ADAM MICKIEWICZ UNIVERSITY IN POZNAŃ

Faculty of Physics

Nonreciprocal properties of GHz frequency surface spin waves in nanopatterned ferromagnetic films

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Microwave and Radar Week MRW 2016

MIKON 2016 - 21st International Conference on Microwaves, Radar and Wireless Communications, May 9-11

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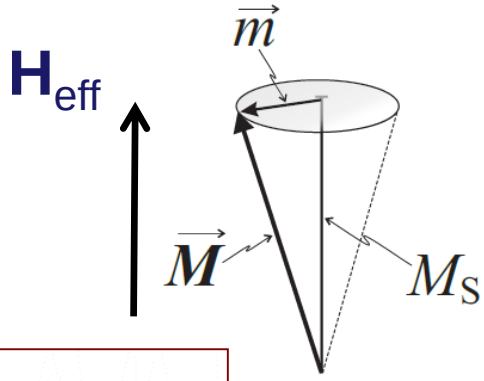
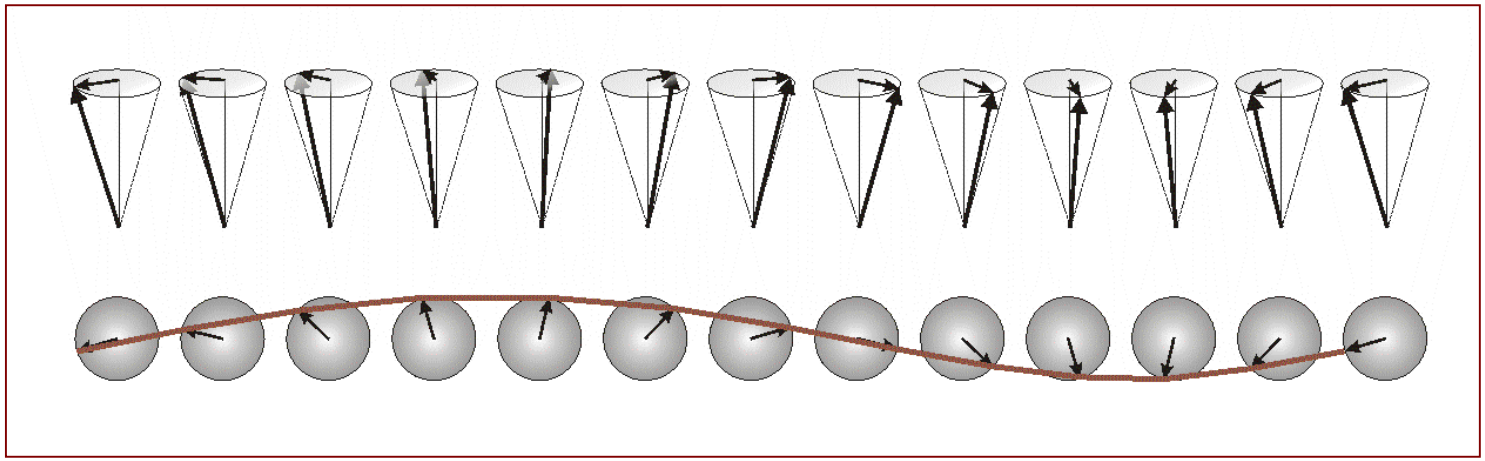
Outline

- ❑ Spin waves, magnonics and motivation
- ❑ Damon-Eshbach waves
- ❑ Magnonic crystals and non-reciprocal SW dispersion relation
- ❑ Surface character of the DE waves in 1D MCs
- ❑ Nonreciprocity of the SW excitations

Spin-waves (magnons)





Landau-Lifshitz-Gilbert equation:

$$\frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t} = \gamma\mu_0 \mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{\text{eff}}(\mathbf{r},t) + \frac{\alpha}{M_S}\left(\mathbf{M} \times \frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t}\right)$$

+ Maxwell equations

+ linear approximation.

Methods

Micromagnetic simulations

mumax^3 – GPU accelareted micromagnetism

Arne Vansteenkiste et al., *The design and verification of mumax3*, AIP Advances **4**, 107133 (2014).

Plane wave method

linear approximation, homogeneous magnetization, decomposition of solutions into the plane waves with taken into acount Bloch theorem

M. Krawczyk et al., *Magnonic band structures in two-dimensional bi-component magnonic crystals with in-plane magnetization*, J. Phys. D: Appl. Phys. **46**, 495003 (2013).

Analytical models

Linear approximation, homogeneous magnetization, homogeneous materials

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

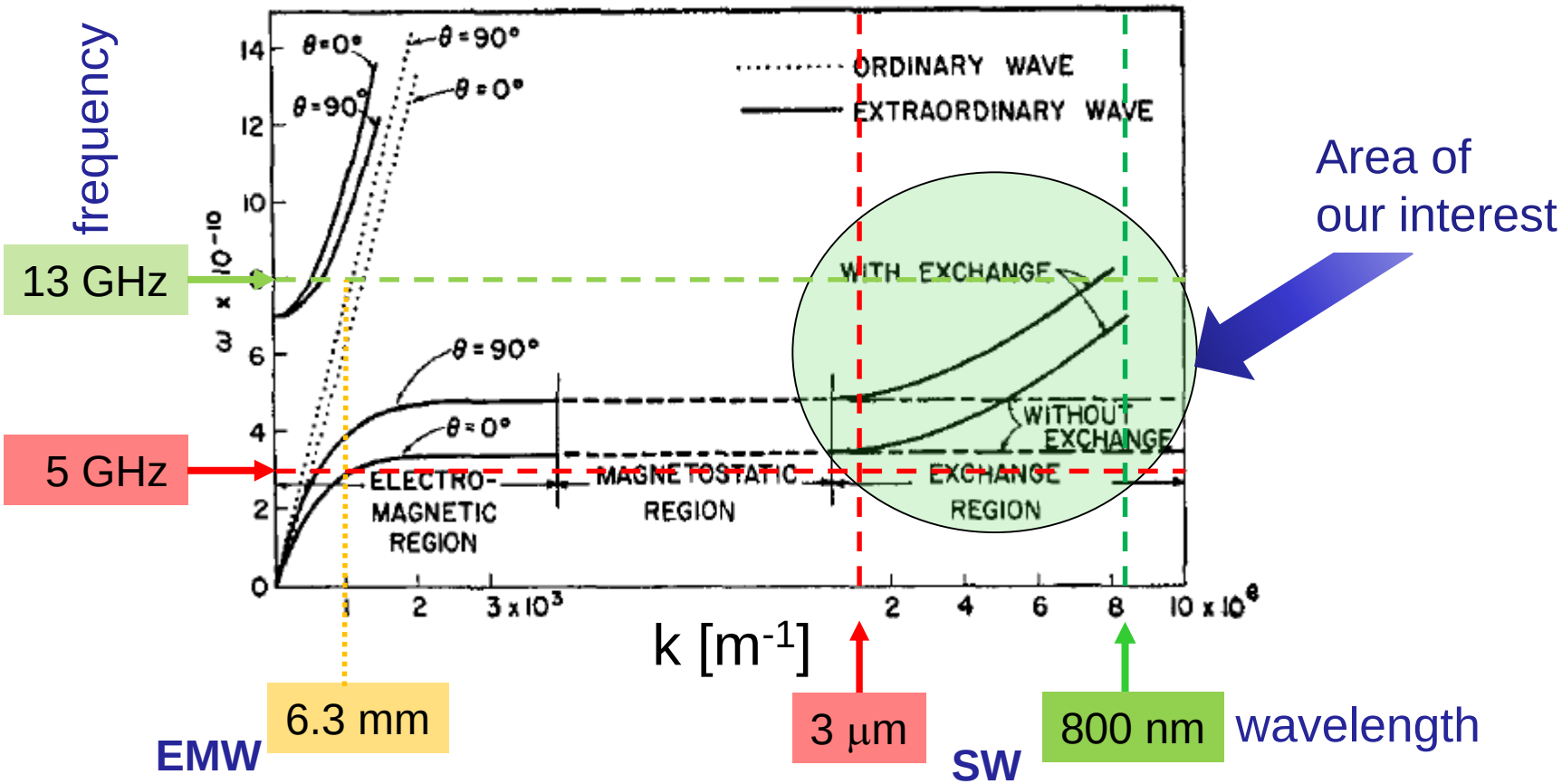
V. V. Kruglyak, et al., *Magnetization boundary conditions at a ferromagnetic interface of finite thickness*, J. Phys.: Condens. Matter **26** 406001 (2014).

Electromagnetic FEM

CST Microwavestudio, COMSOL Multiphysics

Spin wave spectrum in a bulk ferromagnet

$$\omega = \omega(\mathbf{k})$$

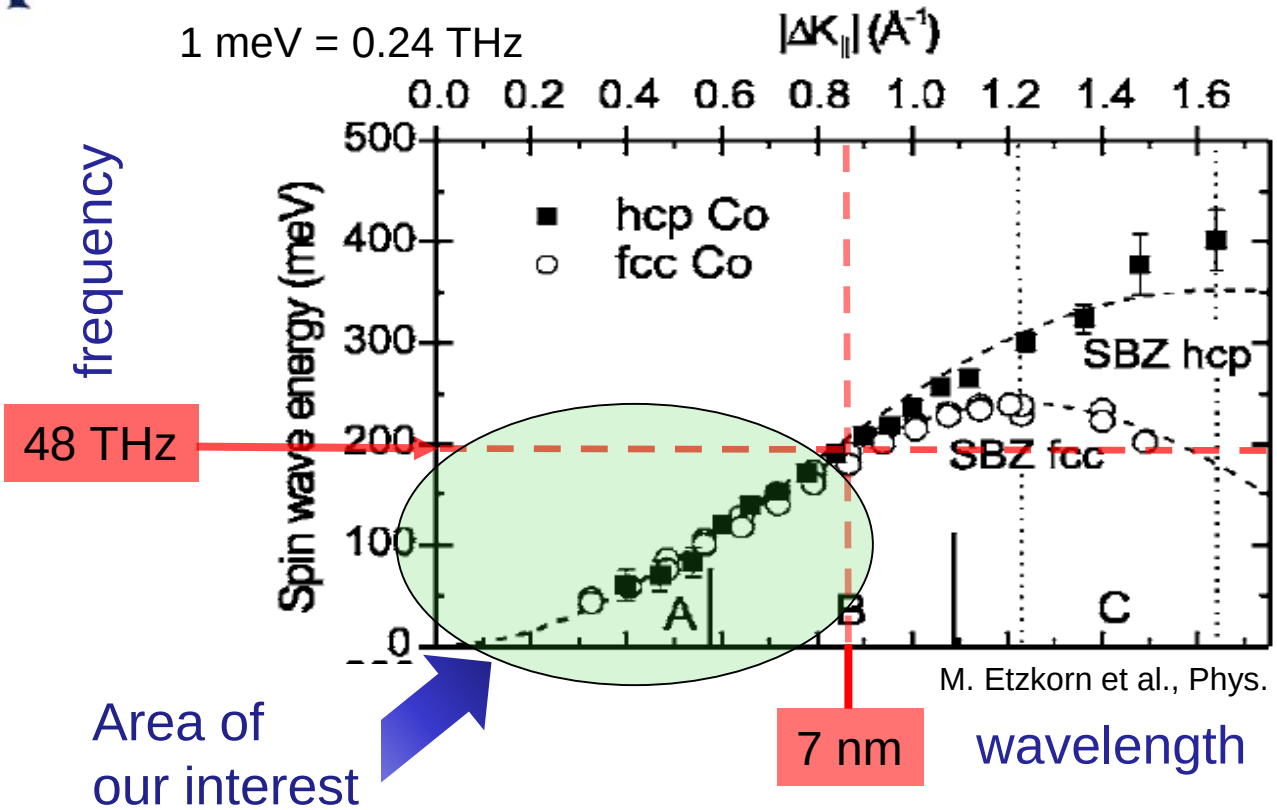


B.A. Auld, *Walker modes in large ferrite samples*, J. Appl. Phys. **31**, 1642 (1960).

Short wavelength limit of spin waves

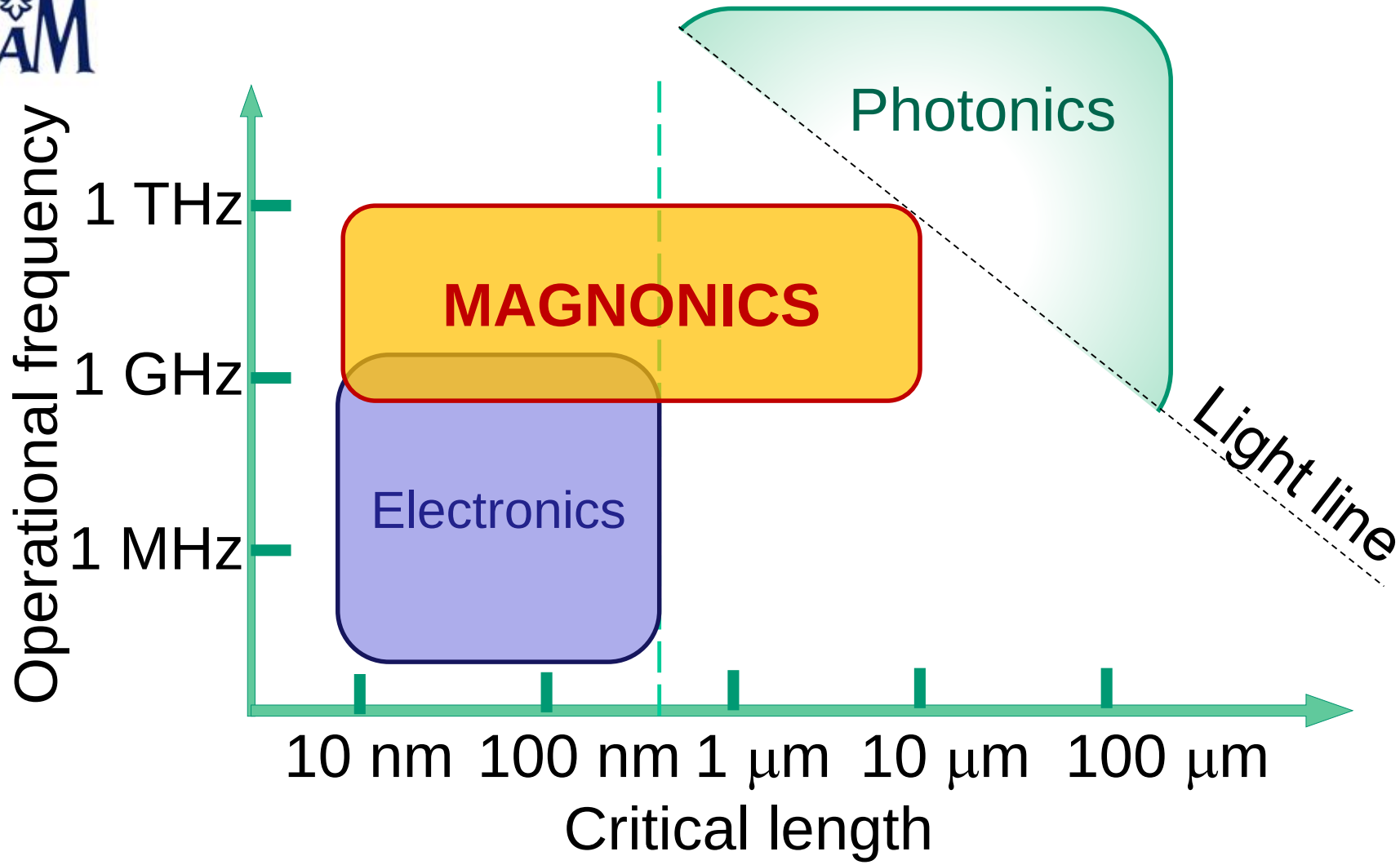
SPEELS on 8 ML of Co on W (hcp) or Cu (fcc).

1 meV = 0.24 THz

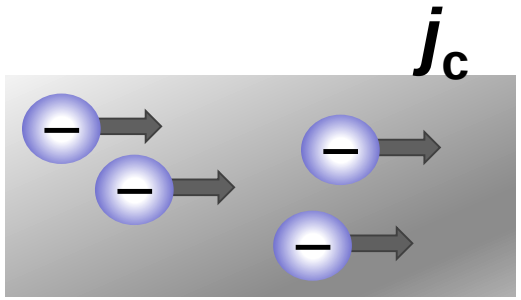


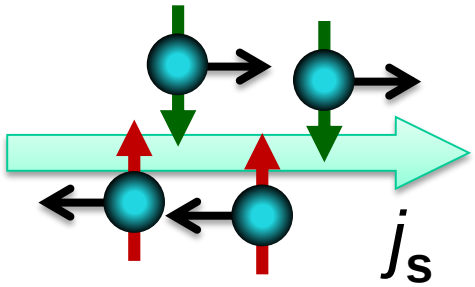
M. Etzkorn et al., Phys. Rev B 72, 184420 (2005).

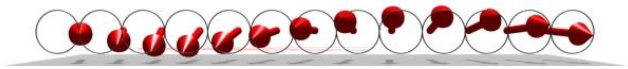
45 THz EMW has a wavelength of 6.7 μm


Photonics
MAGNONICS
Electronics
Light line
Operational frequency
1 THz
1 GHz
1 MHz
10 nm
100 nm
1 μm
10 μm
100 μm
Critical length

Energy consumption





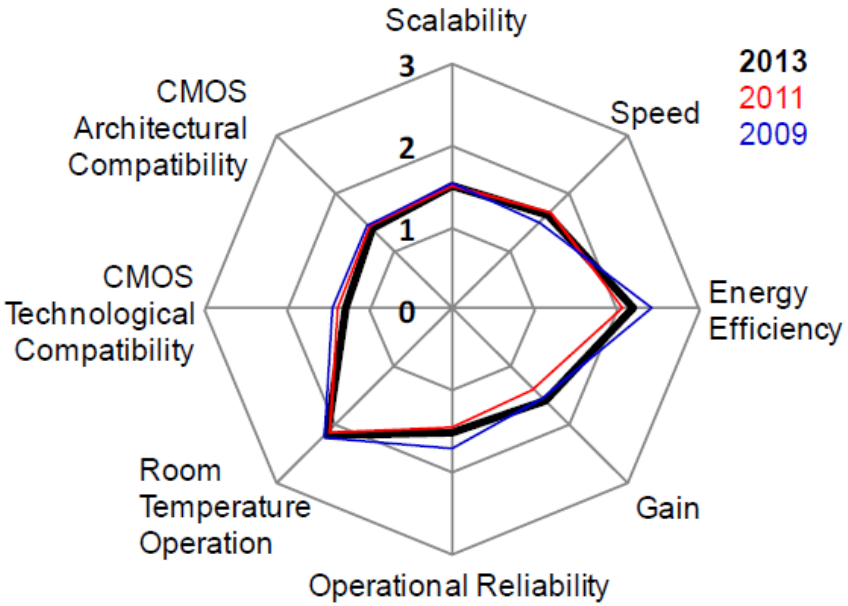


Electronics	Spintronics	Magnonics
Charge of electron	**Spin** of electron	**Magnon**

-
-
-
-

Transport without charge

Evaluation – Logic non-charge



INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS

2013 EDITION

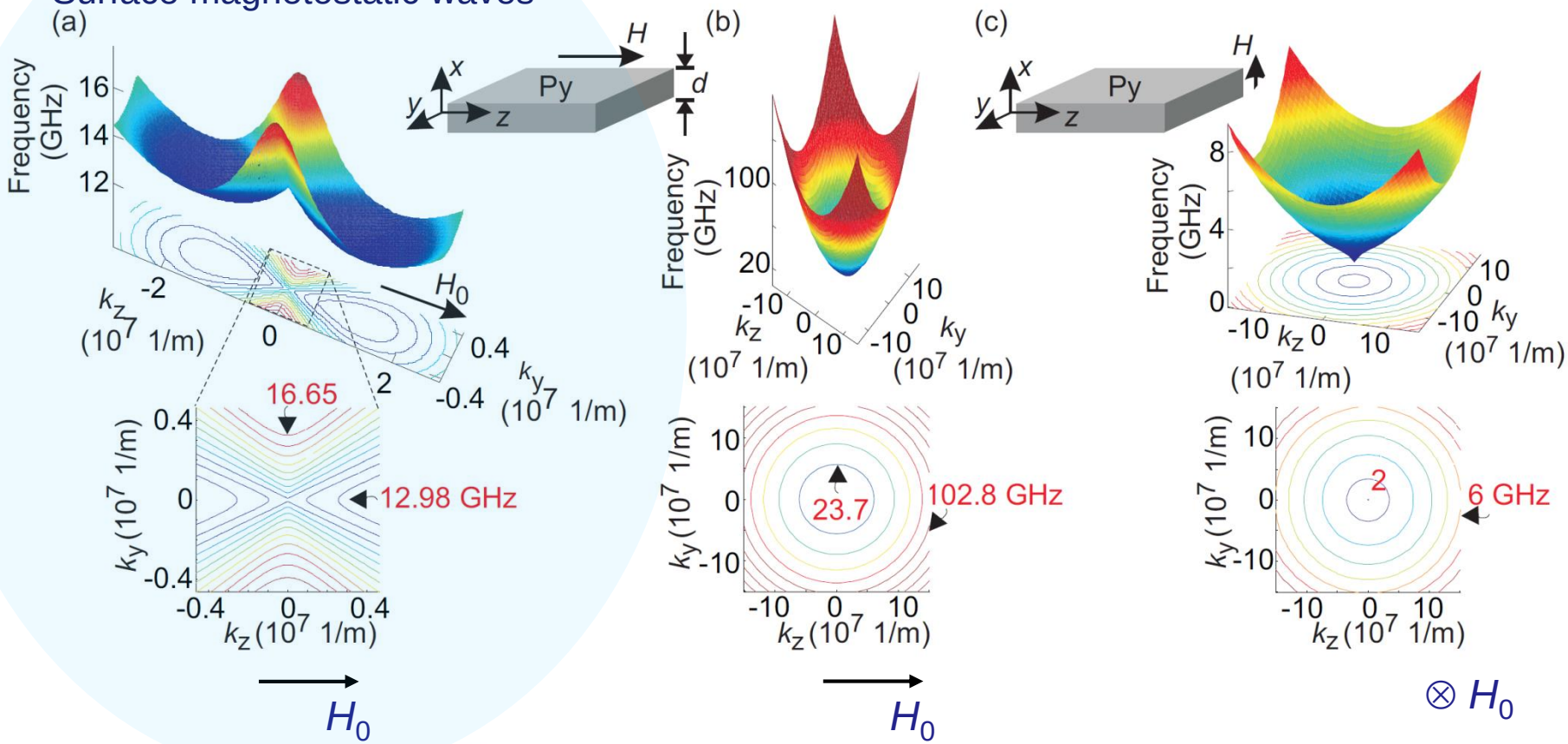
EMERGING RESEARCH DEVICES

Spin waves in thin films

Backward volume waves,
Surface magnetostatic waves

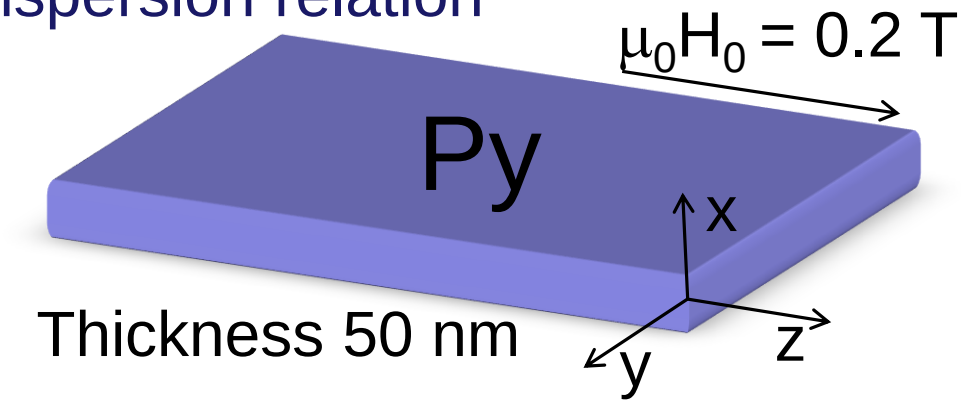
Exchange spin waves

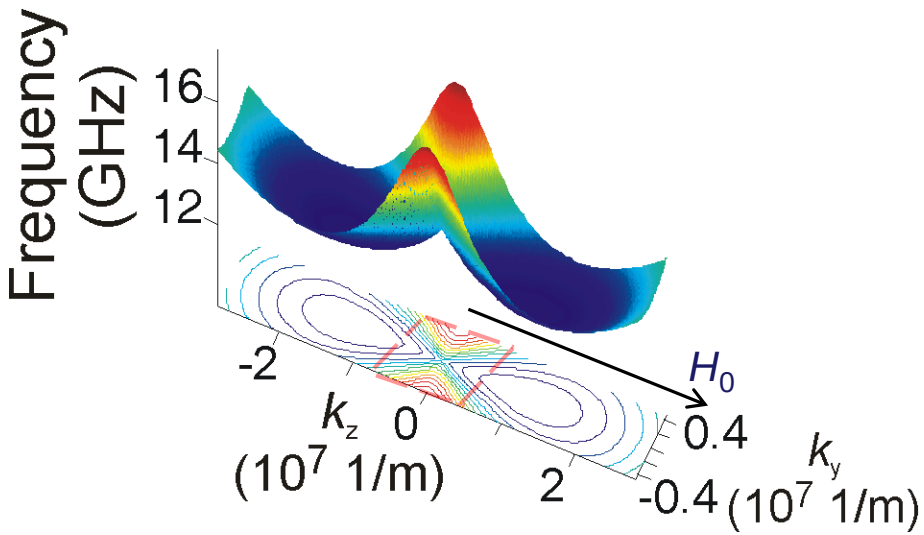
Foreward spin waves

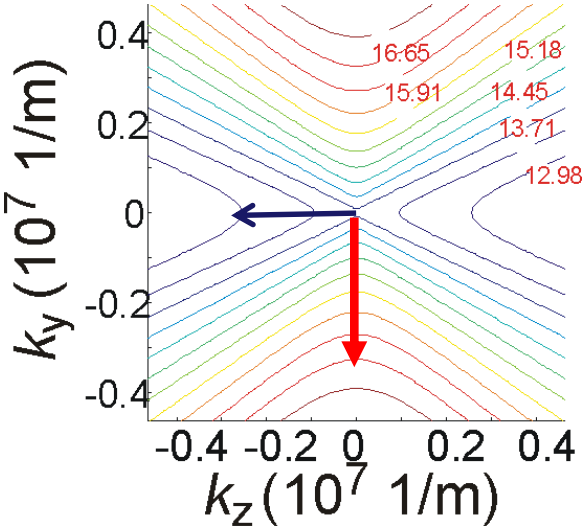


A) Spin waves with dominating dipole interactions with anisotropic dispersion relation

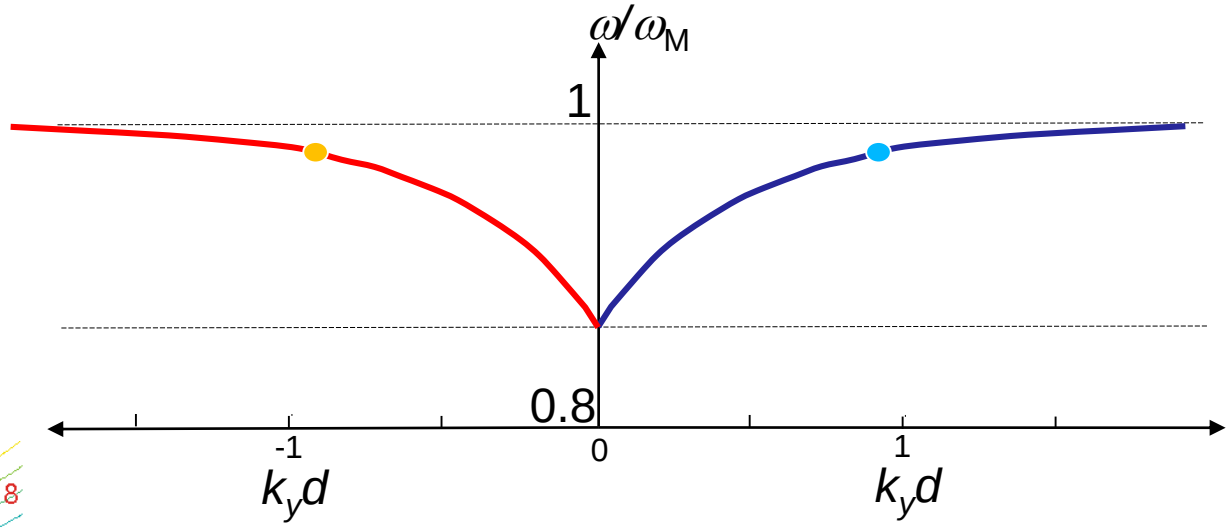
In plane propagation;
In-plane magnetic field

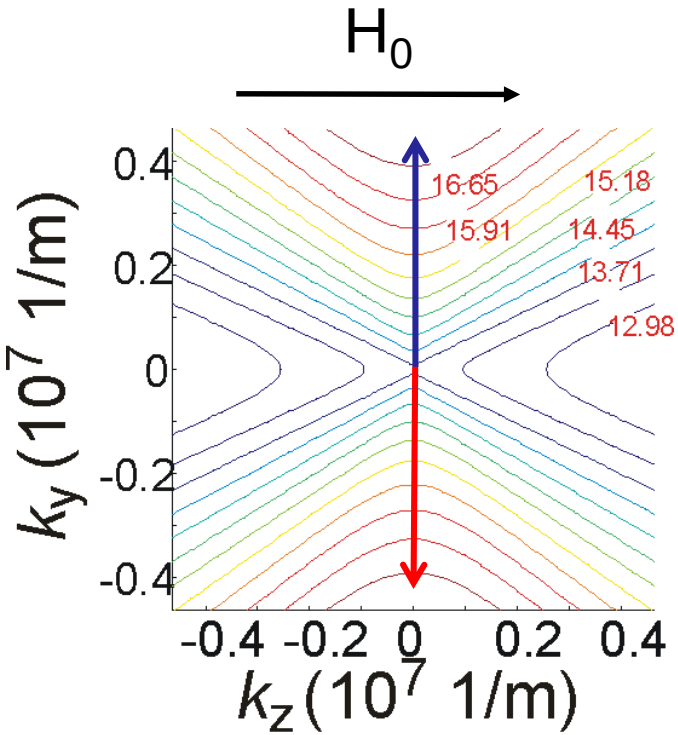




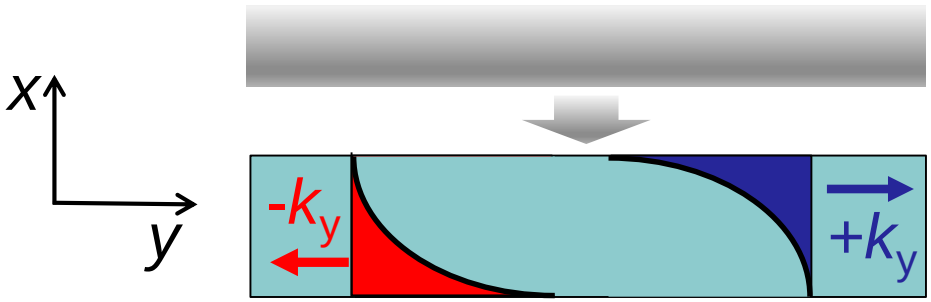


Surface magnetostatic spin wave – Damon-Eshbach mode

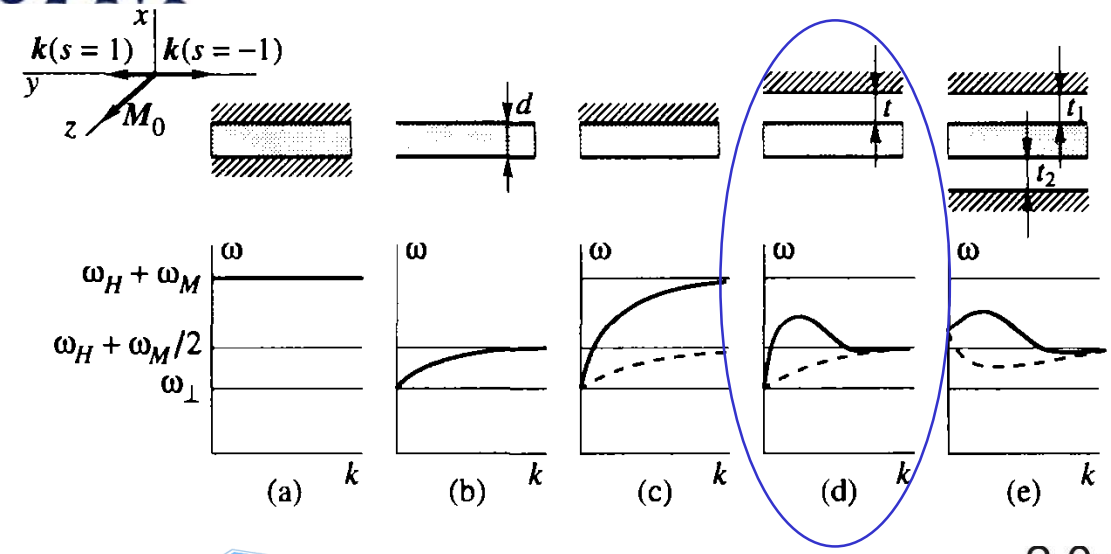




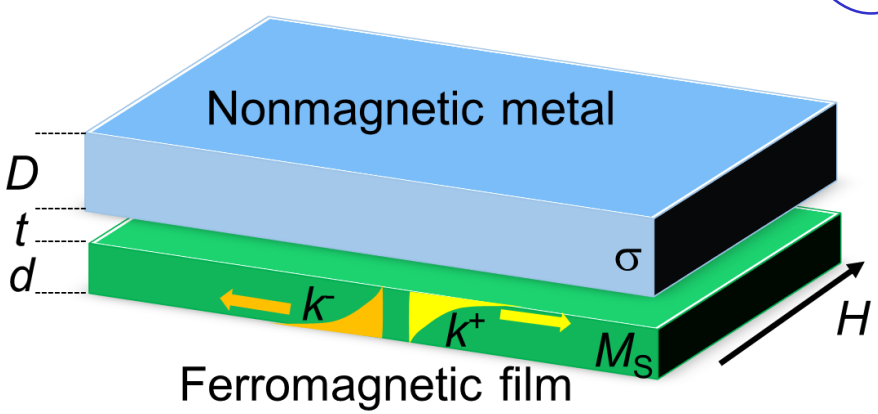
Nonreciprocal property of DE spin wave propagation

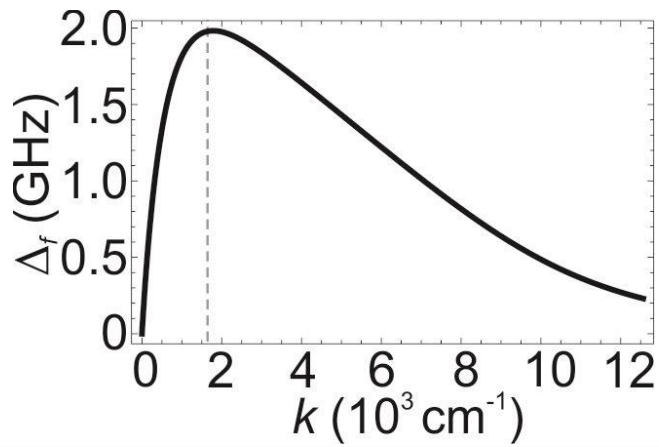


Tayloring of the magnonic band structure by metallic overlayer

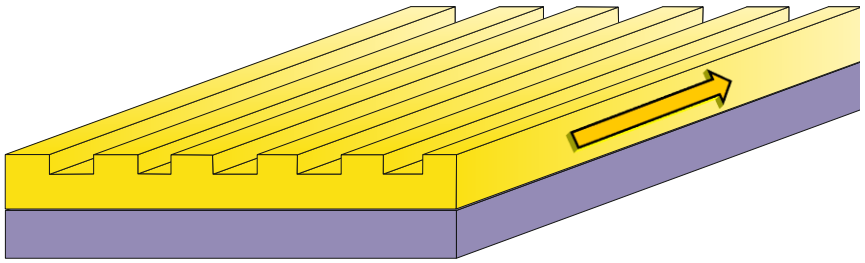


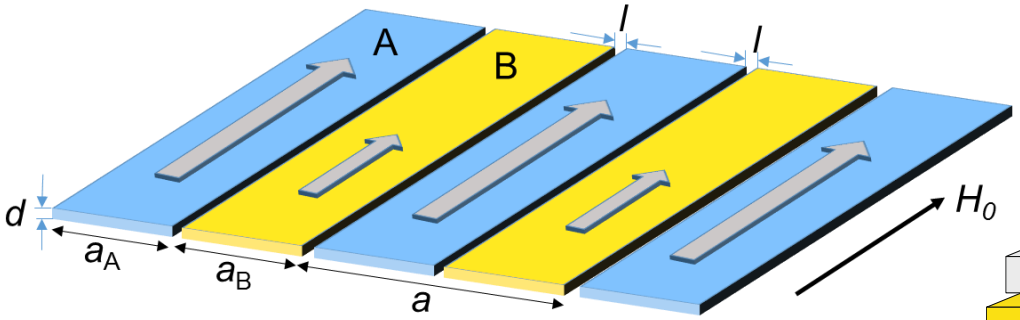
A.G. Gurevich & G.A. Melkov, „Magnetization oscilations and waves", 1996.

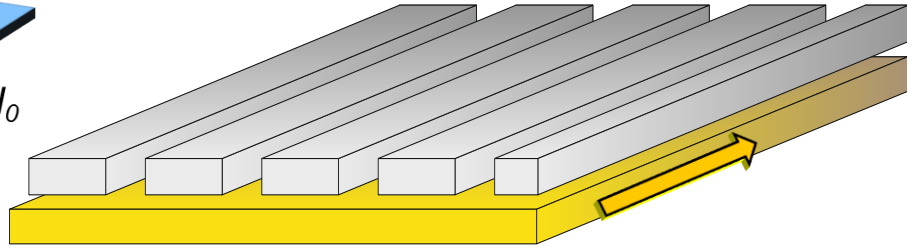




THIN PLATES
1D MAGNONIC CRYSTALS





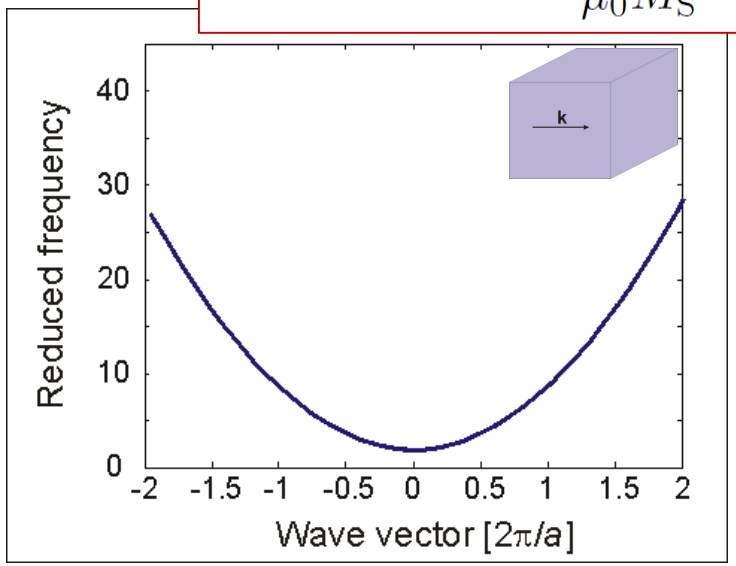


M. Krawczyk and D. Grundler,
Review and prospects of magnonic crystals and devices with reprogrammable band structure,
J. Phys.: Cond. Matter (2014).

Periodicity

Bloch theorem:

$$\omega(\mathbf{k}) = \gamma\mu_0 H_0 + \frac{2A}{\mu_0 M_S} k^2$$



Periodicity in real space:

$$M_S(\mathbf{r}) = M_S(\mathbf{r} + \mathbf{R})$$

Frequency of spin-wave:

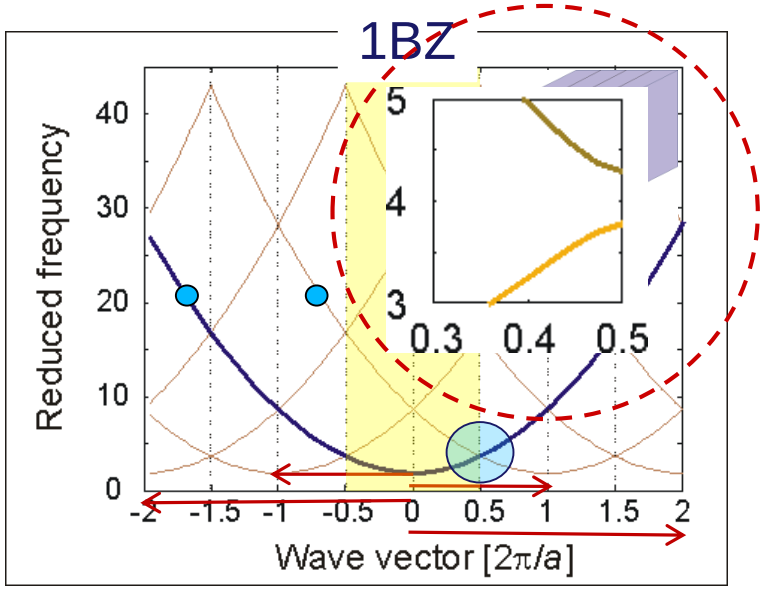
$$\omega(\mathbf{k}) = \omega(\mathbf{k} + \mathbf{G})$$

$\mathbf{k}$ – wave vector

$\mathbf{G}$ – reciprocal lattice vector

Amplitude of spin-wave:

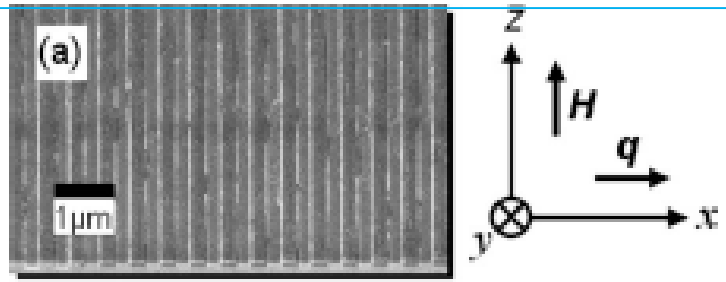
$$\mathbf{m}_{\mathbf{k}}(\mathbf{r}) = \mathbf{m}_{\mathbf{k}+\mathbf{G}}(\mathbf{r})$$



Wang Z.K. et al., Appl. Phys. Lett. 94 (2009) 083112

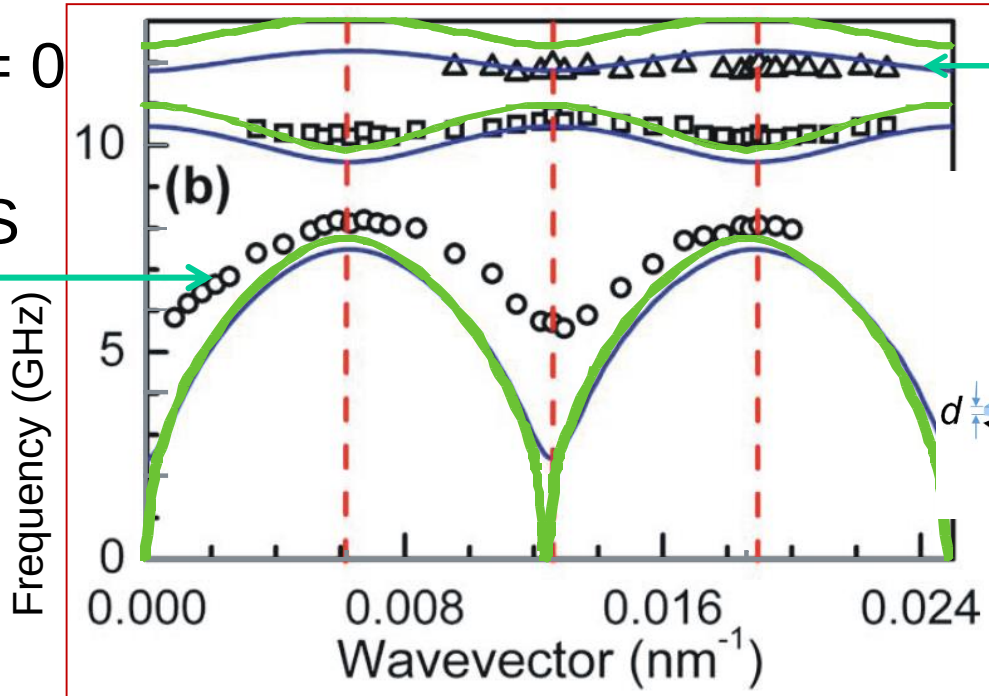
Brillouin light scattering (BLS)

$a_{Co} = a_{Py} = 250$ nm

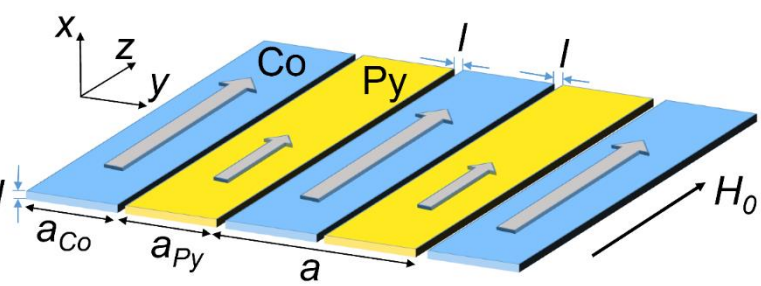


$H_0 = 0$

BLS



Finite element method

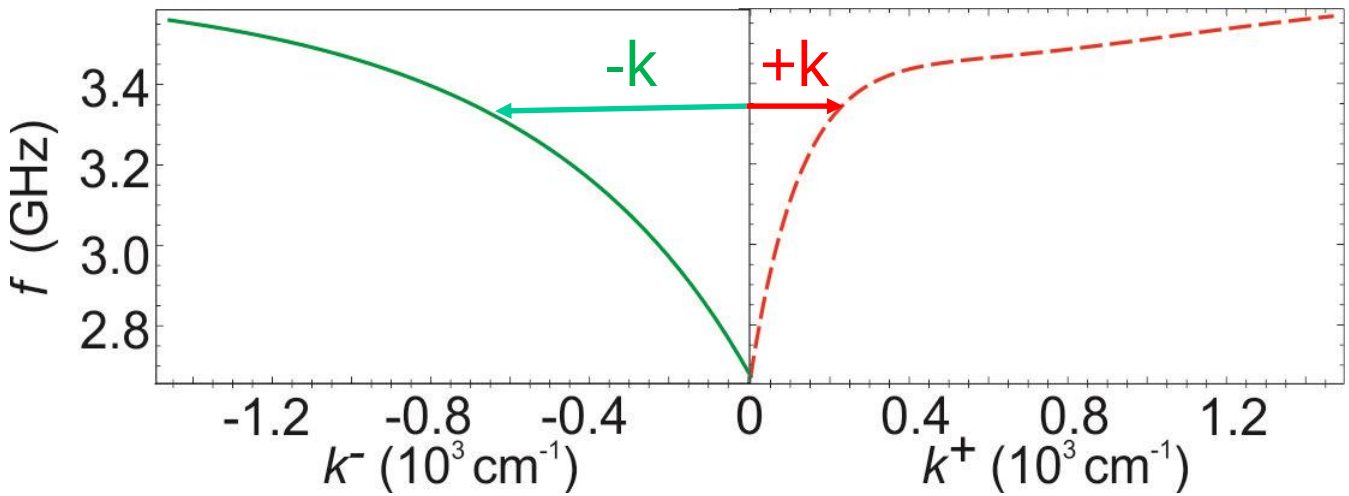


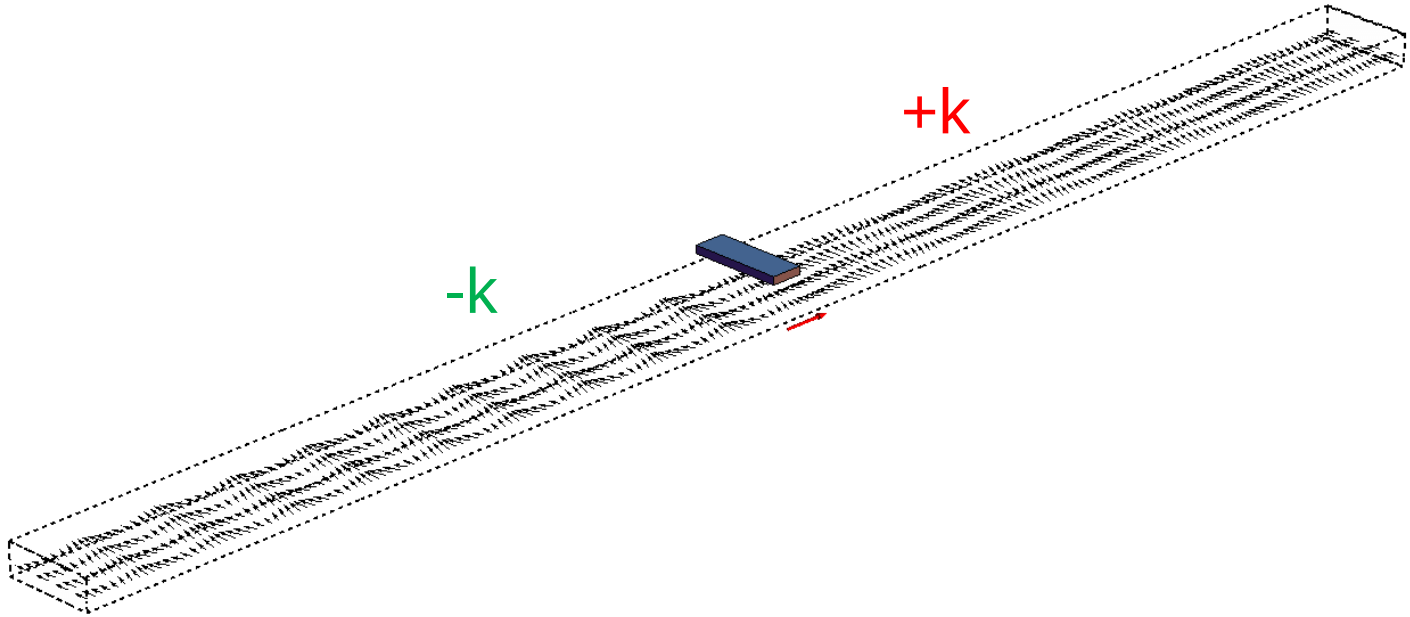
Plane Wave Method

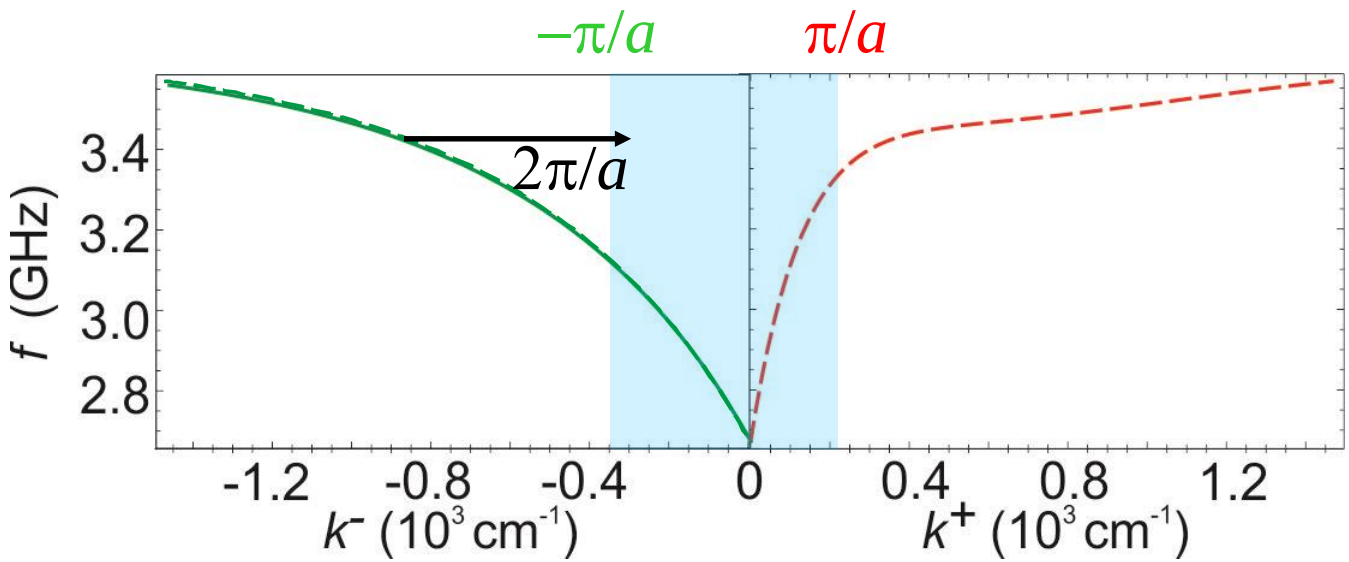
Co: $M_S = 1.15 \times 10^6$ A/m; $A = 2.88 \times 10^{-11}$ J/m; $\gamma = 194.6$ GHz/T;

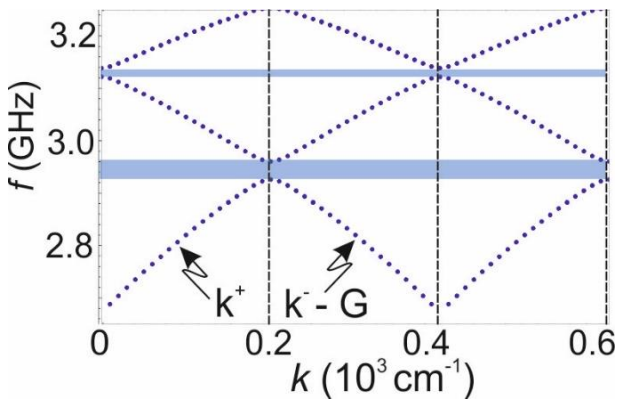
Py: $M_S = 0.658 \times 10^6$ A/m; $A = 1.11 \times 10^{-11}$ J/m; $\gamma = 194.6$ GHz/T

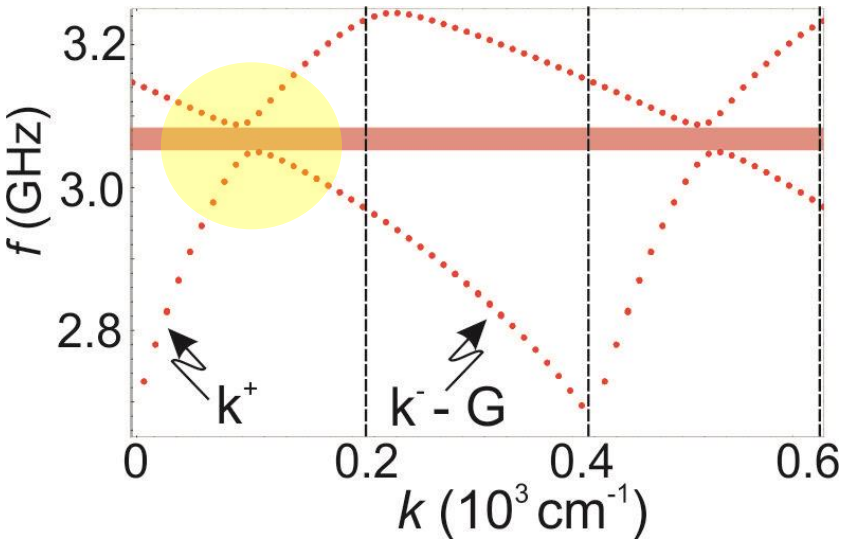
Sokolovskyy M.L.et al. J. Nanopart. Res. **13**, 6085 (2011)


-k
+k
3.4
3.2
3.0
2.8
f (GHz)
-1.2
-0.8
-0.4
0
0.4
0.8
1.2
k⁻ (10³ cm⁻¹)
k⁺ (10³ cm⁻¹)

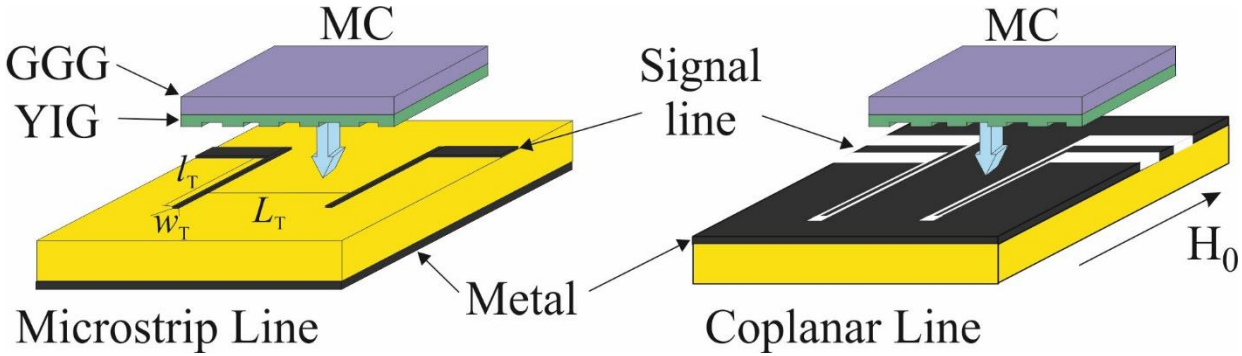

+k
-k

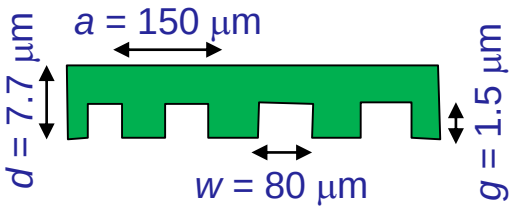


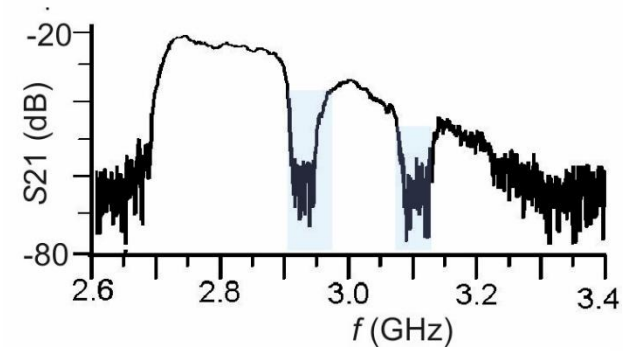


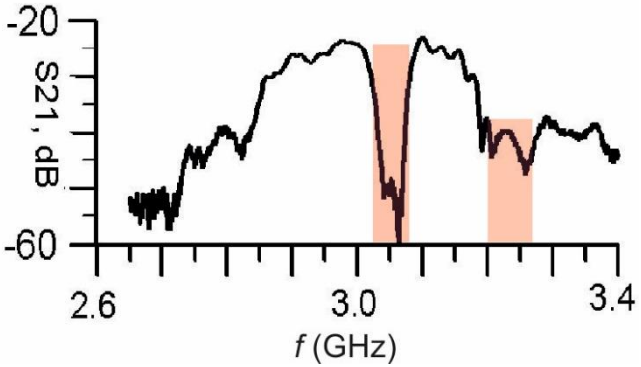


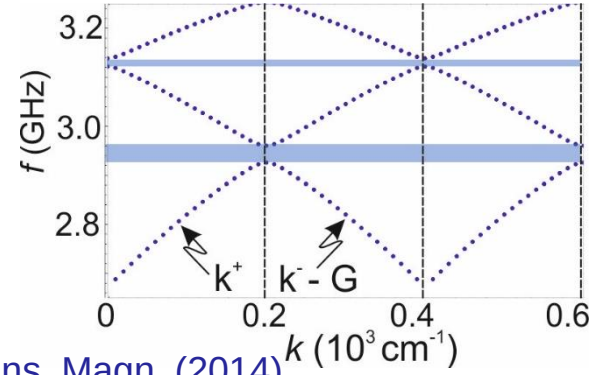
M. Mruczkiewicz et al., NJP (2013).

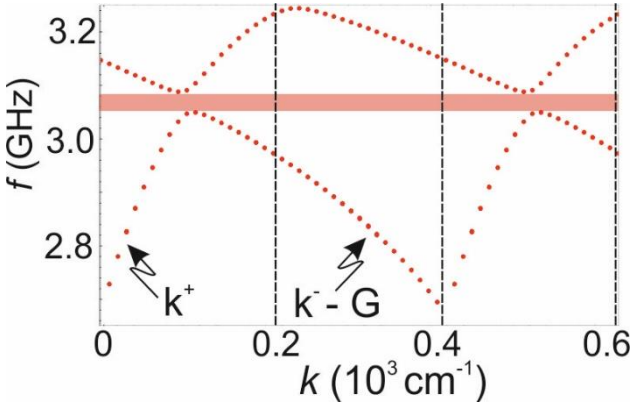










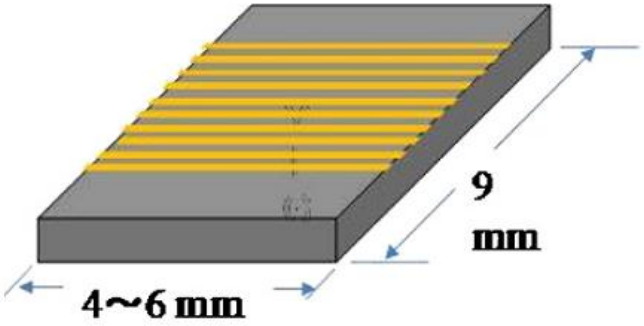


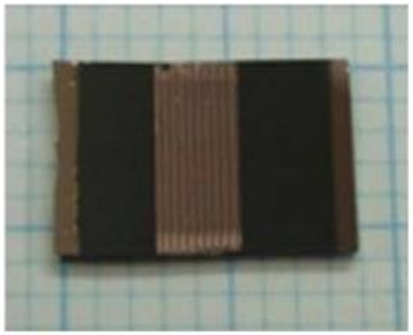
M. Mruczkiewicz et al. IEEE Trans. Magn. (2014).

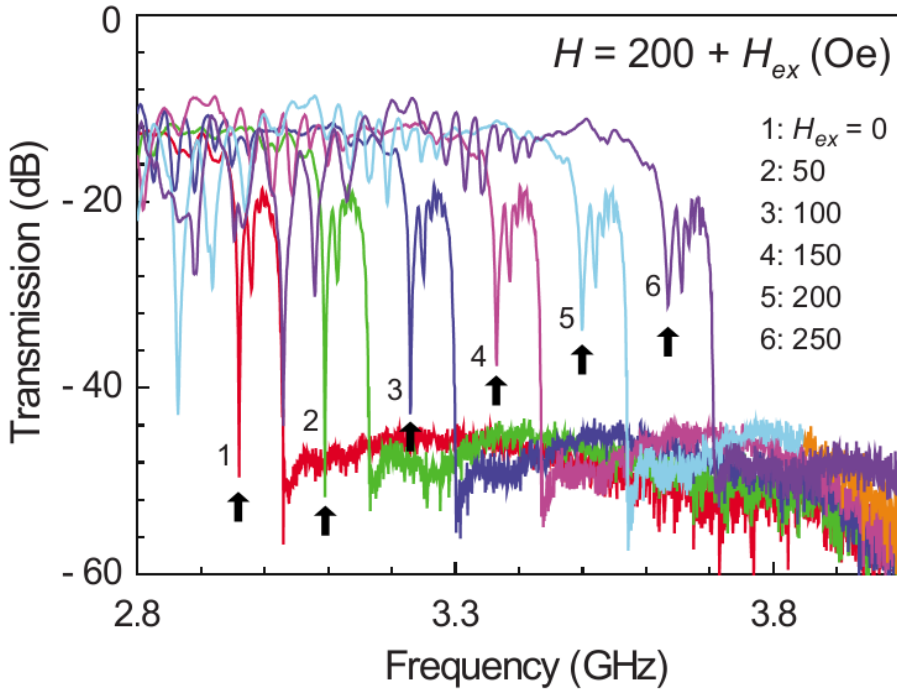
M. Mruczkiewicz et al., Phys. Rev. B (2014).

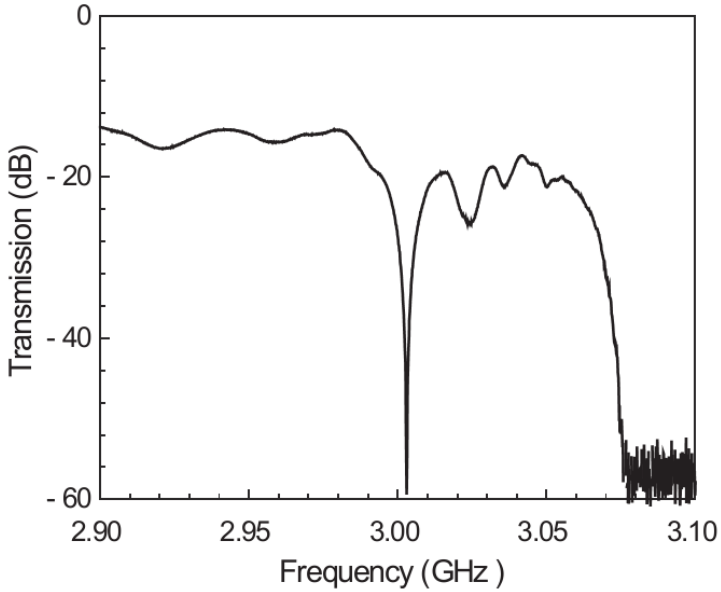
Magnetic field sensors

Thickness of YIG
110 μm



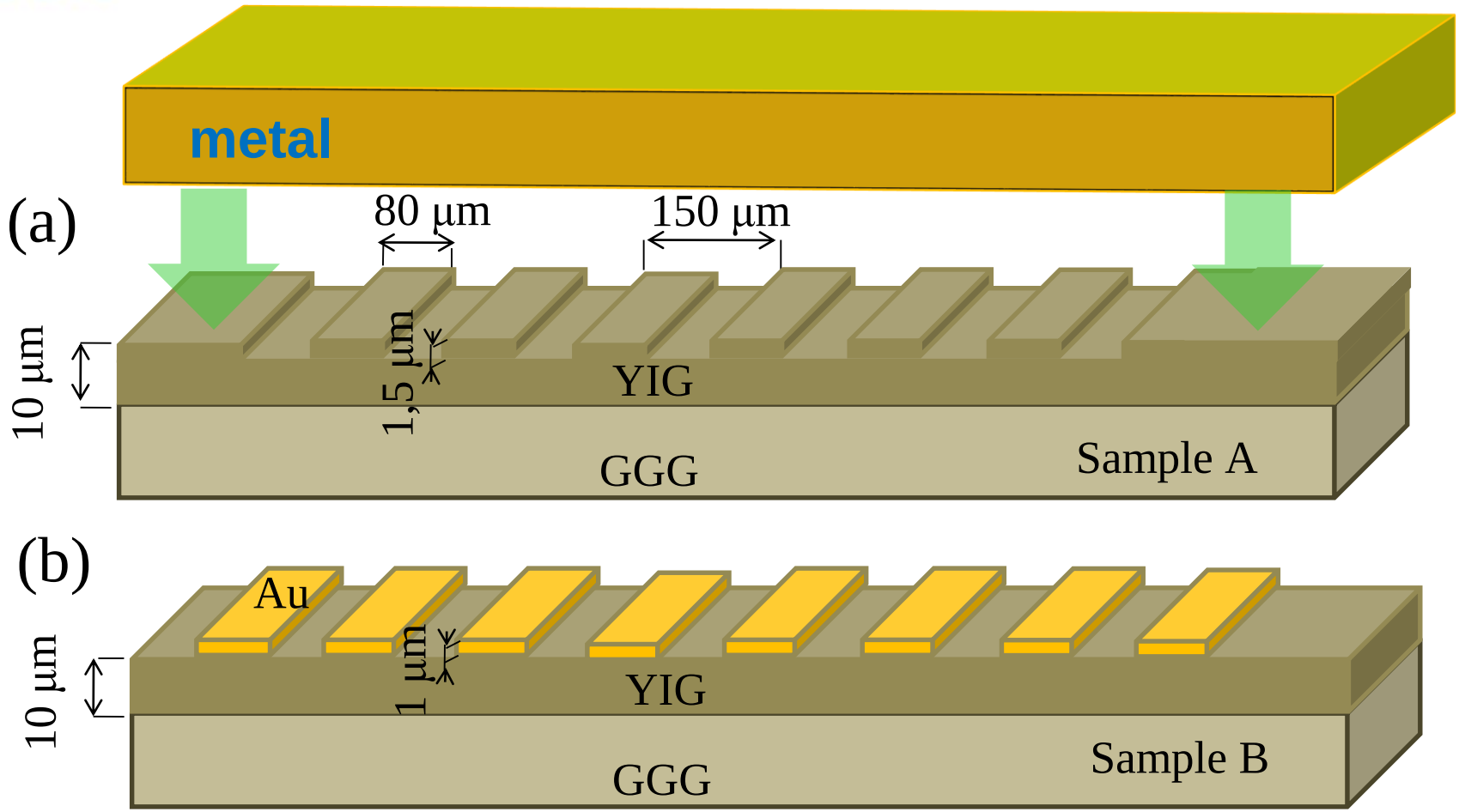


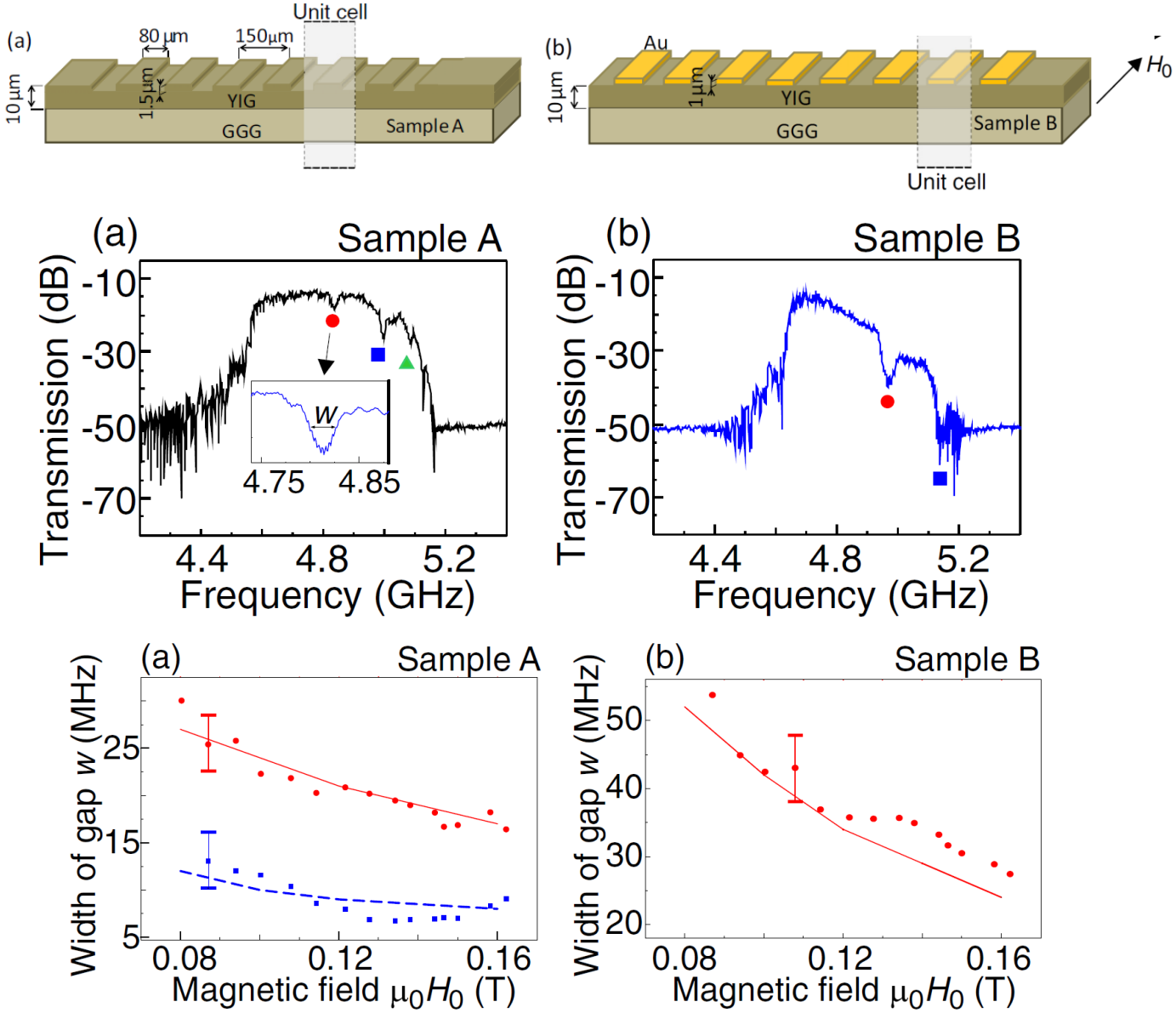




M. Inoue, Appl. Phys. Lett. **98**, 132511 (2011)

Two alternative realizations





V. Bessonov et al. *Magnonic band gaps in YIG-based one-dimensional magnonic crystals: An array of grooves versus an array of metallic stripes*, Phys. Rev. B **91**, 104421 (2015).

Improving computational methods

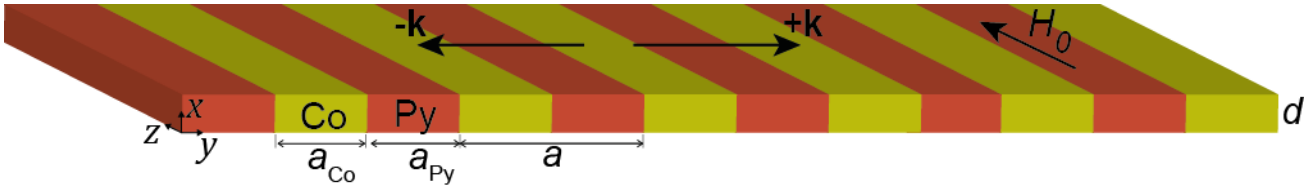
Micromagnetic simulations

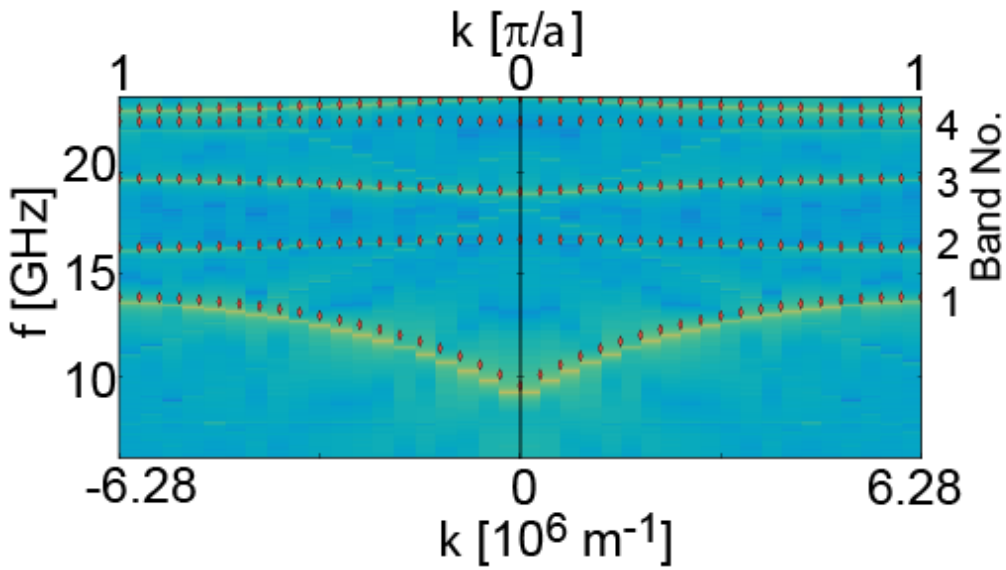
mumax^3 – GPU accelareted micromagnetism

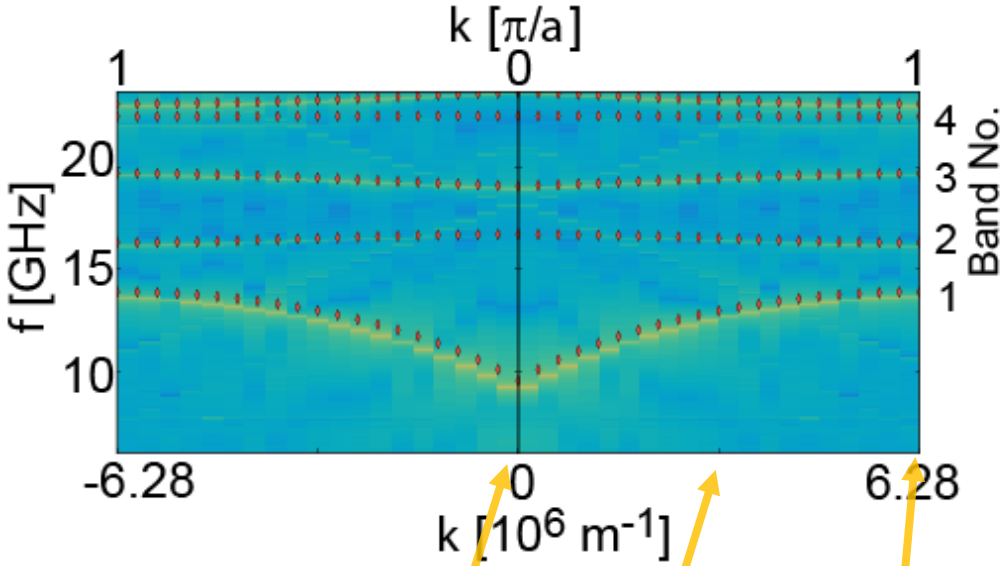
Arne Vansteenkiste et al., *The design and verification of mumax3*, AIP Advances **4**, 107133 (2014).

Electromagnetic FEM

COMSOL Multiphysics

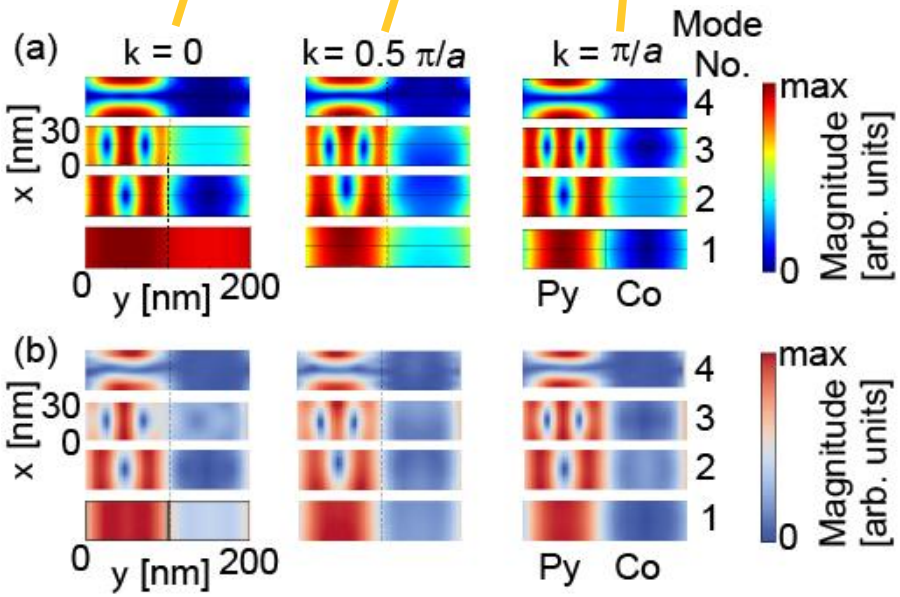




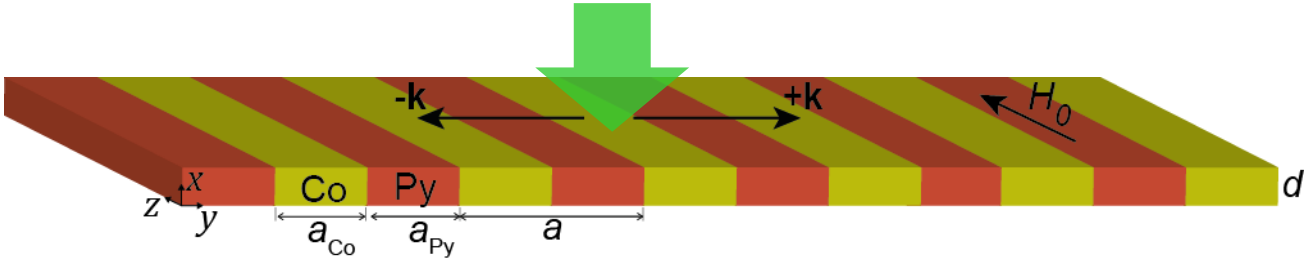


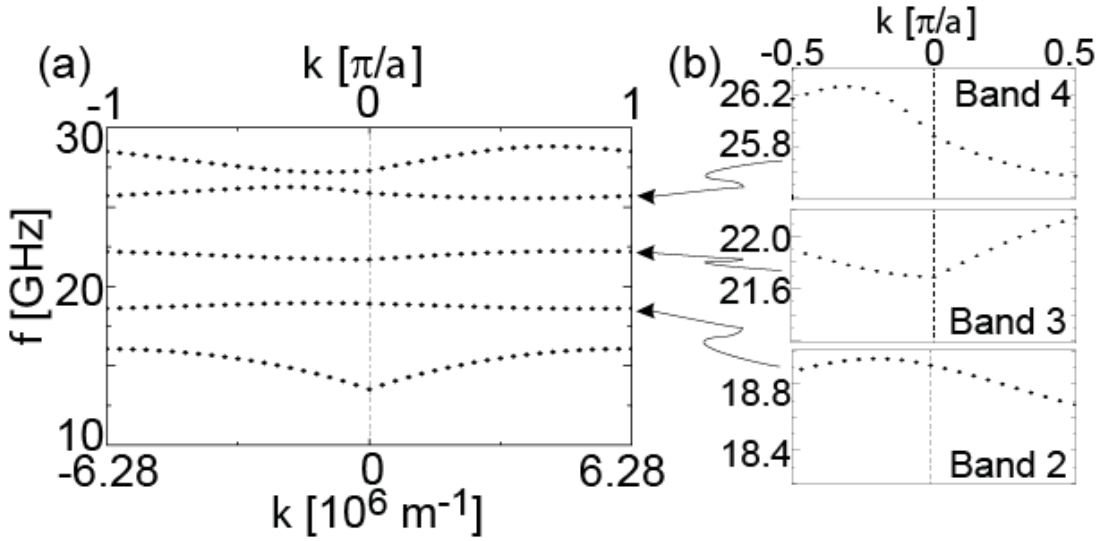
COMSOL Multiphysics

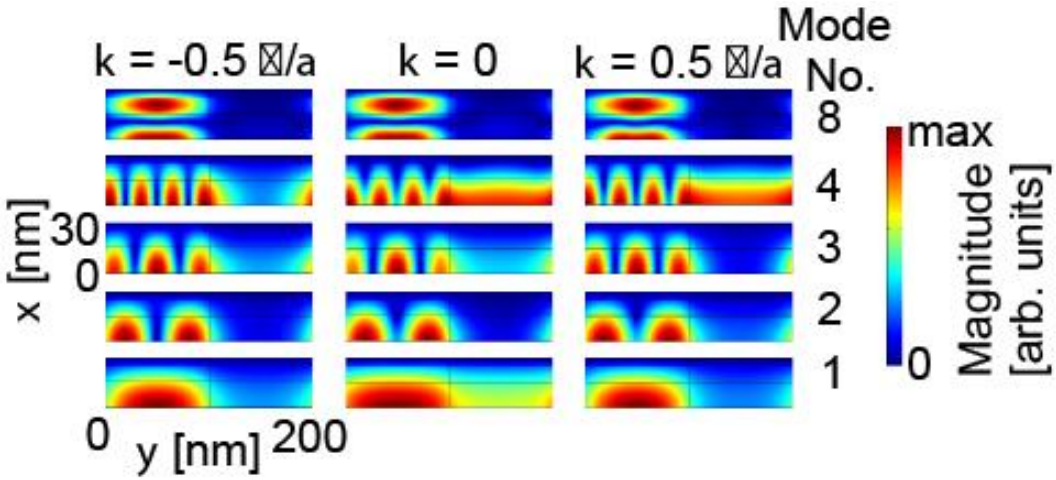
mumax³



Pinned magnetization on the surface

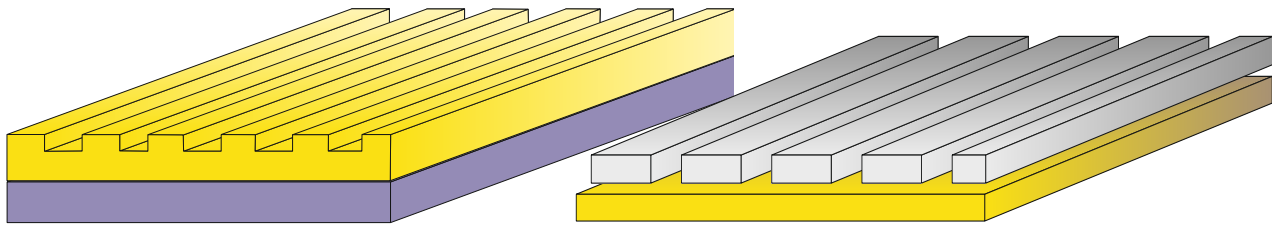




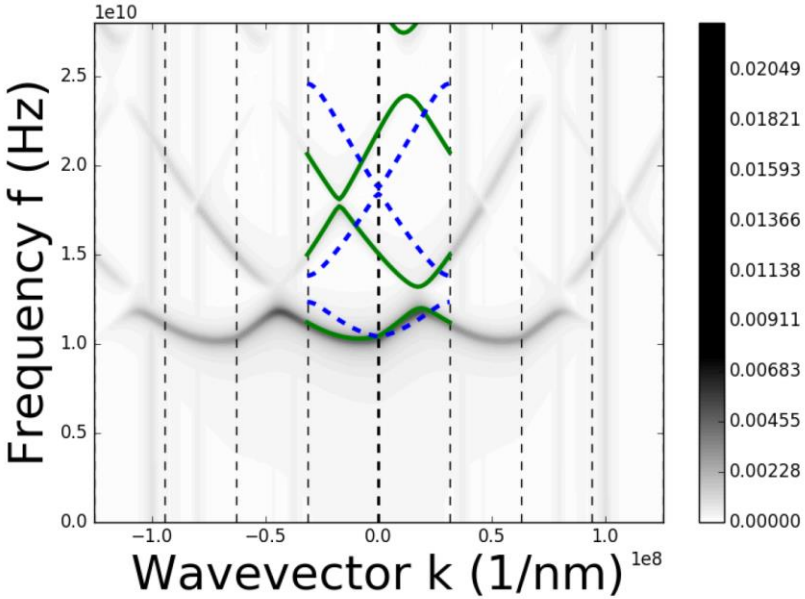


Influence of the Dzyaloshinskii-Moriya interactions

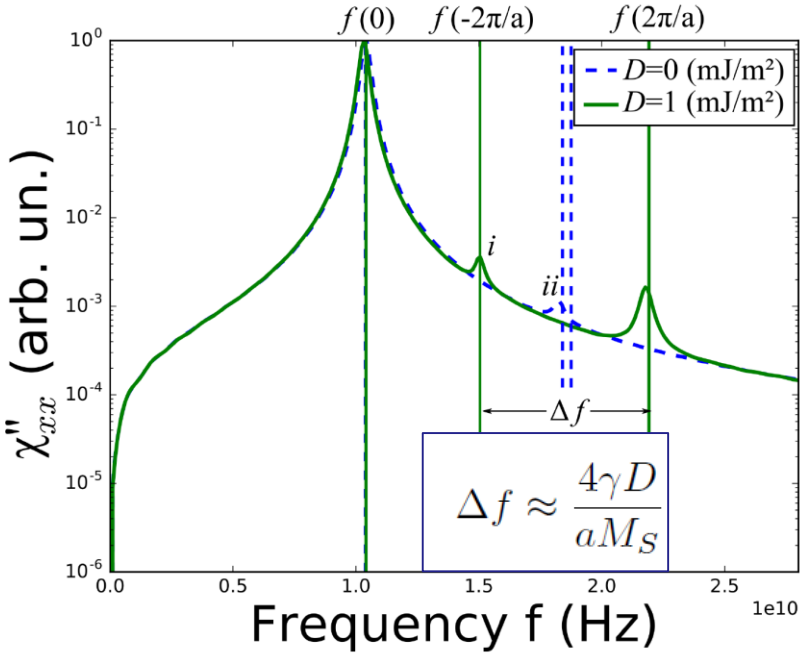
DMI



Magnonic band structure

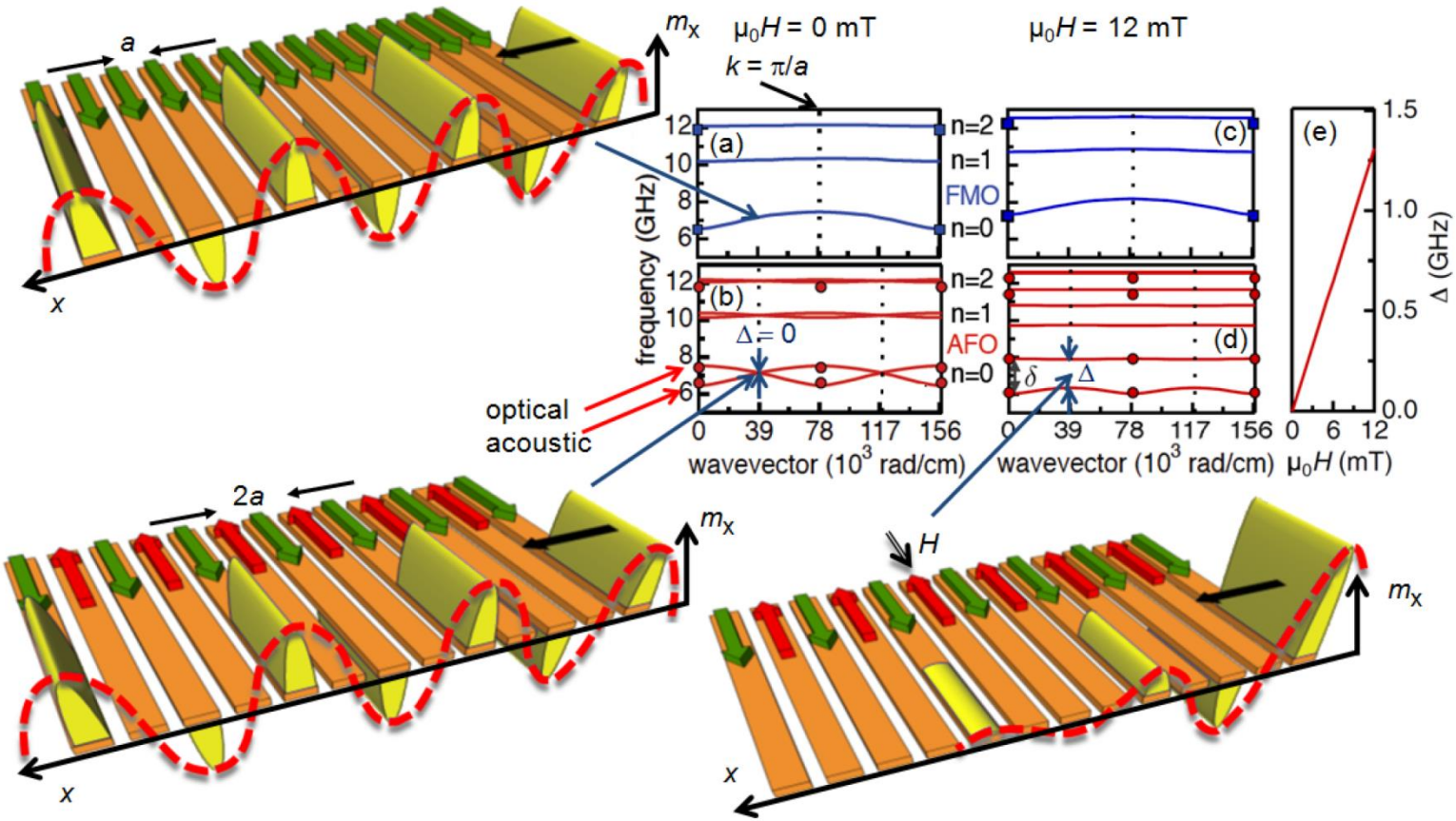


FMR spectrum



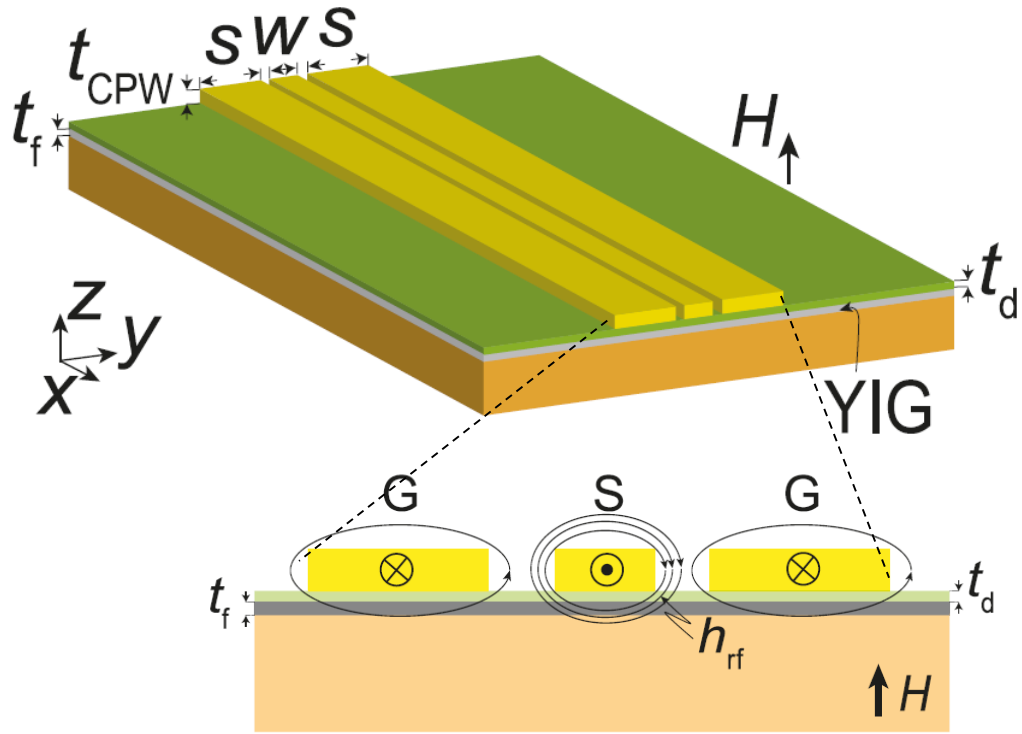
M. Mruczkiewicz et al.,
Influence of the Dzyaloshinskii-Moriya interaction on the FMR spectrum of magnonic crystals and confined structures (2016).

Reprogrammable magnonic band structure

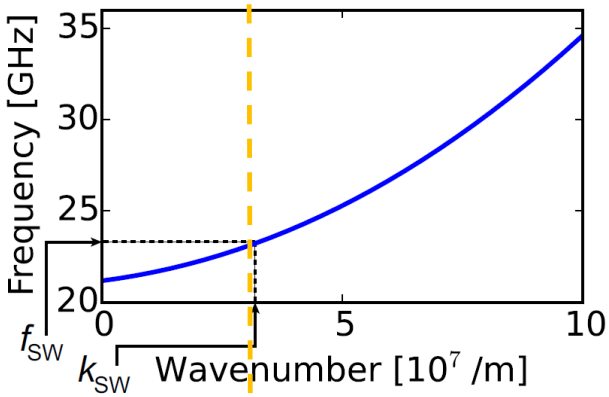


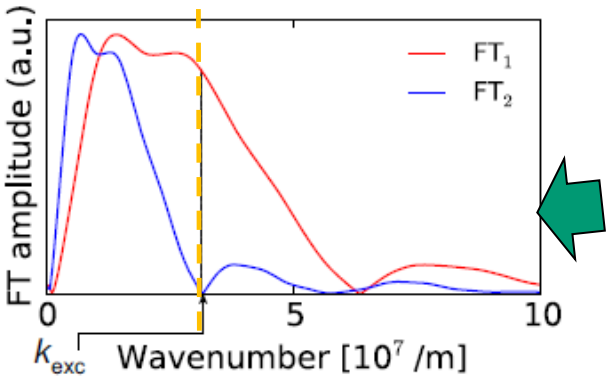
M. Krawczyk and D. Grundler,
Review and prospects of magnonic crystals and devices with reprogrammable band structure, JPC (2014).

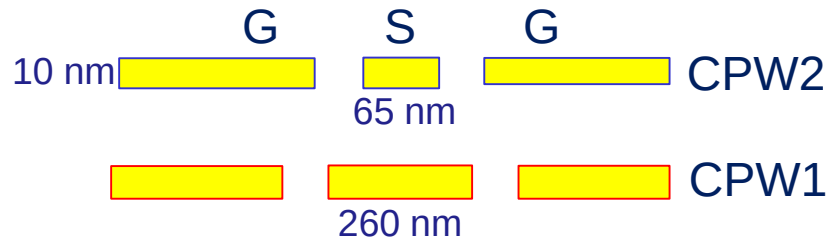
Microwave transducer to generate SW beams



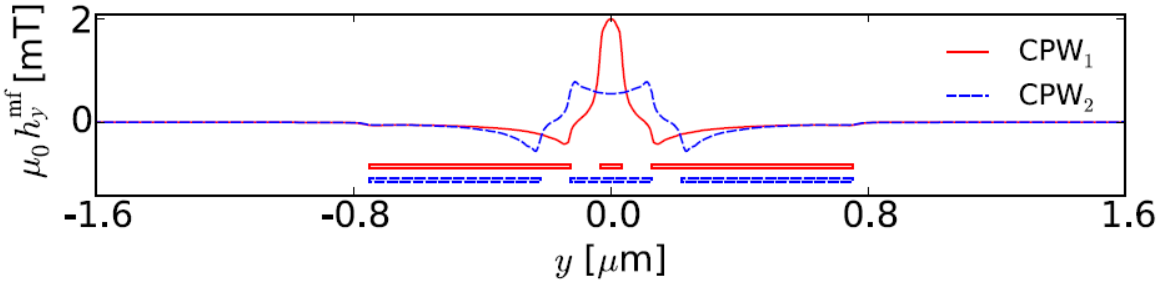
Dispersion relations of SWs



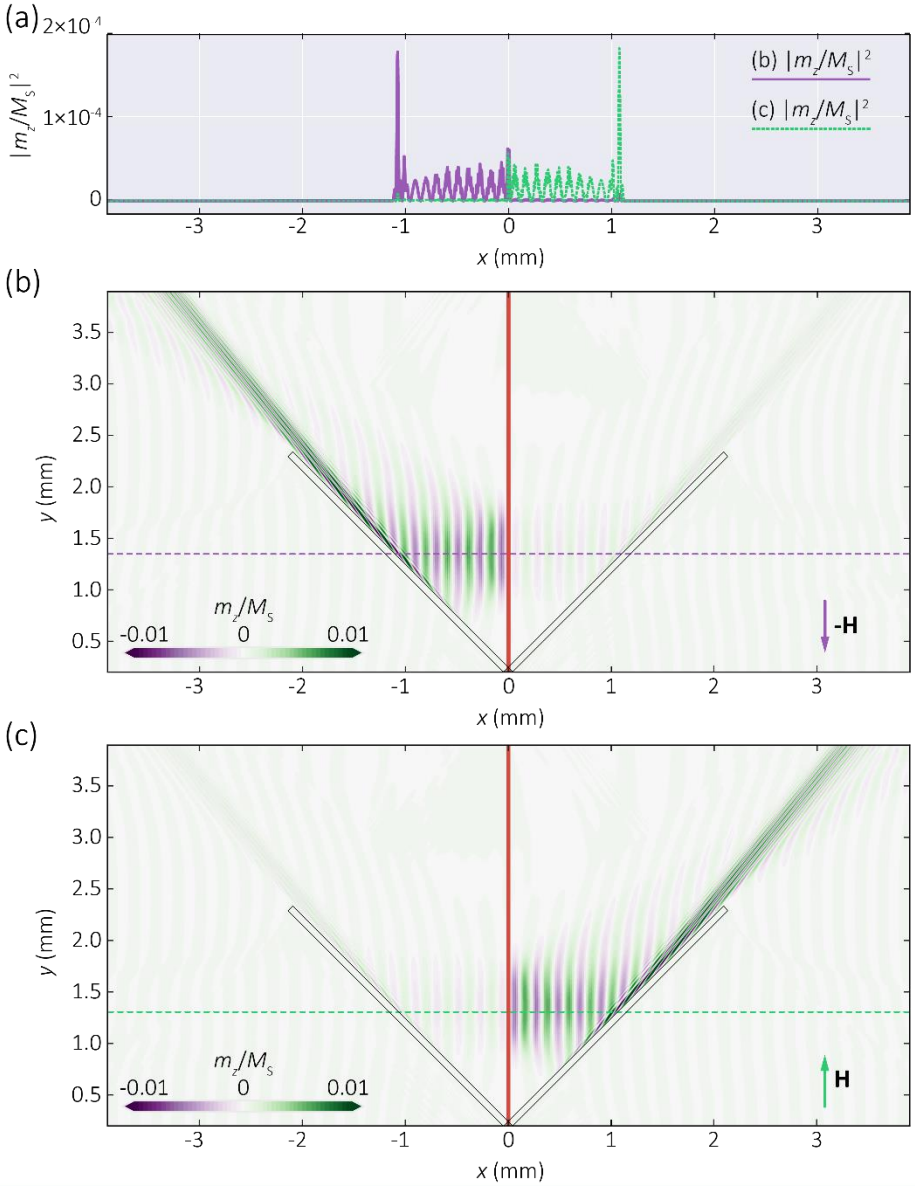




W = 1.5 μm
s = 95 nm



Nonreciprocal excitaiton of spin waves with CPW



R. Gieniusz, et al., under preparation.

Conclusions

- Nonreciprocity can be induced in varius ways, we have shown influence of
  - metal,
  - surface magnetocrystaline anisotropy and
  - DM interactions.
- Spin wave nonreciprocity can be exploited in nanoscale with oscillations in the GHz range.

Collaboration

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- R. Gieniusz, A. Maziewski, Uniwersity of Bialystok, Poland

Founding

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Thank you for attention!