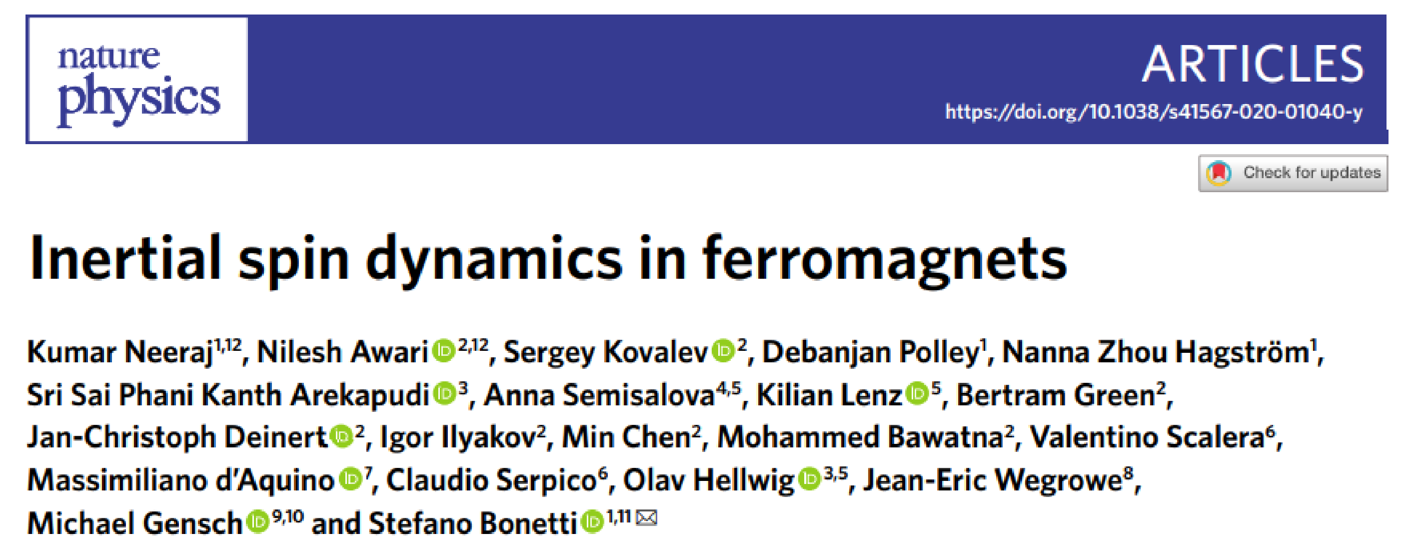
Inertial spin dynamics in ferromagnets

Presented by Ziheng Yang



nature physics

ARTICLES

https://doi.org/10.1038/s41567-020-01040-y

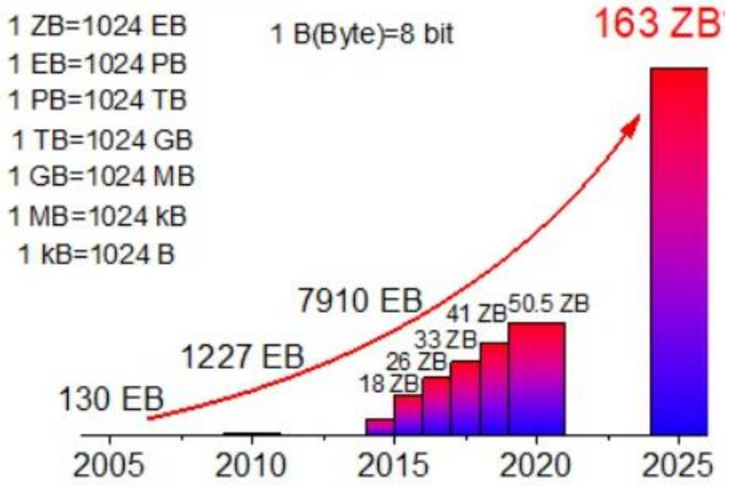
Check for updates

Inertial spin dynamics in ferromagnets

Kumar Neeraj[1,12], Nilesh Awari[2,12], Sergey Kovalev[2], Debanjan Polley[1], Nanna Zhou Hagström[1], Sri Sai Phani Kanth Arekapudi[3], Anna Semisalova[4,5], Kilian Lenz[5], Bertram Green[2], Jan-Christoph Deinert[2], Igor Ilyakov[2], Min Chen[2], Mohammed Bawatna[2], Valentino Scalera[6], Massimiliano d'Aquino[7], Claudio Serpico[6], Olav Hellwig[3,5], Jean-Eric Wegrowe[8], Michael Gensch[9,10] and Stefano Bonetti[1,11] ✉

Content

Date storage nowadays



- Global data storage
- date comes from International Data Corporation， IDC

So how to store and process these massive data quickly and stably has become a difficult problem

About 90% of the world's data will be generated in the next few years

Magnetic storage technology

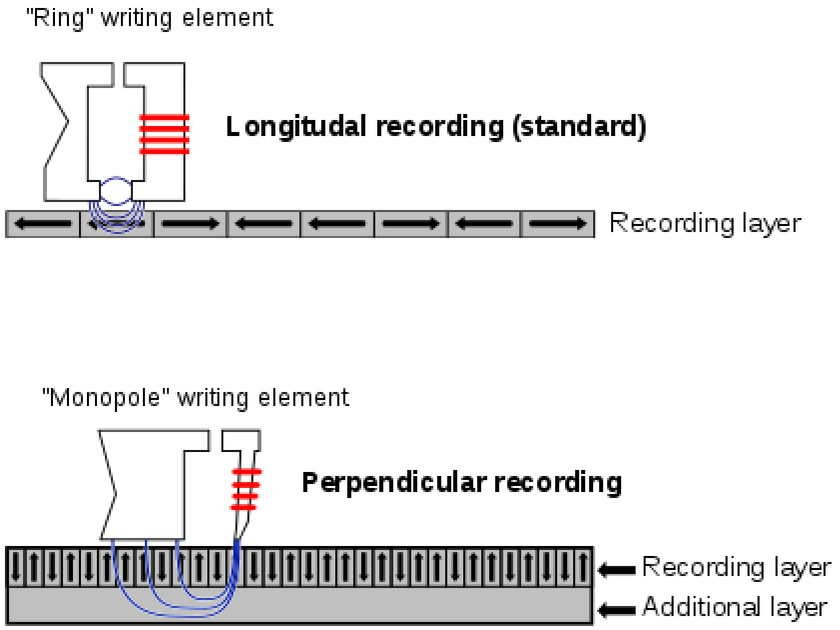
Magnetic pole

south and north

Reflect

Logical ‘1’ and ‘0’

Binary

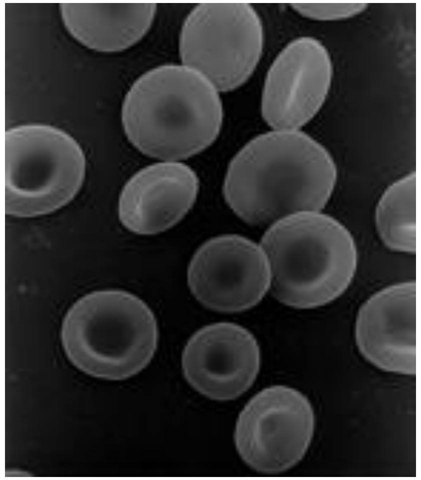


https://en.wikipedia.org/wiki/Magnetic_storage

- So we need to use strongly localized , intense magnetic field to change the magnetization direction.

Timescale

- Picosecond (ps)
- Femtosecond(fs)
- Nanosecond(ns)
- 1 fs = 10^{-15} s
- 1000 fs = 1 ps
- 1000 ps = 1 ns



https://en.wikipedia.org/wiki/Red_blood_cell

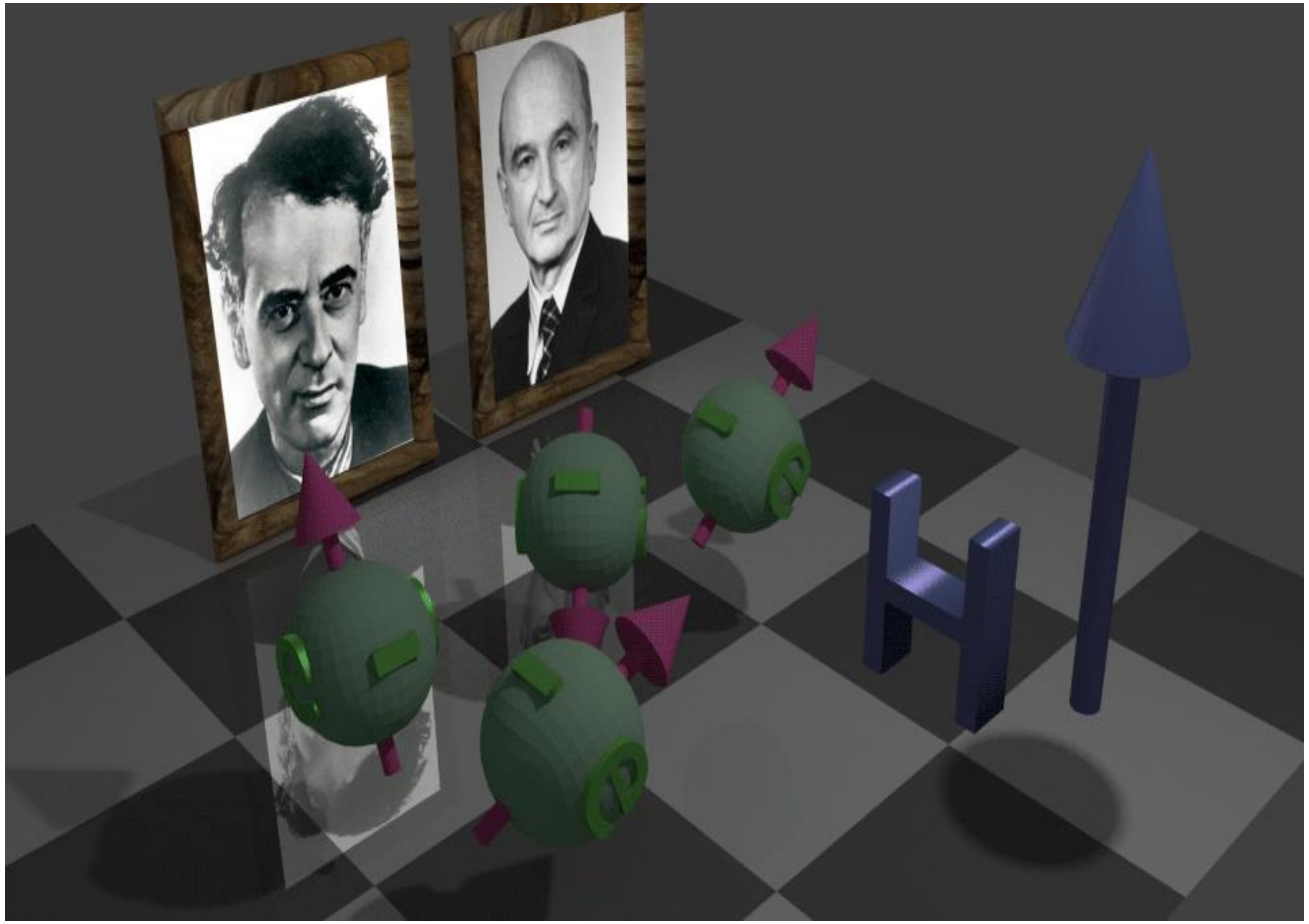
- a ray of light travels approximately 0.3 µm (micrometers) in 1 femtosecond
- Hair diameter about 80 µm
- Red blood cell diameter about 4.5 µm

LLG Equation

- Laudau-Lifshitz-Gilbert (LLG) Equation
- LLG equation can tell us the dynamics of the magnetization
- It can work very well at nanosecond timescale
- Now we need manipulate spins at femtosecond timescale.
- But does it can still work well at this timescale?

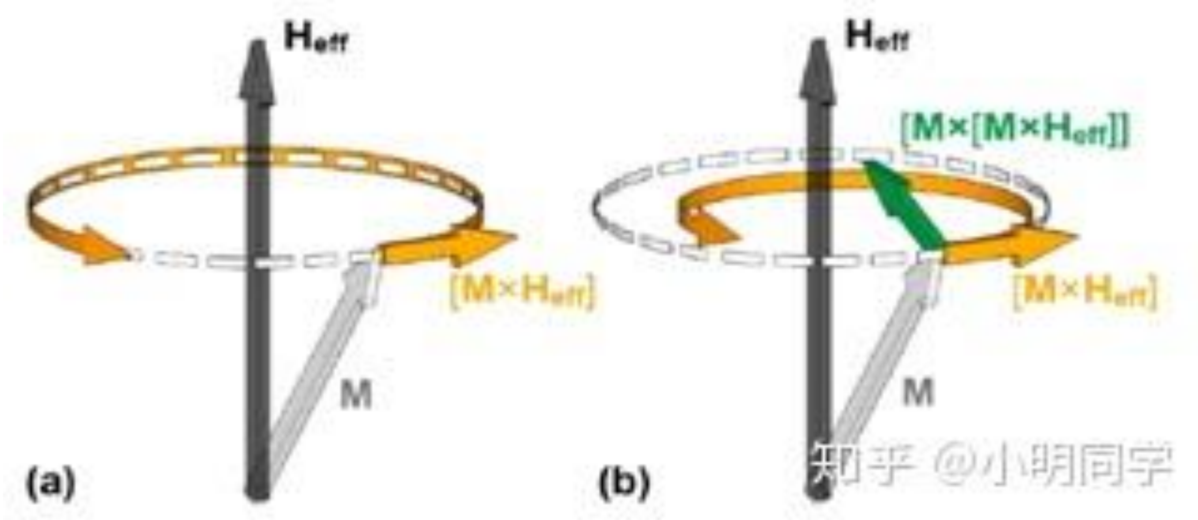
Basic knowledge about LLG equation

- Firstly Landau-Lifshitz (LL) equation
- Interaction between the magnetic field and spin magnetic moment



LL equation

$$\frac{\partial \boldsymbol{M}(x,t)}{\partial t} = \underbrace{-\gamma_{LL}\boldsymbol{M}(x,t) \times \boldsymbol{H}_{eff}}_{\text{Precession}} + \underbrace{\frac{\alpha\gamma_{LL}}{M_s}\boldsymbol{M}(x,t) \times (\boldsymbol{M}(x,t) \times \boldsymbol{H}_{eff})}_{\text{Dumping}} \quad (1)$$



https://zhuanlan.zhihu.com/p/148565062

LLG equation

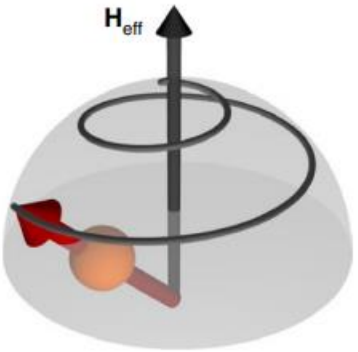
- In 1955 Gilbert replaced the damping term in the Landau–Lifshitz (LL) equation by one that depends on the time derivative of the magnetization (consider the dumping torque)

LLG equation :

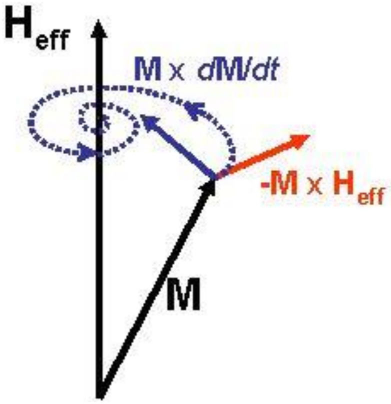
$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -|\gamma|\mathbf{M} \times \left(\mathbf{H}_{\mathrm{eff}} - \frac{\alpha}{|\gamma|M_{\mathrm{s}}}\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t}\right)$$

Basic knowledge about LLG equation

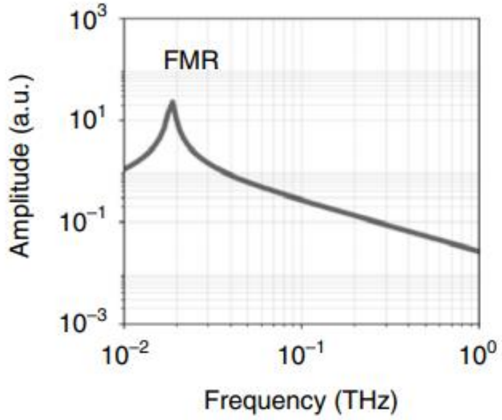
$$\frac{d\mathbf{M}}{dt} = -|\gamma| \underbrace{\mathbf{M}\times\Big(\mathbf{H}_{\mathrm{eff}}}_{\text{Precession}} - \underbrace{\frac{\alpha}{|\gamma|M_s}\frac{d\mathbf{M}}{dt}}_{\text{Gilbert Dumping}}\Big)$$



schematic of the magnetization dynamics and relaxation around an effective magnetic field H according to the standard LLG equation



https://en.wikipedia.org/wiki/Landau%E2%80%93Lifshitz%
0%93Gilbert_equation#Landau%E2%80%93Lifshitz_equation

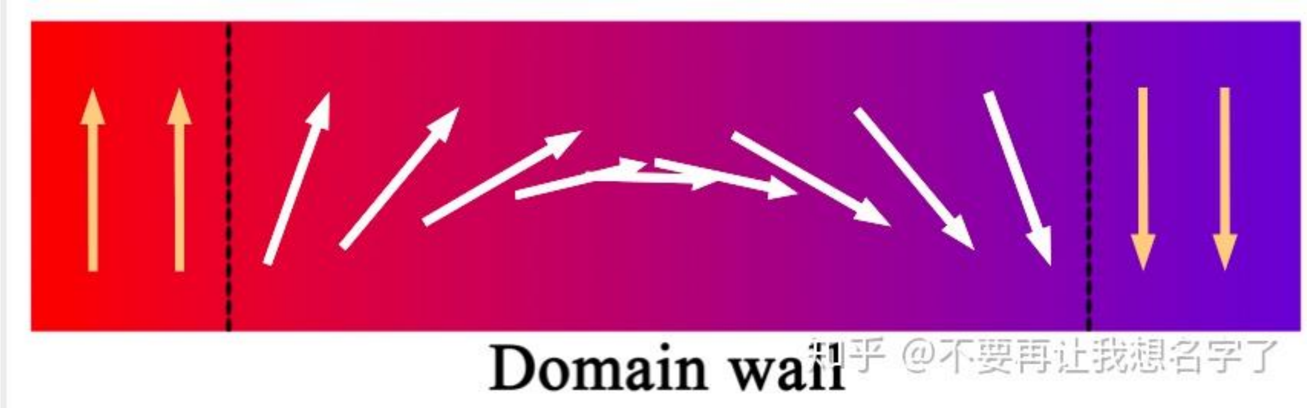


LLG-simulated response (that is, the susceptibility) of a ferromagnetic system to an external a.c. magnetic field of varying frequency.

https://www.nature.com/articles/s41567-020-01040-y

iLLG equation

- i means inertial
- Inertial and mass in macroscopic system
- Such as domain walls

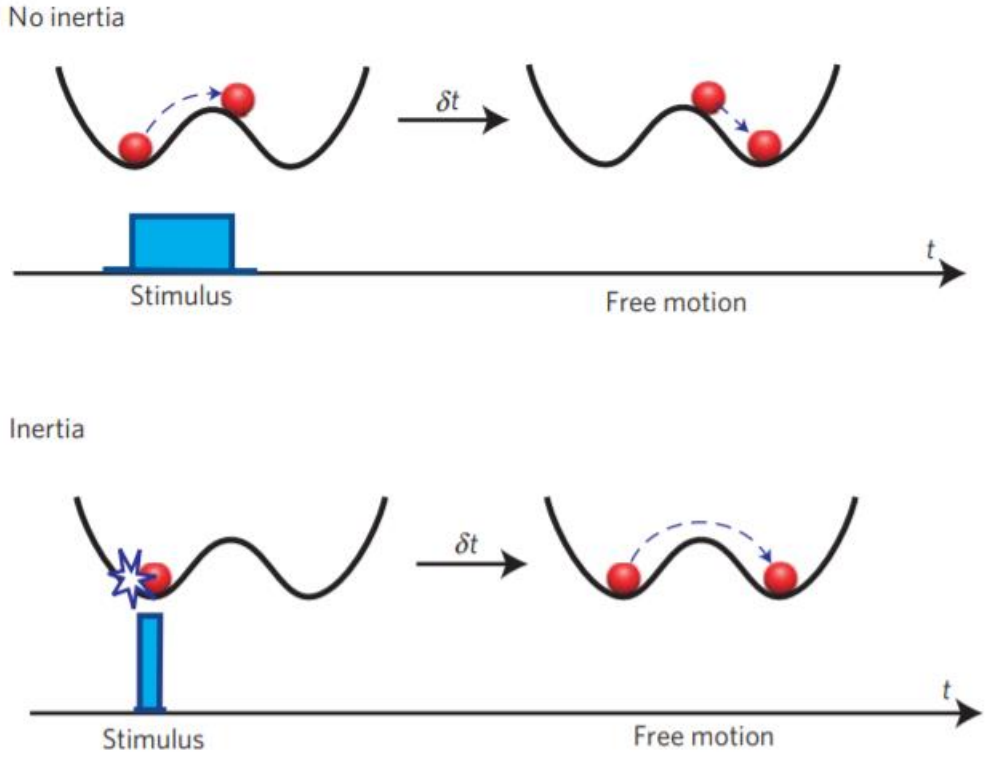


https://zhuanlan.zhihu.com/p/296528143

- Unusual spin behavior in tunnelling barrier between two superconductors
  - Zhu, J.-X., Nussinov, Z., Shnirman, A. & Balatsky, A. V. Novel spin dynamics in a Josephson junction. Phys. Rev. Lett. 92, 107001 (2004).
- In contrast to a simple precession termed it “nutation”

iLLG equation

- In contrast to a simple precession termed it “nutation”
- In reference a very short (femtosecond) magnetic impulse can impart enough energy to the spin system to overcome the potential barrier and flip its orientation.
- Kimel, A. V. et al. Inertia-driven spin switching in antiferromagnets. Nat. Phys. 5, 727–731 (2009).

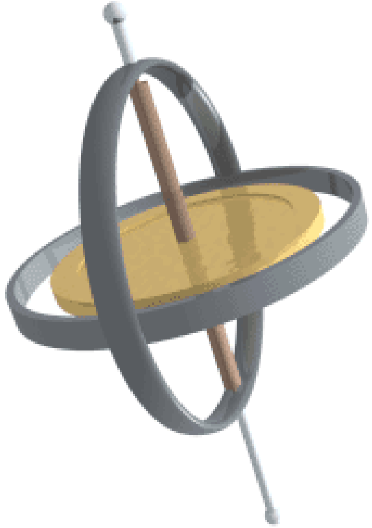


Spinning top

- We may find it is similar to spinning top
- What happenes if we think of this as a classical spinning top

  Nutation occurs when precession angular velocity is small
- So we considers the moment of inertia while solving the Landau–Lifshitz (LL) equation based on the classical analogue of a spinning top

  We can get iLLG equation

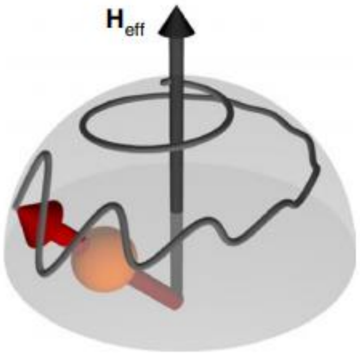


https://en.wikipedia.org/wiki/Top

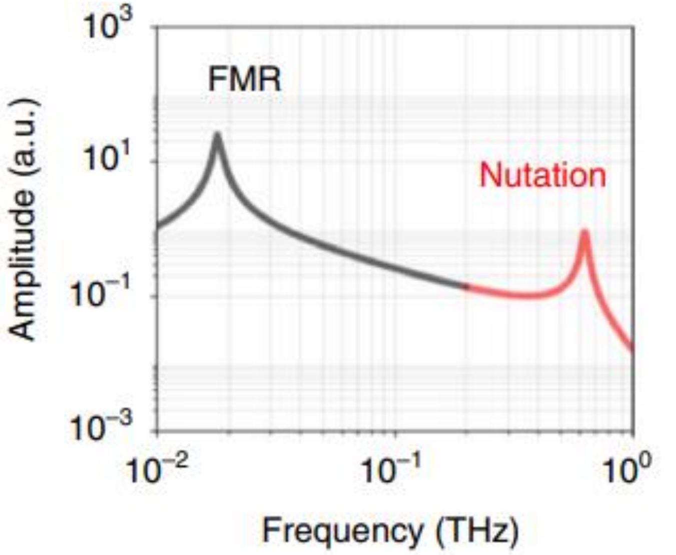
iLLG equation

iLLG equation:

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -|\gamma|\mathbf{M}\times\left[\mathbf{H}_{\mathrm{eff}} - \frac{\alpha}{|\gamma|M_{\mathrm{s}}}\left(\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} + \tau\frac{\mathrm{d}^2\mathbf{M}}{\mathrm{d}t^2}\right)\right]$$



considering the inertial formulation of the LLG equation



Yet to be observed experimentally

https://www.nature.com/articles/s41567-020-01040-y

Angular momentum relaxation time τ

- Simulations reveal that, on timescales shorter than the angular momentum relaxation time τ, nutation oscillations are present on top of the precession motion
- On timescales longer than τ, the usual LLG equation is recovered

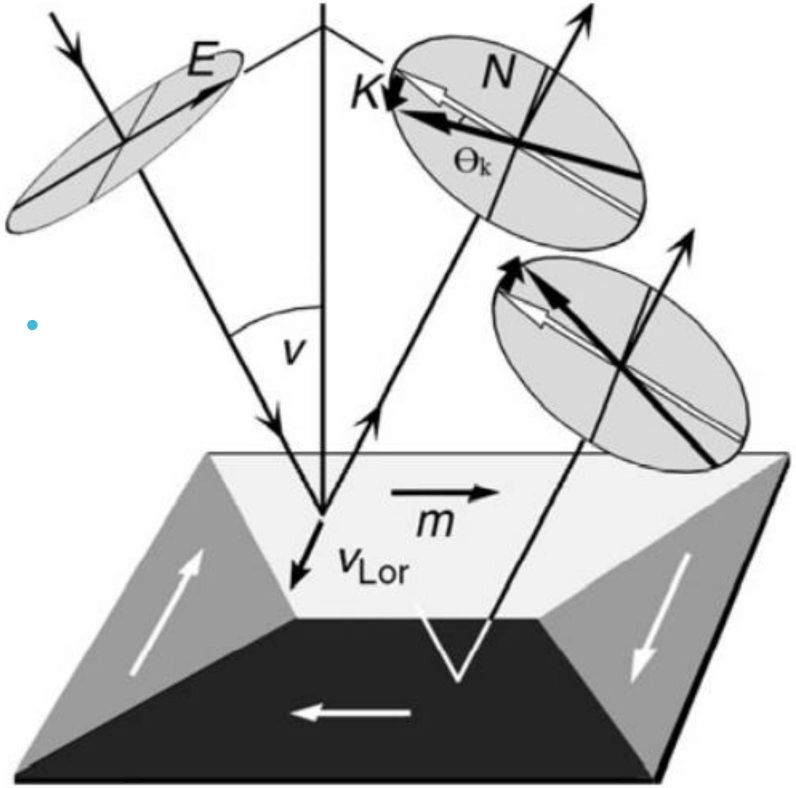
- How we know the value of τ

MOKE mythod

- We know the model of the magnetic torque dynamics of a ferromagnet.
- Then how we detect the magnetization

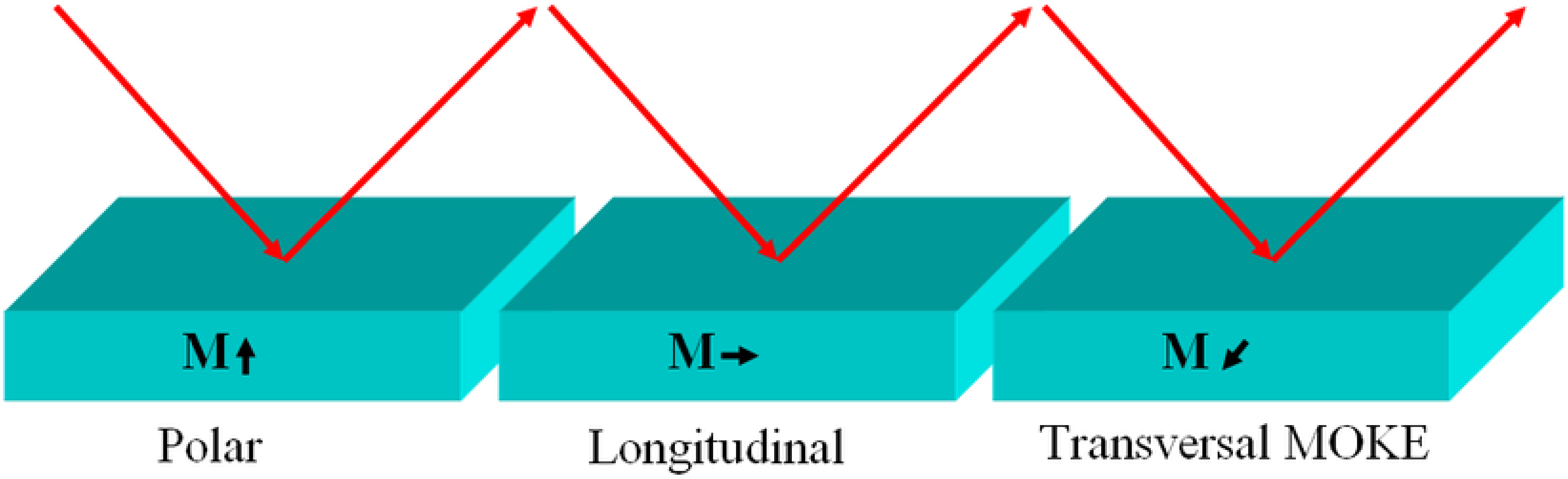
MOKE

- magneto-optic Kerr effect (MOKE)
- It describes the changes to light reflected from a magnetized surface. The magneto-optic Kerr effect relates light that is reflected from a magnetized surface and may change both polarization and reflected intensity.



- Kerr rotation θk

MOKE

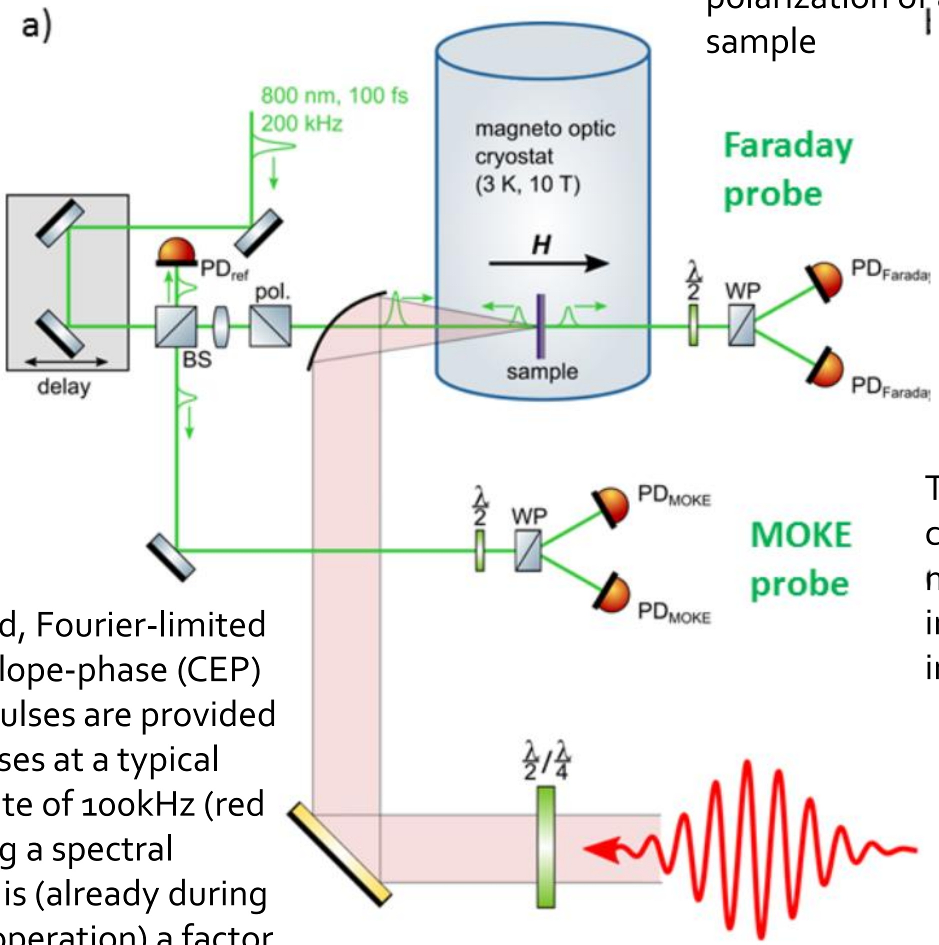


https://en.wikipedia.org/wiki/Magneto-optic_Kerr_effect

- MOKE can be further categorized by the direction of the magnetization vector with respect to the reflecting surface and the plane of incidence.
- Θ_k is proportional to **M**
- We can detect Θ_k to infer **M**

Device

synchronized femtosecond laser



Reflection from the surface of the sample
Magnetization changes modulate the polarization of a beam reflected off the sample

The polarization state changes with the change of magnetization， resulting in the change of light intensity

Narrow-band, Fourier-limited carrier-envelope-phase (CEP) stable THz pulses are provided as pump pulses at a typical repetition rate of 100kHz (red line), offering a spectral density that is (already during early stage operation) a factor of 30 higher than those available from laser-based, single-cycle THz pulses

https://iopscience.iop.org/article/10.1088/1361-6463/aaac75

Problem

- it is necessary to record these changes with femtosecond/picosecond resolution.
- How we attack this problem?

Device

Photo: J.-M. Schulter / dresden-luftfoto.de

TELBE facility in Dresden, Germany
intense and tunable narrowband terahertz magnetic fields can now be generated at superradiant electron sources

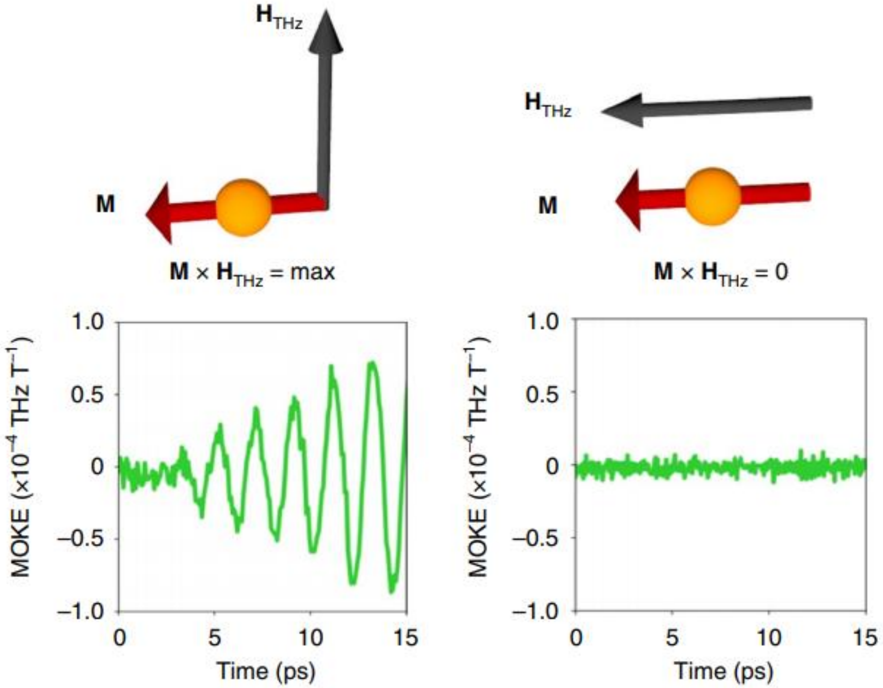
Normalization

m(t)=M(t)/Ms
Ignoring resonance effects can be simplified as:

$$m(t) = |\gamma| \int H_{\mathrm{THz}} \sin \omega t \ \mathrm{d}t = |\gamma| \frac{H_{\mathrm{THz}}}{\omega} \cos \omega t$$

This help us to simplify the MOKE graph

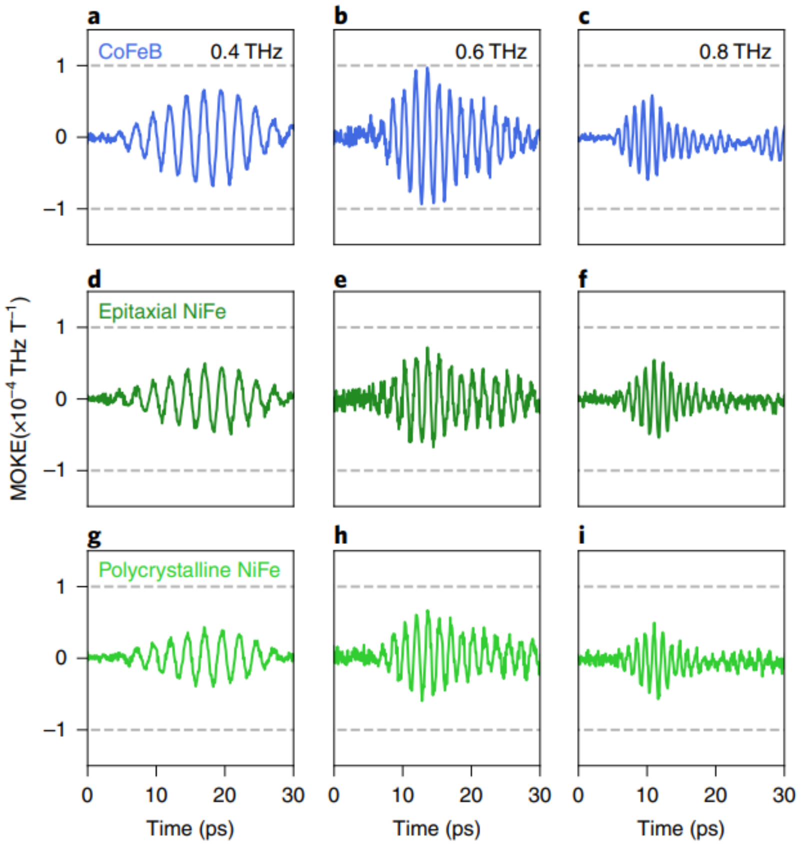
Experiment



Top: the geometrical configuration that maximizes the torque of H_{THz} on the magnetization M (that is, when they are orthogonal and parallel). Bottom: measured response from the polycrystalline NiFe sample in the maximum torque configuration and with a driving field centred at around 0.6 THz.

https://www.nature.com/articles/s41567-020-01040-y

Three samples



In all cases, a clear coherent response of the magnetization to the narrowband terahertz field is observed

absolute amplitudes should be compared only within the same sample at different frequencies, and not between different samples.

https://www.nature.com/articles/s41567-020-01040-y

Esitmate the value of τ

Nutation frequency

$$\omega_{\mathrm{n}} = \frac{\sqrt{1 + \alpha\tau|\gamma|H}}{\alpha\tau} \approx 1/\alpha\tau$$

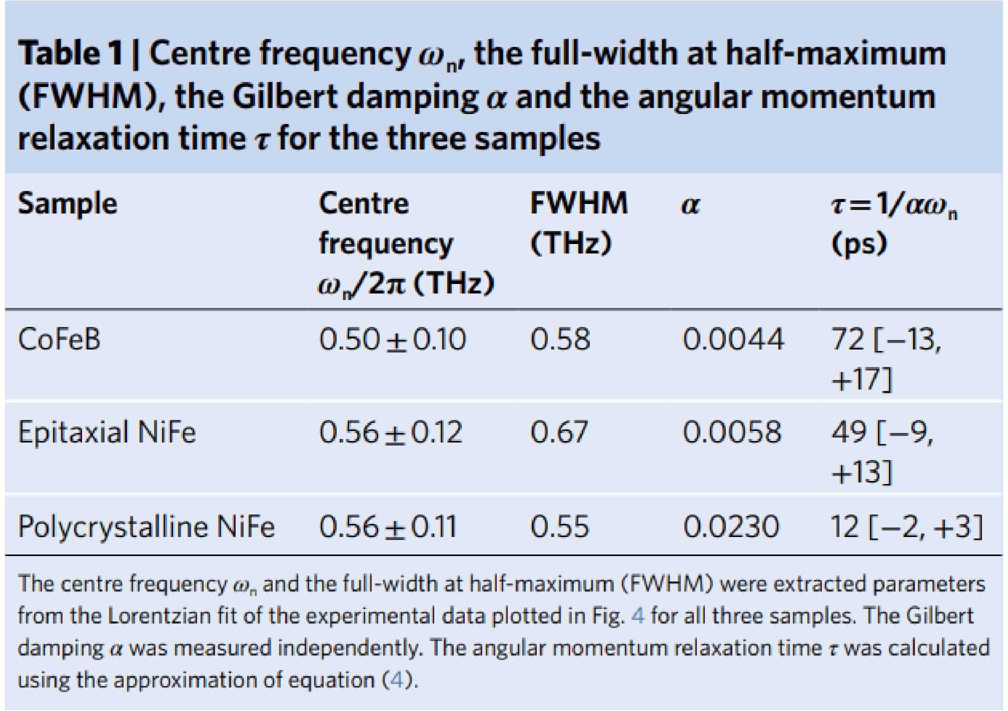


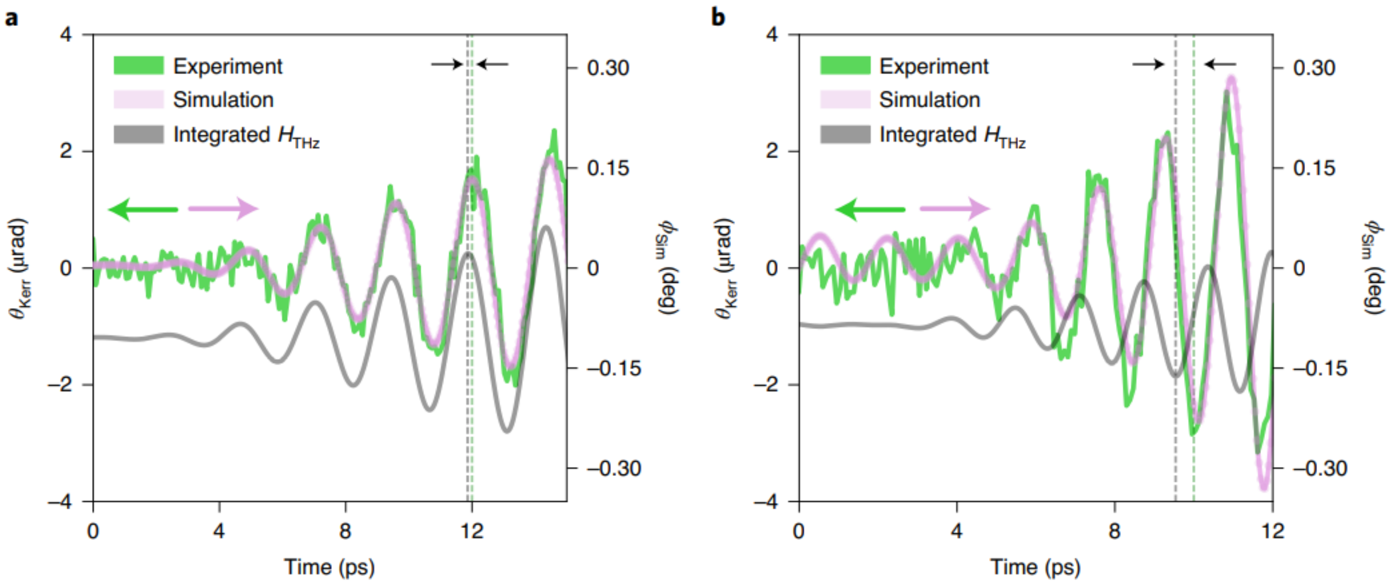
Table 1 | Centre frequency ω_n, the full-width at half-maximum (FWHM), the Gilbert damping α and the angular momentum relaxation time τ for the three samples

Sample	Centre frequency $\omega_n/2\pi$ (THz)	FWHM (THz)	α	$\tau = 1/\alpha\omega_n$ (ps)
CoFeB	0.50 ± 0.10	0.58	0.0044	72 [−13, +17]
Epitaxial NiFe	0.56 ± 0.12	0.67	0.0058	49 [−9, +13]
Polycrystalline NiFe	0.56 ± 0.11	0.55	0.0230	12 [−2, +3]

The centre frequency ω_n and the full-width at half-maximum (FWHM) were extracted parameters from the Lorentzian fit of the experimental data plotted in Fig. 4 for all three samples. The Gilbert damping α was measured independently. The angular momentum relaxation time τ was calculated using the approximation of equation (4).

https://www.nature.com/articles/s41567-020-01040-y

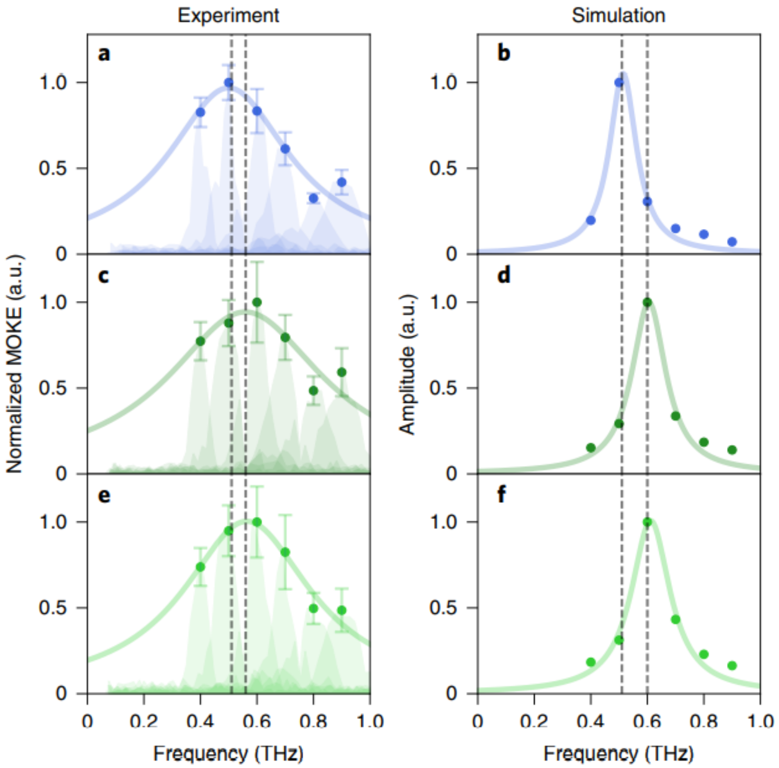
Resonance is present



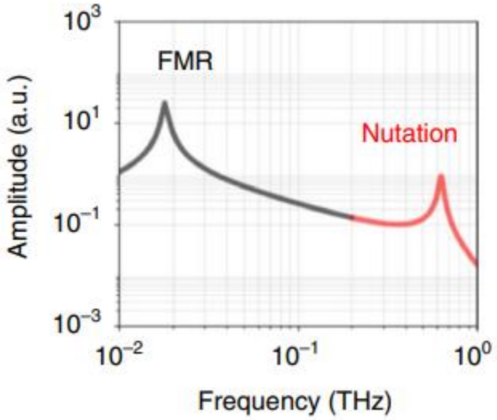
Effect of the driving field frequency on the phase of the response of the magnetization. a,b, Comparison of the phase-resolved MOKE response at 0.4-THz (a) and 0.6-THz (b) centre frequency of the terahertz magnetic field pulse for the polycrystalline permalloy film. Green curves: experimentally measured magneto-optical Kerr rotations, without the scaling described by equation (3). The absolute values of rotation for both frequencies are plotted on the left vertical axes. Pink curves: simulated response using the inertial LLG equation with τ= 11.3 ps and using the experimentally measured HTHz field amplitude. The right vertical axes show the simulated nutation angle. Grey curves: time integral of the experimental terahertz magnetic field HTHz. The vertical dashed lines illustrate the phase difference between the driving terahertz field and the magnetization dynamics.

https://www.nature.com/articles/s41567-020-01040-y

Relaxation time τ



Finally, we comment on the experimentally extracted values of τ of the order of 10–100ps.



Amplitude of the magnetization dynamics for narrowband terahertz fields. a,c,e, Symbols: experimentally measured maximum of the MOKE amplitude normalized according to equation (3) for CoFeB (a), epitaxial NiFe (c) and polycrystalline NiFe (e), respectively. The shaded curves represent the magnitude of the Fourier transform of the experimental traces at the different centre frequencies. Error bars represent the standard deviation of noise before the arrival of the terahertz pulse, first measured in absolute units and then scaled by the same amplitude with the signal. b,d,f, Calculated maximum magnetization response amplitudes solving the inertial LLG equation, corresponding to a, c and e. Solid lines: Lorentzian fit to the data points.

https://www.nature.com/articles/s41567-020-01040-y

Future

- If we have a better understanding of the fundamental mechanisms of ultrafast demagnetization and reversal, with implications for the realization of faster and more efficient magnetic data-processing and storage devices