From magnetic resonance to nanomagnonics: reprogrammable spin wave flow in nanostructured magnets

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Books

Contents (in cgs)/graphs from:

[1]

Graphs also from:

[2]

Further reading:
Contents

Motivation: why spin dynamics (magnonics) from an experimental point of view?

From magnetic susceptibility to ferromagnetic resonance (FMR)

Effective magnetic field

Spin waves in the long wavelength limit

Spin-wave transmission through a reprogrammable 1D magnonic crystal

Spin-wave based electronics/Magnonics - Motivation

Control and manipulation of microwave signals on microscopic scales:
periodically modulated magnetic systems give rise to
(i) grating coupler effect
   (H. Yu et al., Nature Commun. 4, 2702 (2013))
(ii) tailored band structures for spin waves
From piezoelectrics to magnonics

GHz electric field is transferred into an elastic deformation: surface acoustic wave (SAW)

Signal speed: few km/s

Different “transducers” for spin waves:
- coplanar waveguides with GHz magnetic field

Broadband spectroscopy at GHz frequencies

We measure scattering parameters.
Landau-Lifshitz-Gilbert equation \( \text{(SI)} \): the fundamental equation of magnonics

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

\( \vec{H}_{\text{int}} \) contains different (effective) fields:
- applied dc field \( H \)
- demagnetization field \( H_{\text{demagnetization}} \) (shape)
- anisotropy fields (spin-orbit coupling)
- exchange field (interaction \( A_{\text{ex}} \))
- microwave magnetic field \( h_{\text{rf}} \)

- The equation holds on different length scales.

How spins are excited

Static spin orders
From EoM to high-frequency magnetic susceptibility (cgs)

We start from
\[
\frac{\partial \mathbf{H}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H} \quad [I]
\]
and assume \( \mathbf{H} = \mathbf{H}_0 + \mathbf{H}_m \), \( \mathbf{M} = \mathbf{M}_0 + \mathbf{M}_m \) \( [II] \)
with \( h_m \ll h_0 \), \( m_m \ll M_0 \)

1) \( [II] \) in \( [I] \) are approximation:
if only steady components are considered:
\( \mathbf{M}_0 \times \mathbf{H}_0 = 0 \) \( [III] \)

→ this equation provide the equilibrium direction of
the magnetization:
\( \mathbf{M}_0 \parallel \mathbf{H}_0 \); \( \mathbf{H}_0 \) : internal magnetic field

From EoM to high-frequency magnetic susceptibility

2) first approximation, neglecting products of \( \mathbf{H}_0 \) and \( \mathbf{H}_m \) in \( [II] \):
\[
\frac{\partial \mathbf{M}}{\partial t} + \gamma \mathbf{M} \times \mathbf{H}_0 - \gamma \mathbf{H}_m \times \mathbf{H}_0 = 0 \quad [IV]
\]

Assume a harmonic (sinusoidal) time dep. of \( \mathbf{H}_m \),
due to linearization also \( \mathbf{m}_m \) will be harmonic
\( \mathbf{m}_m = m \exp \{i \omega t\} \)
\( \mathbf{H}_m = h \exp \{i \omega t\} \) (complex variable)

\( m, h \) satisfy:
\[
i \omega m + \gamma \mathbf{M} \times \mathbf{H}_0 = -\gamma \mathbf{H}_m \times \mathbf{H}_0 \quad [V]
\]
Components of susceptibility tensor

\[
\begin{align*}
\vec{\chi} &= \begin{pmatrix}
\chi_x & i\chi_y & 0 \\
-i\chi_y & \chi_x & 0 \\
0 & 0 & 0
\end{pmatrix} \\
M &= \begin{pmatrix} X \end{pmatrix} \vec{h}_d
\end{align*}
\]

- Symmetric second rank tensor

Gyrotropy

- \( h_t \) does not produce the ac susceptibility.
- \( h_\perp \) produces an ac susceptibility \( \chi \) having a phase shift of \( \pi / 2 \)

This property is called \textbf{gyrotropy}

and due to the nonsymmetry of \( \vec{\chi} \)
Analysis of tensor components: Resonant behavior

Ferromagnetic resonance (FMR)

Resonant permeability

\[
\begin{align*}
\mu &= \frac{\sigma}{\omega} + \mu_0 \chi \\
\mu &= 1 + \chi_T \chi_a \\
\mu &= \omega \chi_T \chi_a \\
\mu &= \mu_0 + \chi_a
\end{align*}
\]

[1]
Equation of Motion: model system

\[ \frac{d\vec{M}}{dt} = -\gamma \mu_0 (\vec{M} \times \vec{H}_{int}) \]

\( M \) is the sum of microscopic \( m \)

\[ \vec{M} = M_1 \hat{r}_1 + \cdots + M_N \hat{r}_N \]

EoM provides a resonant behavior, with frequencies typically in the GHz frequency regime and beyond.

From classical physics:
Angular momenta \( \vec{L} \) vary if a torque \( \vec{\Theta} \) is present

\[ \frac{d\vec{L}}{dt} = \vec{\Theta} = \vec{r} \times \vec{F} \]

Note: All relevant torques need to be considered (acting on all atoms).

Sepp Kressierer, Technische Universität München
Movie at: [https://www.av.ph.tum.de/Experiment/1000/Film/1306.php](https://www.av.ph.tum.de/Experiment/1000/Film/1306.php)
For comparison

Gravitation

Later on: Relaxation due to damping
Field dependence of resonance in isotropic Ni$_{80}$Fe$_{20}$

Further kind of magnetic anisotropy

Model:

- Easy axis
- Hard axis

Magnetocrystalline anisotropy:

Anisotropy of exchange interaction due to spin orbit interaction: since the shape of atomic electron shells or charge in exchange energy (Smith et al.)
How to consider in EoM? Effective fields (Landau/Lifshitz)

Example:

\[ H_y = \frac{1}{2} \frac{\partial U}{\partial M_y} = -\frac{\delta U}{\delta M_y} + \sum_{k=1}^{2} \frac{2}{(2kM)^2} \frac{\partial U}{\partial M_y} \]

Variational derivative of energy \( U \)

Note: 1) the dc (ac) part of \( U_{ac} \) does not (does) enter the EoM
2) \( H_{ef} \) exhibits dc and ac contributions

How about time-dependent and spatially inhomogeneous \( H_{ef} \)?

Excitation of spin waves

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

electron spins precess at their given position

Solution of EoM for a thin film:

Spin wave modes in the long-wavelength limit

Adapted from: B. Hillebrands, U Kaiserslautern, Germany

Limiting values extracted from Herring-Kittel formula valid for unrestricted geometry:

$$2\pi v = \frac{\gamma}{\epsilon + i \frac{M^2}{\rho_{\text{eff}}}} + \frac{\alpha}{\beta} + \frac{\gamma}{\beta} + \frac{\alpha}{\beta} + \frac{\gamma}{\beta} + \frac{\alpha}{\beta} + \frac{\gamma}{\beta}$$
Different restoring forces

Adapted from: B. Hillebrands, U Kaiserslautern, Germany

Example: ferromagnetic thin film of CoFeB

Example: ferromagnetic thin film of CoFeB


Spin wave transmission

Transmission through 40 air gaps

- Propagation length: 12 µm (across about 40 air gaps)
- Relaxation time: ~1.2 ns
- Group velocity: 4 km/s
- Frequency: 6.9 GHz

Parameters extracted from fitting* (red):


Spin wave dispersion relation:

Quantized spin waves first reported:

In densely packed array: miniband formation by dynamic dipolar interaction

Reconfigurable artificial crystal for spin waves


Field-controlled band-stop filter

Spin-wave based electronics/Magnonics

Control, transmission and manipulation of GHz signals on microscopic scales


Review on reconfigurable devices: