PRECESSIONAL MAGNETIZATION DYNAMICS
(in the f- and t-domain)

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Hard disk: data rate road map


1 Gb/s
1 bit read in 1 ns
Magnetic time scales

100 yr → Recording stability
1 yr
1 hr
1 s
1 ms
10 ms
100 ns
1 ps
1 fs

100 yr
1 yr
1 hr
1 s
Superparamagnetic limit

Coherent dynamics
Creep

Viscous
Domain wall motion
Thermally assisted

Gilbert damping
GHz data rate

Precessional switching
Spin-lattice relaxation
Laser-induced (de)magnetization

Coherent dynamics
This Lecture

Introduction

Local dynamics: “Macro-spin” behavior

- From thermally-driven to precessional (LLG) dynamics
- Precessional modes in thin films (Kittel relation)
- Precessional switching

Measuring precessional dynamics

Nonlocal dynamics: Spin waves and confined structures

Summary
Statics ("macrospin", small particle)
Dynamic Coercivity

\[ M_x (T = 0, \text{arbitrary sweep time}) \]
\[ M_x (T = \text{finite, infinitely slow}) \]
\[ M_x (T = \text{finite, fast}) \]

Observed for:
- Small particles
- Domain wall “unpinning”
Spin precession

\[ z \text{ (= quantization axis)} \quad \Psi = (c_{\uparrow}, c_{\downarrow}) \quad |c_{\uparrow}|^2 + |c_{\downarrow}|^2 = 1 \]

\[ \Psi = \frac{1}{\sqrt{2}} (1, \exp(i\phi)) : \cos \phi \, x + \sin \phi \, y \]
\[ (1, 1)/\sqrt{2} : x (\cos(\theta/2), \sin(\theta/2)) : \cos \, z + \sin \theta \, x \]

Switching on a field along \( z \):

\[ \Psi(t) = (e^{iE_{\uparrow t}/\hbar} \cos \frac{\theta}{2}, e^{iE_{\downarrow t}/\hbar} \sin \frac{\theta}{2}) \]
\[ = \ldots (\cos \frac{\theta}{2}, e^{i\Delta E t/\hbar} \sin \frac{\theta}{2}) \]

precessing spin at frequency:

\[ \omega_L = \frac{\gamma \mu_0 H}{\hbar} \]
\[ \gamma \sim 10^{-4} \text{ eV/T} \]
\[ \hbar \sim 1 \text{ eV fs} \]
so, GHz
Landau-Lifshitz-Gilbert Eq.

\[ \frac{d\vec{M}}{dt} = \gamma \mu_0 \left( \vec{M} \times \vec{H}_{\text{eff}} \right) + \frac{\alpha}{M_s} \left( \vec{M} \times \frac{d\vec{M}}{dt} \right) \]

**Spin Precession**

**Damping**

\[ f_L = \frac{\gamma}{2\pi} \mu_0 H_{\text{eff}} \]

30 GHz / T

\( \alpha \approx 0.01 \)
Examples of Precessional Dynamics
A real experiment

dt = -1000 ps

Rietjens, Jozsa (TU/e)
The effective field =

Applied field +

Shape anisotropy:

\[ \vec{H}_{\text{eff}} = -\vec{N} \cdot \vec{M} \]

Thin film: \[ = -N_{zz} M_z \hat{z} = -\mu_0^{-1} M_z \hat{z} \]

Crystalline anisotropy:

\[ \vec{H}_{\text{eff}} = -\frac{1}{|\vec{M}|} \vec{\nabla} E_{\text{anis}} (\vec{M}) \]

Many shapes! (neglect it here)

Exchange:

\[ \vec{H}_{\text{eff}} = \frac{D}{M} \nabla^2 \vec{M} \]

Macro spin: \[ = 0 \]
Damping of precessional modes

Highly interesting and non-trivial...

... but let’s discuss it a next time...

But just let’s discuss spin-lattice relaxation in a “macroscopic” limit...

\[ L = -M \]

De Haas & Einstein (1918)
Kittel equation - Thin films

\[ H_{\text{eff}}(t) = H \hat{x} - M_z(t) \hat{z} \]

**assumption:** small amplitude
no damping

**solution:**
\[ M_y = \cos(\Omega t) \]
\[ M_z = \varepsilon \sin(\Omega t) \]

Just plug trial solution into LLG

\[ \varepsilon^2 = \frac{H}{H + M_s} < 1 \]

\[ \Omega = \gamma \sqrt{\frac{H}{H + M_s}} \]

...rather than \( \gamma H \)
\[ \vec{M} = M_s \hat{x} + M_y \hat{y} + M_z \hat{z} \]

\[ \vec{H}_{\text{eff}} = H \hat{x} - \mu_0^{-1} M_z \hat{z} \]

\[ \frac{d\vec{M}}{dt} = -\gamma \mu_0 \vec{M} \times \vec{H}_{\text{eff}} \]

\[ \frac{dM_y}{dt} = -\gamma \mu_0 \left( H + \mu_0^{-1} M_s \right) M_z \]

\[ \frac{dM_z}{dt} = -\gamma \mu_0 \left( -H \right) M_y \]

\[ i \omega = -\gamma \mu_0 \cdot i \varepsilon \left( H + \mu_0^{-1} M_s \right) \quad (a) \]

\[ -\varepsilon \omega = -\gamma \mu_0 \cdot -H \quad (b) \]

\[ i \omega = \left( -\gamma \mu_0 \right)^2 \frac{iH}{\omega} \left( H + \mu_0^{-1} M_s \right) \]

\[ i \frac{H}{\varepsilon} \left( -\gamma \mu_0 \right) = -\gamma \mu_0 \cdot i \varepsilon \left( H + \mu_0^{-1} M_s \right) \]

\[ \omega = \gamma \mu_0 \sqrt{H \left( H + \mu_0^{-1} M_s \right)} \]

\[ \varepsilon^2 = \frac{H}{H + \mu_0^{-1} M_s} \]
(Reversal by) Damping

with damping

solution:

\[ M_y = \cos(\omega t) \exp(-t/\tau) \]
\[ M_z = \varepsilon \sin(\omega t + \phi) \exp(-t/\tau) \]

\[ \tau = \frac{2(1 + \alpha^2)}{\alpha \gamma \mu_0 (2H + \mu_0^{-1} M_s)} \]

derive it yourself!

\[ \mu_0 H \gg M_s : \quad \omega \tau = \alpha^{-1} \approx 1/2\pi \alpha \text{ periods} \]
\[ \mu_0 H \ll M_s : \quad \tau = 2/\alpha \gamma M_s \approx 10 \text{ ps} / \alpha \]

Switching: \( \tau_s \gg 1 \text{ ns} \) for \( \alpha = 0.01 \)
Precessional switching

\[ H \]

\[ M(t) \]

\[ \tau_s = \frac{\pi}{\omega_L} = \frac{\pi}{\gamma \mu_0 H} \]

\[ M_s = 1 \text{ T} \]
\[ \gamma \mu_0 H = 0.01 \text{ T} \]
\[ \sim 1.5 \text{ ns} \]

\[ \tau_s \approx \frac{\pi}{\gamma \mu_0 \sqrt{H(H+M_s)}} \]

\[ \sim 150 \text{ ps} \]
Switching/NoSwitching diagrams

experiment

macrospin

theory

2 x 4 μm Permalloy
Schumacher et al.,
PRL 90, 017201 (2003)
Switching a real device

Homogeneous excitation, still strongly non-homogeneous response!!!

Due to:

- Non-homogeneous groundstate
- Excitation of spin waves

Thereby a slow relaxation...
Where are we...

Introduction

Local dynamics: “Macro

Measuring precessional dynamics

Frequency domain

Time domain

All-optical techniques

Nonlocal dynamics: Spin waves and confined structures

Outlook & Summary
Probing spin dynamics

Frequency domain techniques
- Ferromagnetic Resonance
- Brillouin Light Scattering

Time-domain techniques
- Using fast electronics (> 100 ps)
  - Real-time scheme
- Using short laser pulses (down to fs)
  - Stroboscopic techniques
  - Scanning approaches
- Specific case: Pulsed excitation
Ferromagnetic Resonance

Damping as well:

\[ \Delta \omega = \frac{d \omega_{res}}{dH} \Delta H \]

\[ \alpha = \frac{\Delta \omega}{\omega_{res}} \]
Brillouin Light Scattering

\[ \omega \pm \omega_M \]

\[ h\omega \sim 1 \text{ eV} \]
\[ h\omega_M \sim 10^{-4} \ldots 10^{-6} \text{ eV} \]

Hillebrands, U. Kaiserslautern, website
Time-Domain Techniques: Excitation

Magnetic field pulses (50 ps)

Electron bunches (~ ps)

Laser pulses (30 fs)

Or combinations thereof?

• Photo switches, Breaking Schottky barrier, ...
Real time: MR detection

free
NM
pinned

\( C_1 \)
\( C_2 \)

\( J_{\text{pulse}} \)
\( J_{\text{sense}} \)
\( H_{\text{pulse}} \)

5 x 2.3 \( \mu \text{m} \) Py/CoFe
Schumacher et al.,
PRL 90, 017204 (2003)

resolution \( \sim 100 \text{ ps} \)
Stroboscopic: Pump-probe Optics

MO rotation

laser pulses
~ 50 fs

polarized light

pump

probe

time delay

spin system

jitter < fs
pulses < 30 fs
Strob.: Pump-probe “Hybrid”

Electrically generated magnetic field pulses (100 ps)

Capabilities

- Vectorial resolution (4-quadrant detector)
- Time resolution 100 ps (“no limit” for fully optical)
- Spatial resolution (~ 400 nm, diffraction limit)
PIMM ("real time FMR")

Silva et al., JAP 85, 7849 (1999)
Where are we...

Introduction

Local dynamics: "Macro-spin" behavior

Measuring precessional dynamics

Frequency domain

Time domain

All-optical techniques

Nonlocal dynamics: Spin waves and confined structures

Outlook & Summary
A surprising experiment

Heating ferromagnetic Nickel with a 50 fs laser pulse

Beaurepaire et al.,
PRL 76, 4250 (1996)
Laser-induced Demagnetization

- Laser heating
- $\Delta T$
- $T_0$
- $\Delta M$

Diagram showing the processes of laser heating, temperature change, and magnetization change.
All-Optical Probing of Spin Precession


- $f = 9.98 \text{ GHz}$
- $\alpha = 0.05$
- $\Delta t [\text{ps}]$

Bert Koopmans, September 2005 Summerschool Constanta
Frequency vs. Time-Domain

\[ \Omega = \gamma \sqrt{H(H+M_s)} \]

van Kampen (TU/e), Phys. Rev. Lett. 2002
Where are we...

Introduction

Local dynamics: "Macro-spin" behavior

Measuring precessional dynamics

Nonlocal dynamics: Spin waves and confined structures

Exchange-driven: Perpendicular spin waves in thin films

Dipole-driven: Lateral spin waves

Laterally confined structures

Outlook & Summary
Sources of Non-homogeneous Response

**Exchange field + finite $k$**

\[ \lambda = \frac{2\pi}{k} \]

\[ \vec{H}_{\text{eff}} = \frac{D}{M} \nabla^2 \vec{M} \propto Dk^2 \]

**Dipole field + finite $k$**

\[ H_{\text{dip}}(k) \]

\[ d = \frac{\lambda}{2} \]

\[ \vec{H}_{\text{eff}} \propto \frac{1}{d} \propto k \]

**Refinement**

\[ k = n \frac{\pi}{L} \]
Spin Waves - Exchange driven

Using:

\[ \vec{M} = \vec{M}_0 + \delta \vec{M} \cdot e^{i(\vec{k} \cdot \vec{r} - \omega t)} \]

\[ \vec{H}_{\text{eff}} = \vec{H}_{\text{appl}} + \frac{D}{M} \nabla^2 \vec{M} = \vec{H}_{\text{appl}} + Dk^2 \frac{\delta \vec{M}}{M} \]

we find:

\[ \omega = \gamma \mu_0 \sqrt{(H + Dk^2)(H + Dk^2 + \mu_0^{-1} M_s)} \]

i.e., mode **stiffening**, independent of direction of wave vector

\[ D = 2JSa^2 \]

\[ \approx 1 \text{eV}a^2 \]
Standing Spin Waves

**Free surface:**

\[ \frac{d\delta \vec{M}}{dz} \bigg|_{\text{int}} = 0 \]

\[ \omega = \omega_0 + D \left( \frac{n\pi}{d} \right)^2 \]

**General:**

\[ \frac{d\delta \vec{M}}{dz} \bigg|_{\text{int}} + \frac{K_s}{D} \delta \vec{M} \bigg|_{\text{int}} = 0 \]

\[ \omega = \omega_0 + D \left( \frac{(n + \phi)\pi}{d} \right)^2 \]
All-Optically Probing Standing Spin-Waves

Inhomogeneous excitation/detection

\[ f = f_0 + \frac{a}{t^2} \]

frequency, \( f \) [Ghz]

thickness, \( t \) [nm]

\( \Delta M_z \) [%]

40 nm nickel

delay [ps]

Bert Koopmans, September 2005
Summerschool Constanta 38
Optically Probing Spin Waves: Analysis

Observed:

\[ \omega = \omega_0 + Dk^2 \]

Conclusions:

Boundary conditions: Free surface

\[ D = 0.44 \text{ eV}A^2 \] (as we expected)
And the amplitudes... (why no n = 2?)

Laser extinction depth ~ 15 nm
Artificial Spin-Chains: Basic Results

1d-Heisenberg system

\[ H = -J \vec{S}_i \cdot \vec{S}_{i+1} \]

300 nm pillars

H_{stray}

Kerr ellipticity [a.u.]

\begin{itemize}
\item measurement
\item fit
\item acoustical mode
\item optical mode
\end{itemize}

10x Py[3]
10x Al_{2}O_{3}[1.8]
Artificial Spin Chains: Analysis

Surprising! Mode with more nodes has lower frequency.

Negative dispersion...

Yes! System likes to be in anti-phase.
Spin waves – Dipole driven

Three sorts

\[ \omega = \gamma \mu_0 \sqrt{H \left( H + \mu_0^{-1} M_s \right)} \]

\[ \omega = \gamma \mu_0 H \]
**Magnetostatic Backward Volume Mode**

- **Just replace:** \( \mu_0^{-1} M_s \rightarrow \mu_0^{-1} M_s - kd \cdot A_{MBVM} \)

- **then:** \( \omega = \gamma \mu_0 \sqrt{H\left(H + \mu_0^{-1} M_s - kd \cdot A_{MBVM}\right)} \)

- **Limit of** \( kd >> 1 \): \( \omega = \gamma \mu_0 H \)

No stray field \( \Rightarrow \) No k-dep. restoring field
Magnetostatic Forward Volume Mode

• Now we get a stiffening, rather than a softening!

• Limit of \( kd \gg 1 \):

\[
\omega = \gamma \mu_0 \sqrt{H \left( H + \mu_0^{-1} M_s \right)}
\]
Magnetostatic surface mode (Damon-Eshbach)

- Now it gets complicated:
  - Softening during out-of-plane phase
  - Hardening during in-plane phase
- The latter is known to win...
Dipolar modes - Summary

\[ \gamma \mu_0 \sqrt{H(H + \mu_0^{-1} M_s)} \]

\[ \gamma \mu_0 H \]

\[ \omega \]

large \( k \): exchange, \( k^2 \)

Negative group velocity!

\[ v_g(k \to 0) \approx \frac{\gamma \mu_0 \sqrt{H\mu_0^{-1} M_s}}{2/d} \approx 180 \text{ GHz/T} \]

\[ 0.5 \text{ T} \approx \frac{1}{10 \text{ nm}} \approx 10^3 \text{ m/s} \]
Damping by Emission of Spin Waves

Strip line

Current pulse

MSSM

Excitation

$H_{\text{pulse}}$

MSSM

MSBVM

Excitation
Observation of localized modes

Perzlmaier, PRL 94, 057202 (2005)
Link with lateral spin waves

TR-MOKE
μ-BLS

Positive dispersion: “MSSM”

Negative dispersion: “MSBVM”

2.1 GHz 2.4 GHz

4.0 GHz 5.5 GHz 7.1 GHz
Dynamics of Real Devices

Rietjens (TU/e) – Boeve (Philips Research) et al., APL submitted
Dephasing after homogeneous excitation

Raster scans at fixed time delay (50 ps steps)

Different frequency and damping at edges
Results: Time domain

Positions of time scans

Lower frequency, higher damping

EDGES Same frequency, higher damping
Results: Frequency domain

Comparing simulations with experiment

- Graph showing frequency domain with x-position from -4 to 4 µm, and frequency from 0 to 4 GHz.
- Two plots comparing strayfield and no strayfield conditions.
- Graphs for strayfield and no strayfield conditions are labeled accordingly.
Final analysis

Bias field dependence of uniform and localized mode

![Graph showing bias field dependence of uniform and localized mode.](image)
Summary

Local dynamics: “Macro-spin”
- LLG equation
- Kittel relation for thin films
- Precessional Switching

Measuring precessional dynamics
- In the f- and t-domain (including “all-optical”)

Nonlocal dynamics: Spin waves and confined structure
- Exchange modes
- Dipolar modes (positive and negative dispersions!)
- Manifestation in confined structures
- Complicated dynamics in “real” devices
wow
it's fast...

it switched!
it should!
why would it?

it didn't
it cannot
why not?

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BOOM

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I

H

T

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