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

Dirk Grundler

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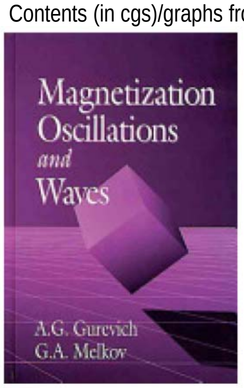
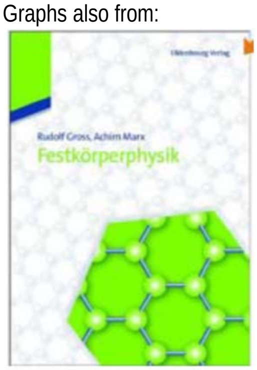
Books

Contents (in cgs)/graphs from:



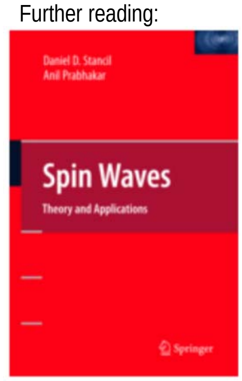
[1]

Graphs also from:



[2]

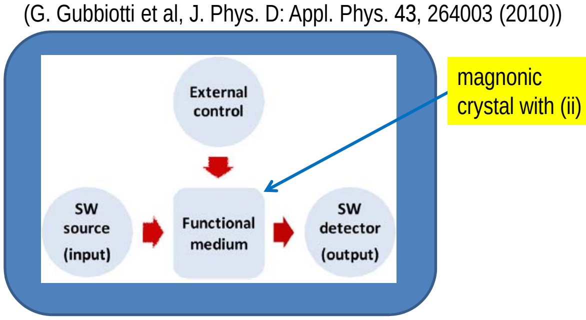
Further reading:



Contents

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
(G. Gubbiotti et al, J. Phys. D: Appl. Phys. 43, 264003 (2010))

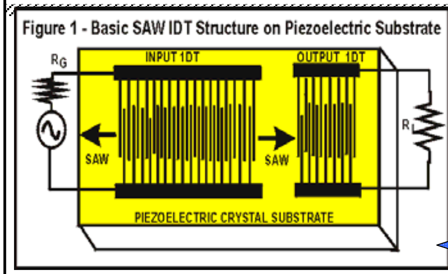


J. Phys. D: Appl. Phys. 43, 264001 (2010)

Internet of Things

@2020: > 24 billion devices interconnected wirelessly

From piezoelectrics to magnonics

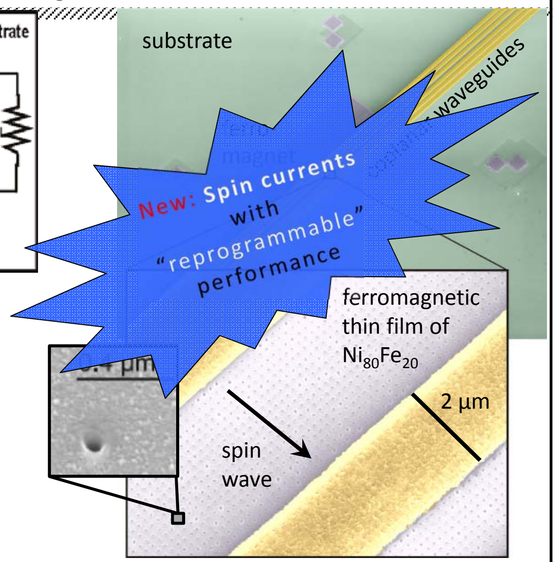


http://www3.sympatico.ca/colin.kydd.campbell/

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

Signal speed: few km/s

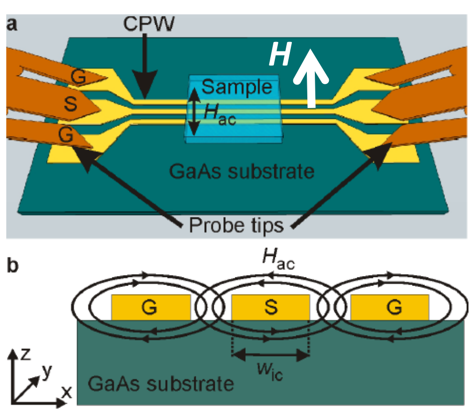
Different "transducers" for spin waves:
coplanar waveguides with
GHz **magnetic** field



2D magnonic crystal

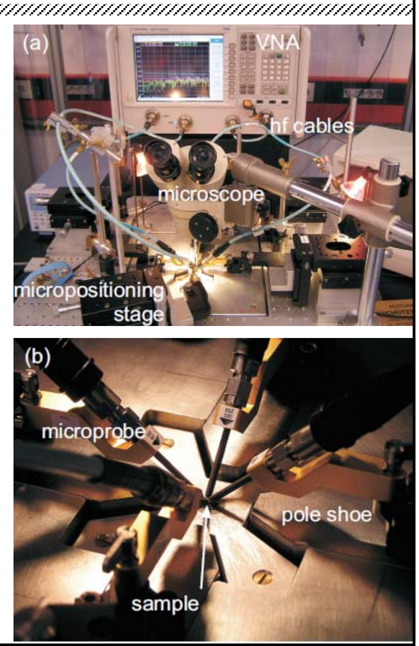
S. Neusser, PhD thesis, TU Munich (2011)

Broadband spectroscopy at GHz frequencies



T. Schwarze, PhD thesis, TU Munich (2013)

We measure
scattering
parameters.

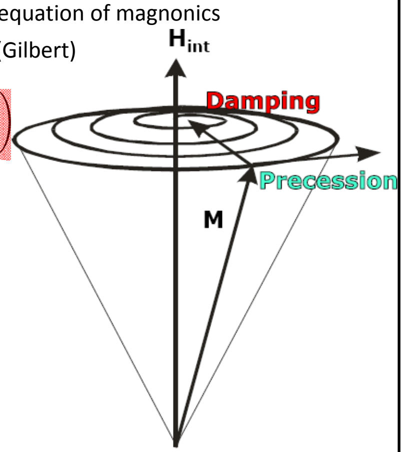


How spins are excited

Landau-Lifshitz-Gilbert equation (SI): the fundamental equation of magnonics

gyromagnetic factor — damping constant α (Gilbert)

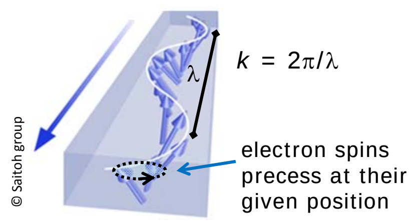
$$\frac{d\vec{M}(t)}{dt} = -|\gamma|\mu_0\left(\vec{M}(t)\times\vec{H}_{int}(t)\right) + \frac{\alpha}{M_S}\left(\vec{M}\times\frac{d\vec{M}(t)}{dt}\right)$$

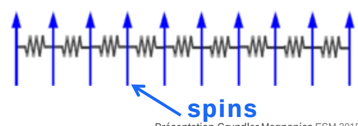


H_{int} contains different (effective) fields:

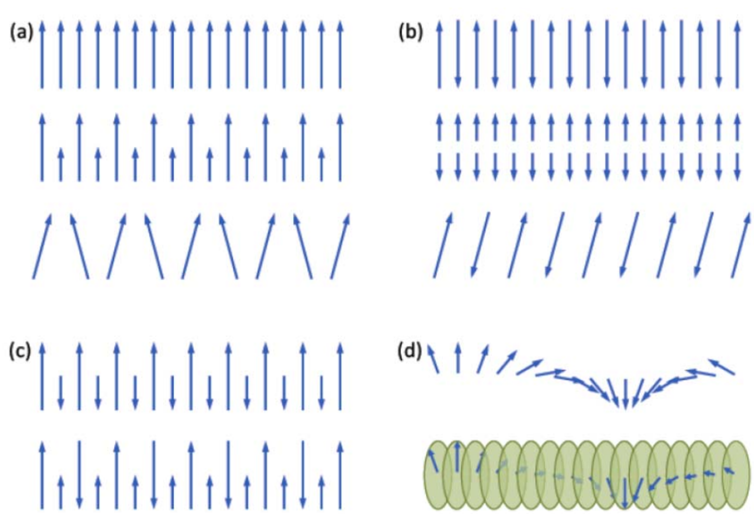
- applied dc field H
- demagnetization field $H_{demagnetization}$ (shape)
- anisotropy fields (spin-orbit coupling)
- exchange field (interaction A_{ex})
- microwave magnetic field h_{rf}

- **The equation holds on different length scales.**





Static spin orders



[2]

From EoM to high-frequency magnetic susceptibility (cgs)

We start from $\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}$ [II]

and assume $\vec{H} = \vec{H}_0 + \vec{h}_\sim$, $\vec{M} = \vec{M}_0 + \vec{m}_\sim$ [III]

with $h_\sim \ll H_0$ $m_\sim \ll M_0$

1) [III] in [II] zero approximation:

if only steady components are considered: $\vec{M}_0 \times \vec{H}_0 = 0$ [IV]

⇒ this equation provides the equilibrium direction of the magnetization: $\vec{M}_0 \uparrow\uparrow \vec{H}_0$ H_0: internal magnetic field

From EoM to high-frequency magnetic susceptibility

2) first approximation: neglecting products of ac quantities and considering [IV]

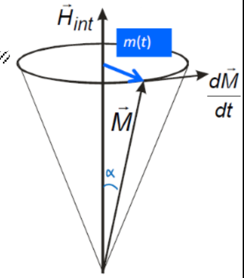
$$\frac{\partial \vec{m}_\sim}{\partial t} + \gamma \vec{m}_\sim \times \vec{H}_0 = -\gamma \vec{M}_0 \times \vec{h}_\sim$$ linearization of EoM [V]

• assume a harmonic (sinusoidal) time dep. of $\vec{h}_\sim$, due to linearization also $\vec{m}_\sim$ will be harmonic

$\tilde{m} = m \exp\{i\omega t\}$ $\tilde{h} = h \exp\{i\omega t\}$ (complex variables)

m, h satisfy: $i\omega m + \gamma m \times \vec{H}_0 = -\gamma \vec{M}_0 \times \vec{h}$ [Vb]

Components of susceptibility tensor



we assume $\vec{H}_0, \vec{M}_0 \parallel \vec{e}_z$

$$\Rightarrow \quad \begin{aligned} i\omega m_x + \gamma H_0 m_y &= \gamma M_0 h_y \\ -\gamma H_0 m_x + i\omega m_y &= -\gamma M_0 h_x \\ i\omega m_z &= 0 \end{aligned}$$

Solution: (Polder, 1949)

$m_x = \chi h_x + i\chi_a h_y \qquad m_y = -i\chi_a h_x + \chi h_y \qquad m_z = 0$

with

$$\chi = \frac{\gamma M_0 \omega_H}{\omega_H^2 - \omega^2} \qquad \chi_a = \frac{\gamma M_0 \omega}{\omega_H^2 - \omega^2} \quad [VI] \qquad \omega_H = \gamma H_0$$

$m = \overleftrightarrow{\chi} h$

non-symmetric second rank tensor

$$\overleftrightarrow{\chi} = \begin{pmatrix} \chi & i\chi_a & 0 \\ -i\chi_a & \chi & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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Gyrotropy

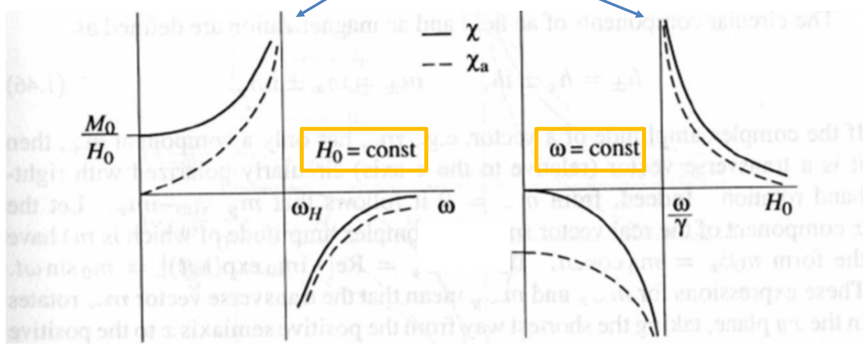
- h_z does not produce the ac magnetization
- $h_\perp$ produces m parallel to $h_\perp$ and perpendicular to it having a phase shift of $\frac{\pi}{2}$ ("i")

this property is called GYROTROPY and due to the nonsymmetry of $\overleftrightarrow{\chi}$

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Analysis of tensor components: Resonant behavior

Ferromagnetic resonance (FMR)



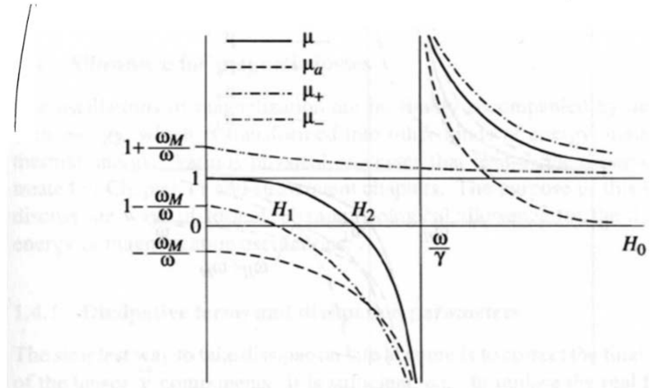
[1]

Resonant permeability

$\overleftrightarrow{\mu} = \overleftrightarrow{I} + 4\pi \overleftrightarrow{\chi}$ (cgs) $\mu = 1 + 4\pi\chi = \frac{\omega_H(\omega_H+\omega_M) - \omega^2}{\omega_H^2 - \omega^2}$ $\mu_a = 4\pi\chi_a = \frac{\omega\omega_M}{\omega_H^2 - \omega^2}$

unit tensor with $\omega_M = \gamma 4\pi M_0$

$$\overleftrightarrow{\mu} = \begin{vmatrix} \mu & i\mu_a & 0 \\ -i\mu_a & \mu & 0 \\ 0 & 0 & 1 \end{vmatrix}$$

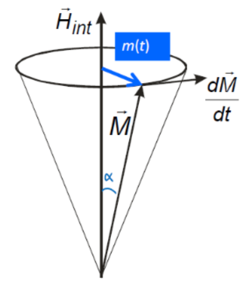


[1]

Equation of Motion: model system

$$\frac{d\vec{M}}{dt} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}_{int}\right)$$

Landau, Lifshitz



M is the sum of microscopic *m*

= sum of quantum-mechanical angular momenta (spins)

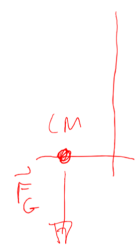
$$\vec{M} = -\gamma\hbar\vec{J}\cdot N$$

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

From classical physics:
Angular momenta *L* vary if a torque Θ is present

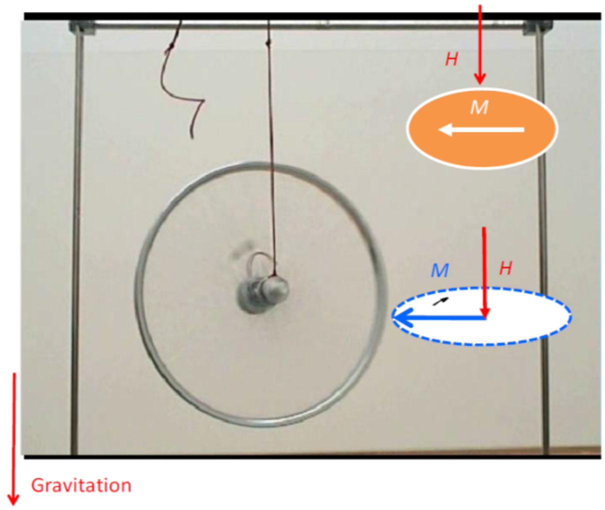
$$\frac{d\vec{L}}{dt} = \vec{\Theta} = \vec{r}\times\vec{F}$$

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



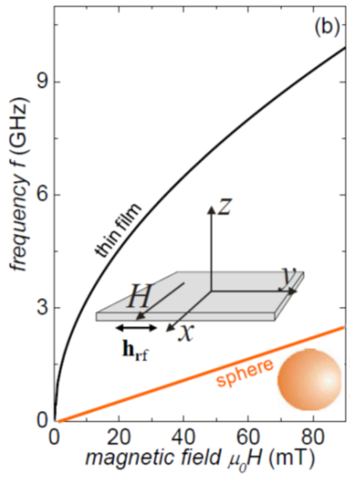
Sepp Kressierer, Technische Universität München
Movie at: https://www.av.ph.tum.de/Experiment/1000/Film/1306.php

For comparison



Later on: Relaxation due to damping

Field dependence of resonance in isotropic $Ni_{80}Fe_{20}$



Kittel formula of FMR

$$\omega_0 = \gamma \sqrt{\left(H_{ext,0} + (N_x - N_z) M_0\right)\left(H_{ext,0} + (N_y - N_z) M_0\right)}$$

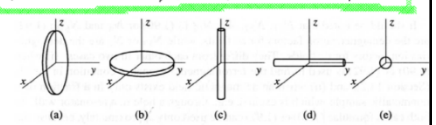


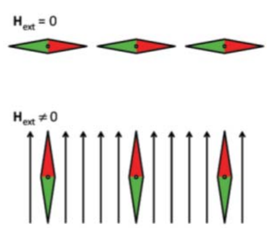
FIGURE 1.9
Limiting cases of an ellipsoid.

Sample	Magnetization direction	See Fig. 1.9	Demagnetization factors N_x	N_y	N_z	Eigenfrequency
Infinitely thin plate	Tangential	(a)	0	4π	0	$\left(\frac{\omega_0}{\gamma}\right)^2 = H_{e0}(H_{e0}+4\pi M_0)$
	Normal	(b)	0	0	4π	$\frac{\omega_0}{\gamma} = H_{e0}-4\pi M_0$
Infinitely thin cylinder	Longitudinal	(c)	2π	2π	0	$\frac{\omega_0}{\gamma} = H_{e0}+2\pi M_0$
	Transverse	(d)	2π	0	2π	$\left(\frac{\omega_0}{\gamma}\right)^2 = H_{e0}(H_{e0}-2\pi M_0)$
Sphere		(e)	$\frac{4\pi}{3}$	$\frac{4\pi}{3}$	$\frac{4\pi}{3}$	$\frac{\omega_0}{\gamma} = H_{e0}$

Shape anisotropy

Further kind of magnetic anisotropy

Model:



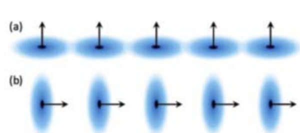
easy axis

[2]

hard axis

Magnetocrystalline anisotropy:

Anisotropy of exchange interaction due to spin-orbital interaction:
turns of spins change the shapes of atomic electron shells
⇒ change in exchange energy ("orbital overlap")



[2]

How to consider in EoM? Effective fields (Landau/Lifshitz)

EFFECTIVE FIELD

$$\vec{H}_{ef} = -\frac{\delta U}{\delta \vec{M}} = -\frac{\partial U}{\partial \vec{M}} + \sum_{p=1}^{3} \frac{\partial}{\partial x_p}\left[\frac{\partial U}{\partial(\partial \vec{M}/\partial x_p)}\right]$$

Variational derivative of energy U

Example: Energy for anisotropic ferromagnet: $U = U_{ex} + U_{mg} + U_{an}$

exchange, Zeeman (in internal field), anisotropy

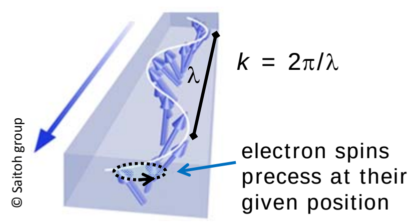
Eq. of equilibrium: $\vec{M}_0 \times \vec{H}_{ef,0} = 0$

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{ef} + \vec{R}$$

Note: 1) the dc (ac) part of U_{ex} 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



$k = 2\pi/\lambda$

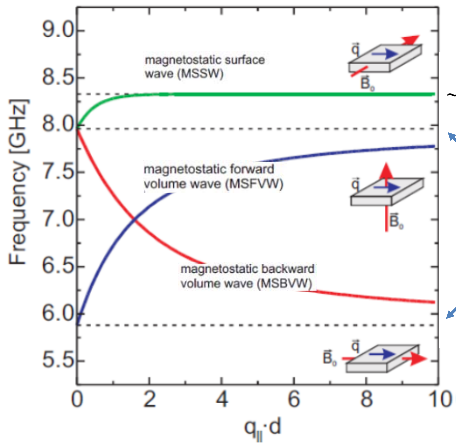
electron spins precess at their given position

Solution of EoM for a thin film:

B. Kalinikos and A. Slavin: *Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions*, J. Phys. C **19**, 7013 (1986).

Spin wave modes in the long-wavelength limit

Adapted from: B. Hillebrands, U Kaiserslautern, Germany

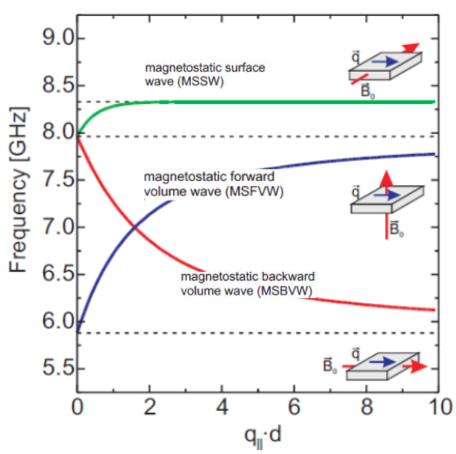


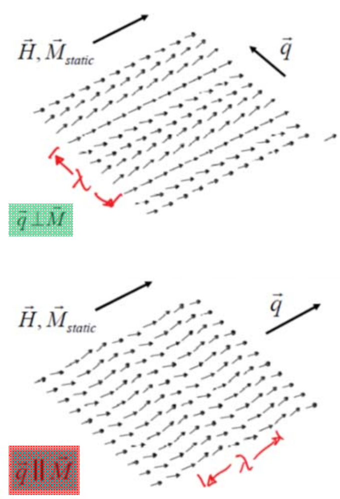
~ Damon-Eshbach mode

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

$$2\pi\nu = \gamma\left[\left(H+\frac{2A}{M_s}q^2\right)\left(H+\frac{2A}{M_s}q^2+4\pi M_s\sin^2\theta_q\right)\right]^{1/2}$$

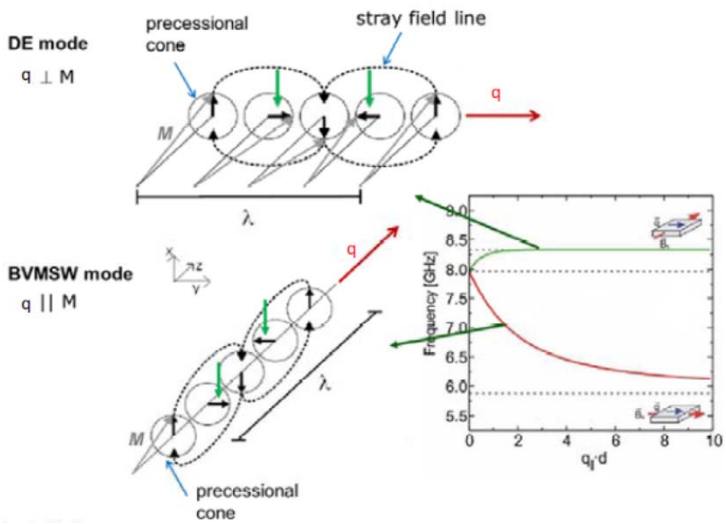
Spin wave modes in the long-wavelength limit





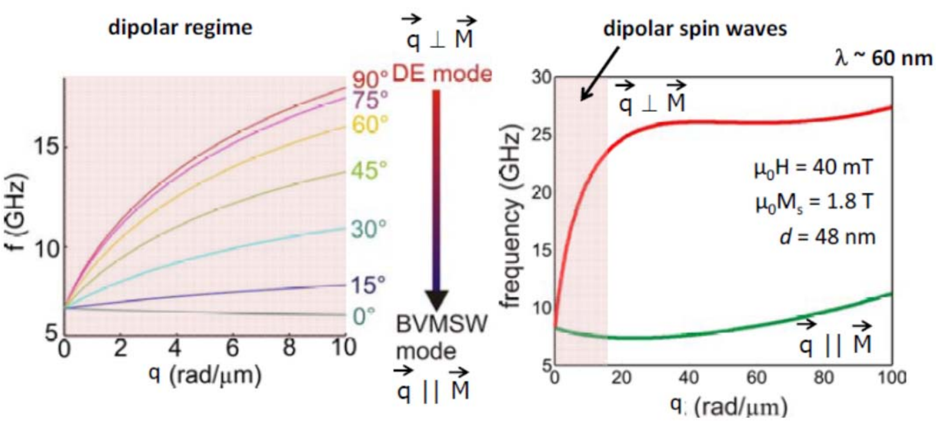
Adapted from: B. Hillebrands, U Kaiserslautern, Germany

Different restoring forces



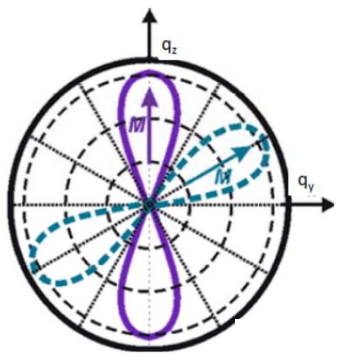
Adapted from: B. Hillebrands, U Kaiserslautern, Germany

Example: ferromagnetic thin film of CoFeB

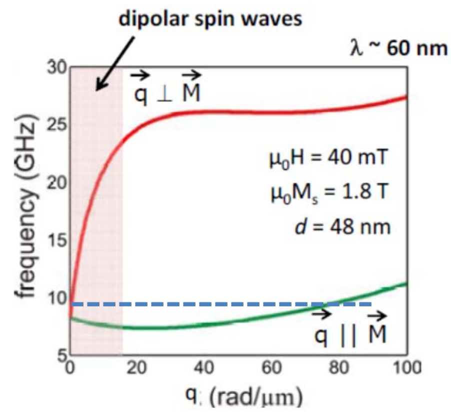


B. Kalinikos and A. Slavin: *Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions*, J. Phys. C **19**, 7013 (1986).

Example: ferromagnetic thin film of CoFeB

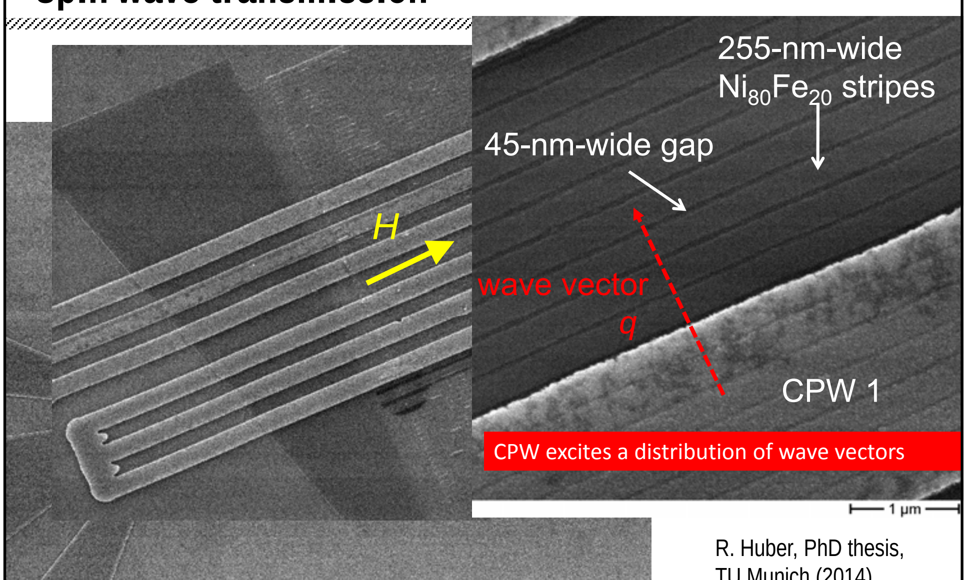


isofrequency contours



B. Kalinikos and A. Slavin: *Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions*, J. Phys. C **19**, 7013 (1986).

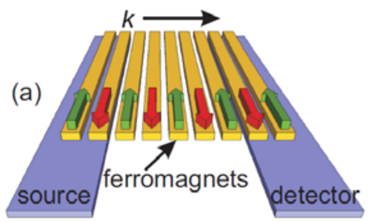
Spin wave transmission



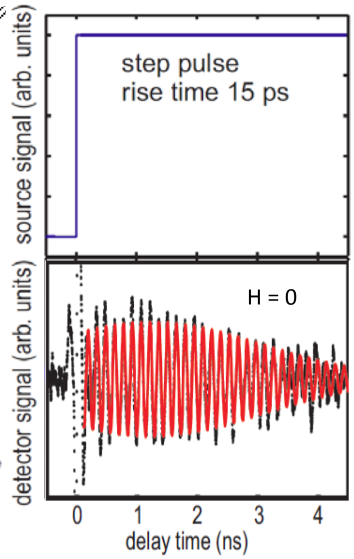
R. Huber, PhD thesis, TU Munich (2014)

Transmission through 40 air gaps

propagation length:
12 µm
(across
about 40 air gaps)



G. Duerr et al.,
J. Phys.: Condens. Matter **24**, 024218 (2012)

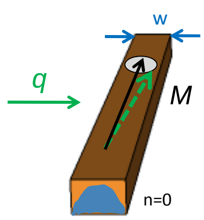


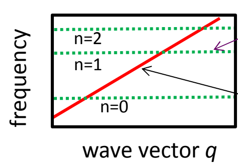
Parameters extracted from fitting* (red):

relaxation time: ~ 1.2 ns
group velocity: 4 km/s
frequency: 6.9 GHz

*M. Covington et al., Phys. Rev. Lett. 89, 237202 (2002).

Spin wave dispersion relation:





quantized modes with different numbers n of nodes

Dipolar spin wave for plain $Ni_{80}Fe_{20}$ (Py) film at $\vec{q} \perp \vec{M}$

Quantized spin waves first reported:
C. Mathieu et al., Phys. Rev. Lett. **81**, 3968 (1998).

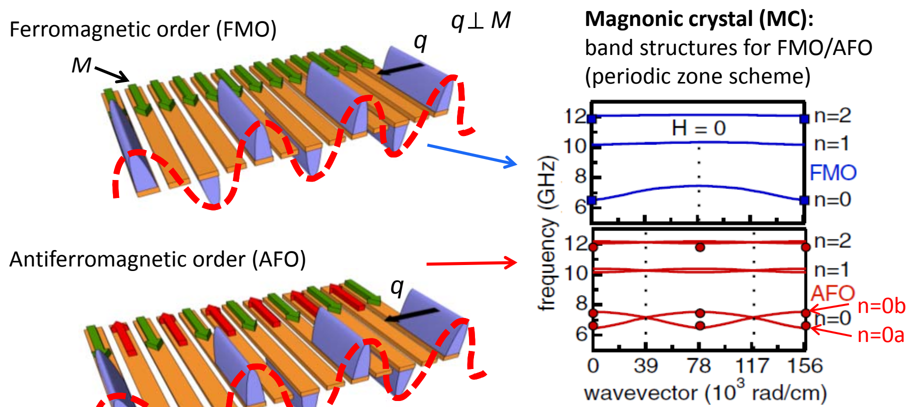
In densely packed array : miniband formation by dynamic dipolar interaction

G. Gubbiotti *et al.*, Appl. Phys. Lett. **90**, 092503 (2007).

Reconfigurable artificial crystal for spin waves

J. Topp et al., Phys. Rev. Lett. **104**, 207205 (2010)

Magnonic crystal (MC):
band structures for FMO/AFO
(periodic zone scheme)



Pure Appl. Chem., Vol. 83, No. 11, pp. 1989–2001, 2011.
doi:10.1351/PAC-CON-11-03-06
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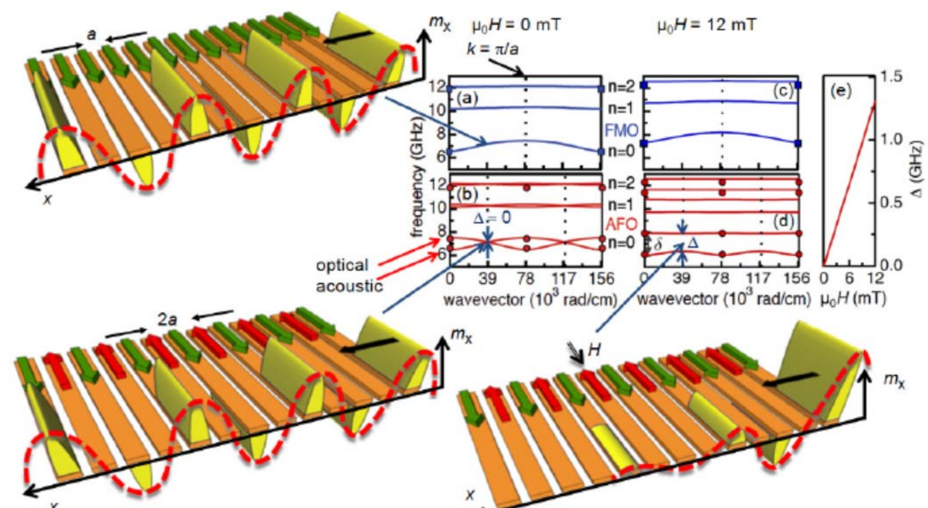
Reprogrammable magnonic crystals formed by interacting ferromagnetic nanowires*

Jesco Topp[1], Georg Duerr[2], Klaus Thurner[2], and Dirk Grundler[2,‡]

Field-controlled band-stop filter

M. Krawczyk and D.Grundler,
J. Phys.: Condens. Matter 26, 123202 (2014)

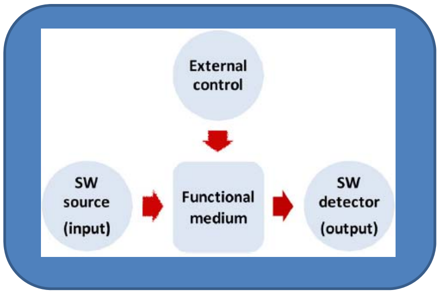


Reconfigurable 1D magnonic crystals (exp.):
S. Tacchi et al., Phys. Rev. B **82**, 184408 (2010);
J. Ding et al., Phys. Rev. Lett. **107**, 047205 (2011).

Reconfigurable 2D magnonic crystals (theory):
J. Shibata et al., Phys. Rev. B **70**, 012404 (2004);
R. Verba et al., Phys. Rev. B **85**, 014427 (2012).

Spin-wave based electronics/Magnonics

Control, transmission and manipulation of GHz signals on microscopic scales



J. Phys. D: Appl. Phys. 43, 264001 (2010)

Review on reconfigurable devices:
M. Krawczyk and D.G.,
J. Phys.: Condens. Matter 26, 123202 (2014)

Présentation Grundler Magnonics ESM 2015 33