{=}0) = \varphi_0 e^{-z/\delta}$, where $\varphi_0 \sim I_0/\delta$ is proportional to the intensity of the pump pulse I_0, and inversely proportional to the light penetration depth δ (see Supplementary section S2). The strongly non-uniform spin excitation distributes the initial deflection among magnon modes at different k-wavenumbers, with the amplitudes given by the reciprocal space image A_k of the initial excitation set up by the penetration depth (see inset Fig. 3c). As a result, the finite-k mode is expected to have spectral amplitude A_k (see Supplementary Section S2):

$$A_k \sim \frac{I_0}{1+(k\delta)^2} \tag{3}$$

This expression not only agrees well with the observations of Fig. 3c ($k \approx 3.7\times10^5$ cm^{-1}, λ = 170 nm), where it is plotted as a best fit to the pump intensity I_0, but also confirms the intuitive interpretation that a stronger confinement shifts the spectral amplitude of the excited magnon wave packet towards larger k.

The excitation of a continuum of coherent antiferromagnetic spin waves forms a broadband magnon wavepacket, in which individual spectral components propagate independently, each adhering to the dispersion relation $\omega_k = 2\pi f_k$ (Eq. (1)). In order to visualize the time evolution of the excited magnon wavepacket, we make use of the linearized sine-Gordon equation for the space- (z) and time- (t) dependent amplitude of the spin deflections $\varphi(z,t)$[30]. We find that the evolution of the spin dynamics is described by the following simple formula (see Supplementary section S2):

$$\varphi(z,t) = \frac{2}{\pi}\int_{-\infty}^{\infty} \mathrm{d}k[A_k \cos(kz)\cos(\omega_k t)] \tag{4}$$

By integrating this equation, under the assumption of the exponential distribution of the time-zero spin deflections and δ = 50 nm, we obtain the complete dynamics of the magnetic excitation. As 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 after ~10 ps that propagates into the bulk. This front is composed by the short-wavelength magnons with $k \gtrsim 20\times10^5$ cm^{-1} propagating with the limiting group velocity v_0.

Applying the Bragg condition of Eq. (2), we can experimentally map out the spectral components of the excited broadband magnon wave packet, as well as determine the group velocity and propagation length of individual magnon modes. First, we vary the incidence angle γ of the probe pulse, (inset Fig. 4b) and find that the central frequency of the oscillations is

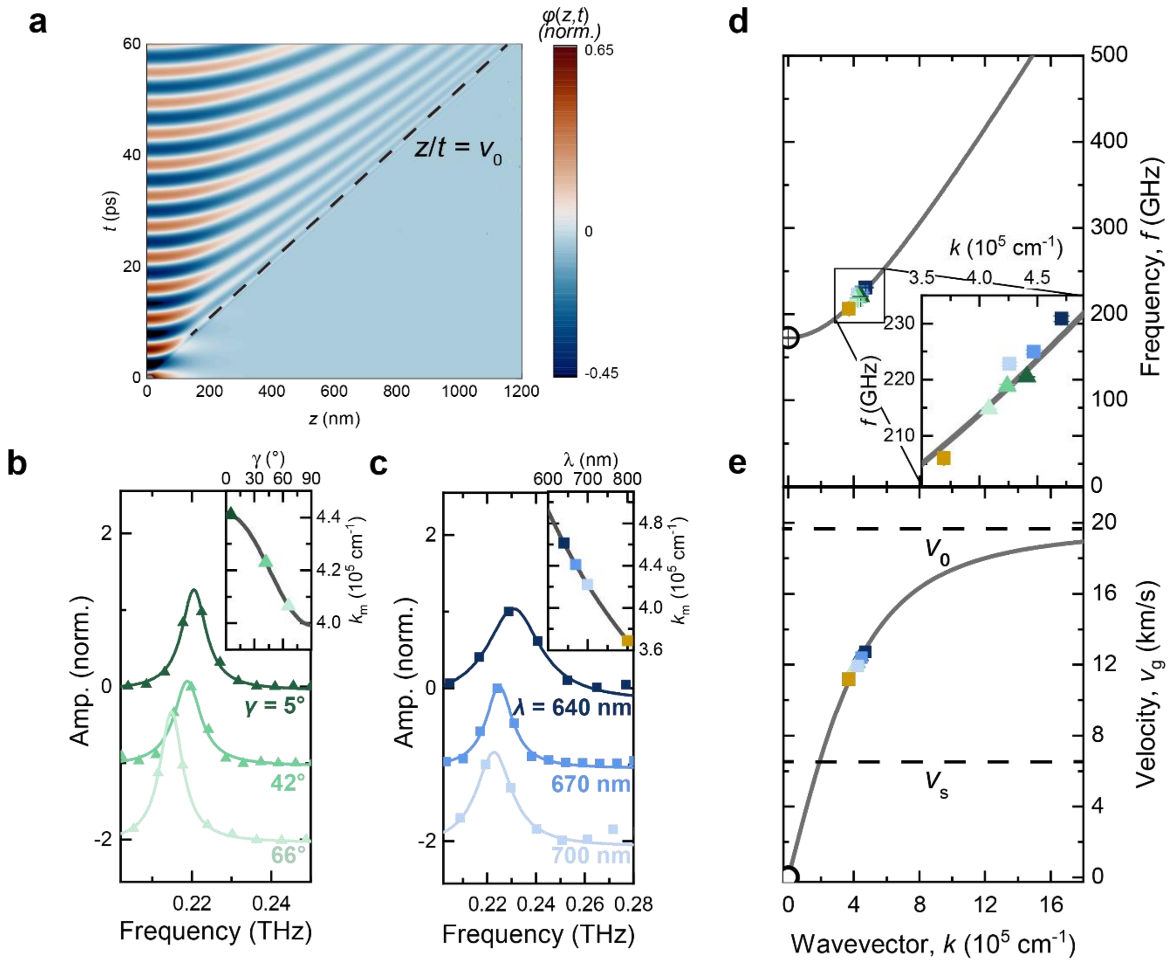

Figure 4: Revealing spectral components of the broadband antiferromagnetic magnon wavepacket. (**a**) Simulation of the time- and position-dependent spin deflection $\varphi(z,t)$ after optical excitation at 3.1 eV with a penetration depth of 50 nm, as determined by Eq. (3). (**b,c**) Fourier spectra of time-resolved measurements of the polarization rotation of a near-infrared probe pulse obtained in the reflection geometry after excitation with pump pulses with a photon energy of 3.1 eV at the temperature T = 60 K for different probe incidence angles γ (λ = 680 nm) (a) and probe wavelengths λ (γ = 5°) (b). The solid superimposed lines are Lorentzian fits of the Fourier peaks. Insets: The magnon wavenumber k_m to which the probe is sensitive, as a function of the angle γ (b) and probe wavelength λ (c), with the measured points indicated by coloured markers. (**d,e**) The extracted central magnon frequencies (d) and the calculated group velocity (e) from the data in panel (b) and (c) at their respective calculated wavenumbers plotted with a best fit of the spin-wave dispersion curve (d) and the group velocity corresponding to the dispersion fit (e). The marker colours and shapes correspond to the measurements in panel (b) and (c).

reduced upon increasing γ' (Fig. 4b), in perfect agreement with Eq. (2) and the magnon dispersion of Eq. (1). Next, upon decreasing the probe wavelength, we observe a systematic increase in the magnon frequency, as shown in 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 (see Fig. 4d). These points are fit to the dispersion relation given by Eq. (1), with the spin-wave gap ω_0 defined by the experimentally obtained zone-center magnon frequency. The best fit of the experimental data yields a limiting group velocity v_0 = 19.7 ± 0.1 km/s. This value stands in good agreement with the limiting group velocity of ~20 km/s extracted from the speed limit of the magnetic domain walls in $DyFeO_3$, as reported in Ref. [30]. Using the extracted value of the limiting group velocity we evaluate the group velocities $v_g = \frac{\partial \omega_k}{\partial k}|_{k=k_m}$ of the optically detected magnons given by $v_g = v_0^2 \frac{k_m}{\omega_k}$. These values, shown in Fig. 4e, indicate that while the zone-center magnons do not support propagation, the shortest-wavelength components of the magnon wavepacket detected in our experiment (λ = 125 nm) propagate at a supersonic (v_s = 6 km/s, see Supplementary Section S3) velocity of nearly 13 km/s. We note that magnons with these wavelengths already approach the exchange wave regime characterized by the limiting group velocity v_0. This remarkable feature, inherent to antiferromagnets, stands in sharp 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 $\lambda_m \lesssim 10$ 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[33-35]. Using the extracted lifetime of the oscillations τ = 85 ps (see Extended Data Fig. 5), we estimate the coherence length l_c of the spin-wave transport $l_c = v_g \tau$ = 1.1 μm. We note that this length, dramatically enhanced as compared to metallic antiferromagnets[8,36], also agrees with studies of diffusive spin transport in other insulating antiferromagnets[9,37]. 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 by the reflected probe light (~λ/2). These striking observations make antiferromagnetic insulators such as $DyFeO_3$ a promising platform for the realization of high-speed wave-based magnonic devices.

By optical pumping of above-bandgap electronic transitions, we have explored an efficient and virtually universal route to launch 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, e.g. focusing[38-40], enabling the emission of a broadband continuum of short-wavelength antiferromagnetic magnons. The universal mechanism opens up prospects for terahertz coherent AFM magnonics and opto-spintronics[7] 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 (e.g. hematite[37] and $FeBO_3$), in which the spin-wave gap ω_0 is reduced and the high-velocity exchange wave regime can be achieved at significantly smaller wavenumbers k. The demonstrated approach holds promise for a wide range of fundamental studies exploiting the excitation and propagation of non-linear spin waves such as magnetic solitons[12,41] as well as the investigation of the giant magneto-elastic coupling between antiferromagnetic magnons and acoustic phonons[42] directly in the time-domain.

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Methods

Sample.

A single crystal of $DyFeO_3$, 60 μm thick, grown by a floating zone melting technique was used in this work. The sample is cut perpendicularly to the crystallographic *z*-axis.

Time-resolved experiment.

The experimental setup is schematically shown in Extended Data Figure 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 (OPA, TOPAS-Twins, Light Conversion). The OPA delivers linearly polarized, 100 fs output pulses, with photon energies $\hbar\omega$ in the range 0.45-1 eV (λ = 2.7 – 1.4 μm). The photon energy of these output pulses was doubled or tripled using a β-barium borate (BBO) single crystal in order to obtain tunable excitation pulses which cover the photon energies in the optical range of 1.5-3.1 eV (wavelength 400-800 nm). A small portion of the amplifier pulses was sent through a mechanical delay line and used as probe of the spin dynamics in the reflection and transmission geometries.

Pump and probe pulse were focused onto the $DyFeO_3$ sample (pump spot diameter: 300 μm, typical fluence 2 mJ/cm^2, probe spot diameter: 80 μm), 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 1-2.2 eV. The resulting absorption is shown in Figure 1b. 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 2.5-4 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 Figure 1b.

Data Availability:

All data needed to evaluate the conclusions in the paper are present in the paper and/or Supplementary Materials. The source data for figures are publicly available with identifier (DOI) 10.5281/zenodo.4716539

Code Availability:

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

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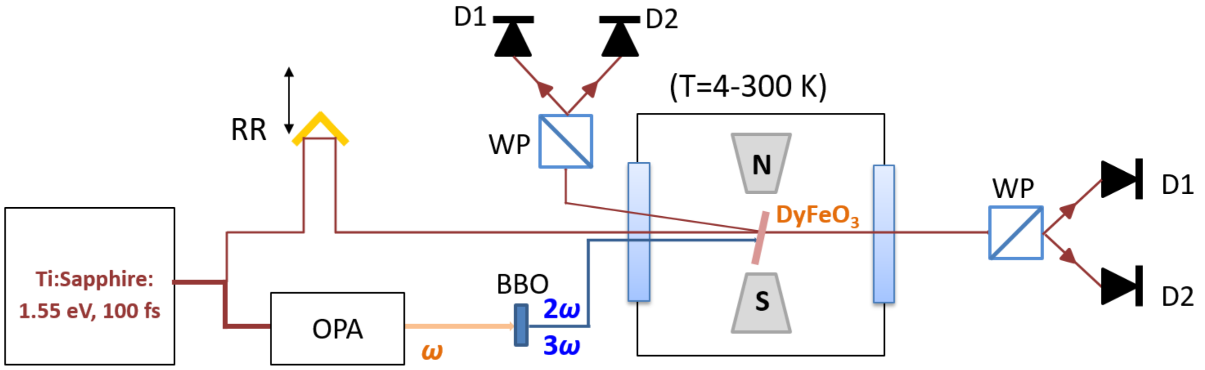
Author contributions:

D.A. and A.D.C. conceived the project. J.R.H., D.A. and M.M performed the experiments, 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 co-authors.

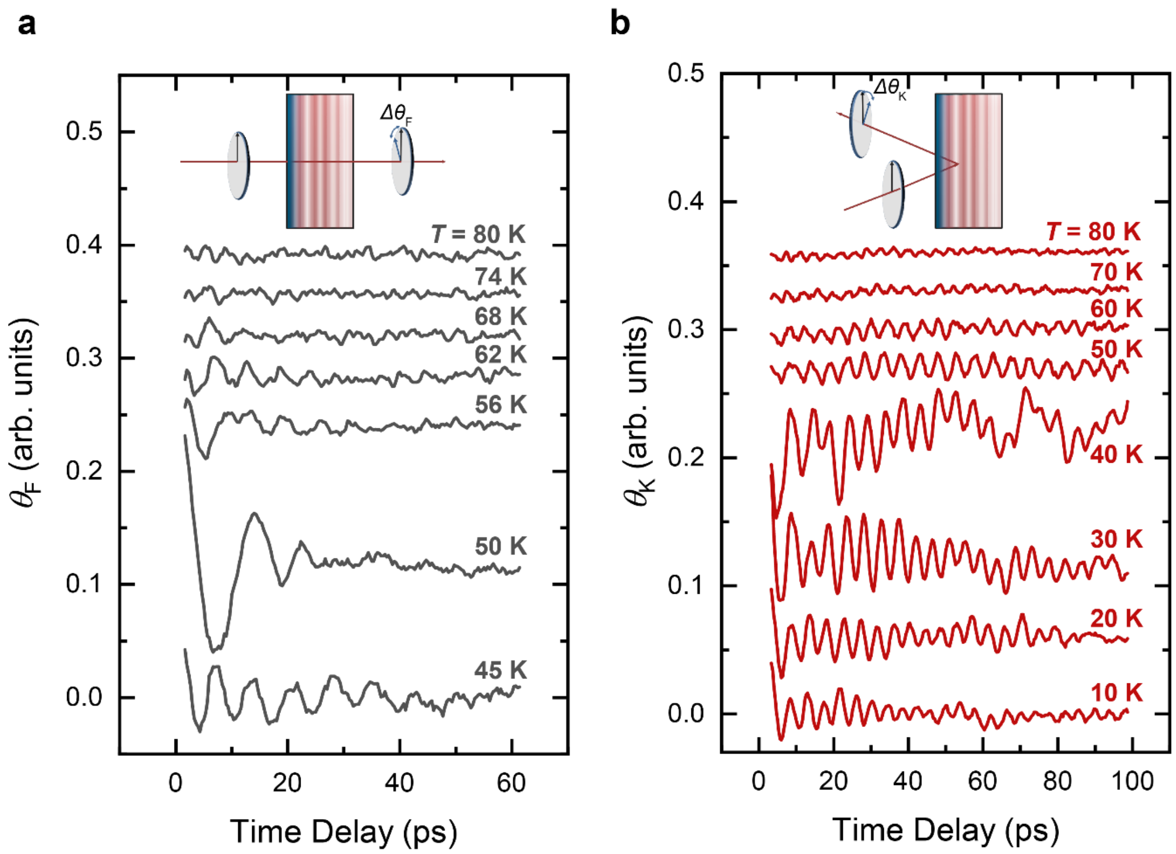
Competing interests:

The authors declare no competing interests.

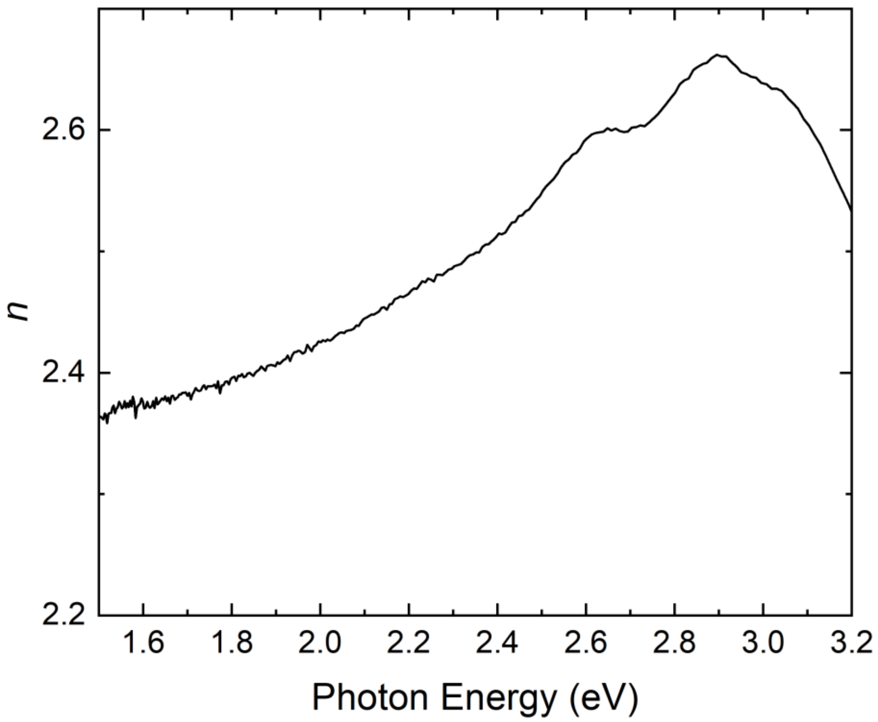
Extended Data Figures



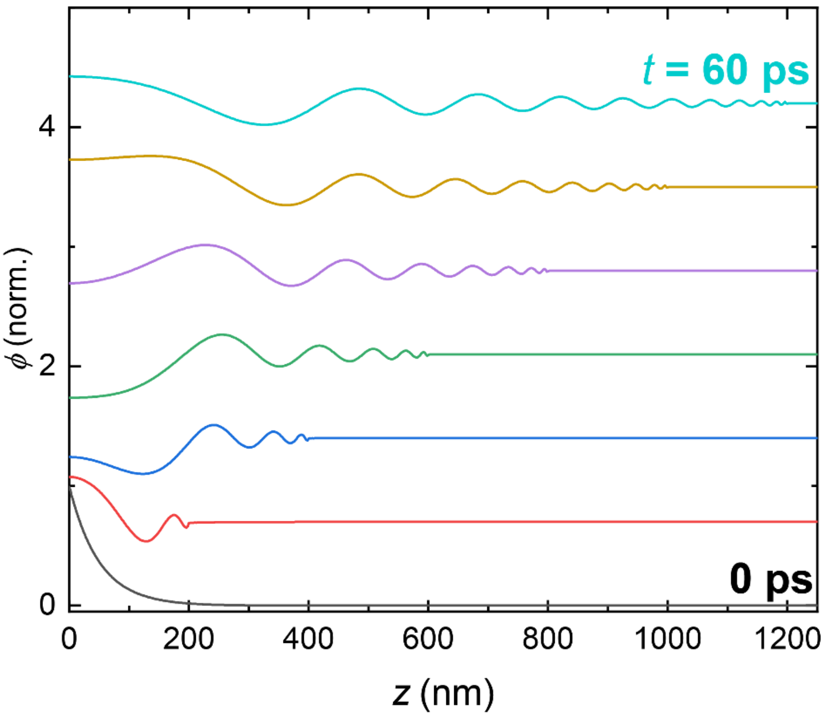
Extended Data Figure 1: Experimental setup. RR: gold retroreflector mounted on a motorized precision delay stage, OPA: optical parametric amplifier, BBO: β-barium borate crystal, WP: Wollaston Prism, D1, D2: pair of balanced silicon photodetectors.



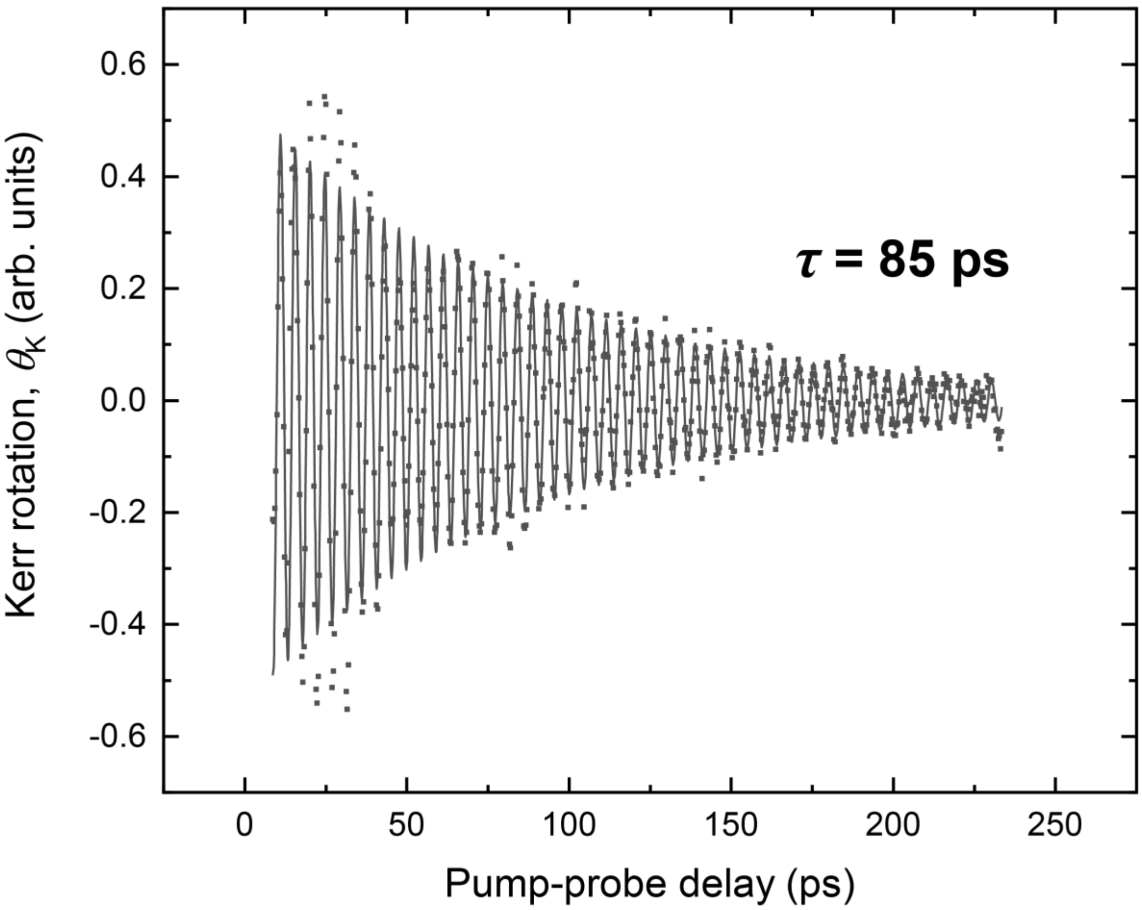
Extended Data Figure 2: Magnon time traces at different temperatures. (**a,b**) Time resolved polarization rotation in the transmission (a) and reflection geometry (b) following excitation at $h\nu$ = 3.1 eV at different temperatures. The probe incidence angle is near-normal, with λ = 640 nm and λ = 700 nm for the measurements in panel a and b, respectively.



Extended Data Figure 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 Figure 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 Eq. (3).



Extended Data Figure 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 ~85 ps. With the largest estimated group velocities v_g of the measured magnons of about 13 km/s, this gives a propagation distance $l_c = v_g \tau$ = 1.1 μm.