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

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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


Plane wave method

Linear approximation, homogeneous magnetization, decomposition of solutions into the plane waves with taken into account Bloch theorem


Analytical models

Linear approximation, homogeneous magnetization, homogeneous materials


Electromagnetic FEM

CST Microwavestudio, COMSOL Multiphysics
Spin wave spectrum in a bulk ferromagnet

\[ \omega = \omega (k) \]

Short wavelength limit of spin waves

$1 \text{ meV} = 0.24 \text{ THz}$

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

Area of our interest

45 THz EMW has a wavelength of 6.7 $\mu$m
### Energy consumption

#### Electronics | Spintronics | Magnonics
---|---|---
Charge of electron | Spin of electron | Magnon

- **J_c**
- **J_s**

- 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

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

In-plane propagation; In-plane magnetic field

Thickness 50 nm

\[ \mu_0 H_0 = 0.2 \ T \]
Surface magnetostatic spin wave – Damon-Eshbach mode

Nonreciprocal property of DE spin wave propagation
Tayloring of the magnonic band structure by metallic overlayer

THIN PLATES
1D MAGNONIC CRYSTALS

M. Krawczyk and D. Grundler,
*Review and prospects of magnonic crystals and devices with reprogrammable band structure*,
Periodicity

**Bloch theorem:**

**Periodicity in real space:**

\[ M_S(r) = M_S(r + R) \]

**Frequency of spin-wave:**

\[ \omega(k) = \omega(k + G) \]

\( k \) – wave vector

\( G \) – reciprocal lattice vector

**Amplitude of spin-wave:**

\[ m_k(r) = m_{k+G}(r) \]
Brillouin light scattering (BLS)

\[ a_{Co} = a_{Py} = 250 \text{ nm} \]

\[ H_0 = 0 \]

Finite element method

Plane Wave Method

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

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


M. Mruczkiewicz et al., NJP (2013).
Magnetic field sensors

Thickness of YIG
110 µm

$H = 200 + H_{ex}$ (Oe)

M. Inoue, Appl. Phys. Lett. 98, 132511 (2011)
Two alternative realizations

Sample A

- GGG
- YIG
- 10 μm
- 1.5 μm
- 80 μm
- 150 μm

metal

Sample B

- GGG
- YIG
- 10 μm
- 1 μm
- Au
Improving computational methods

Micromagnetic simulations

**mumax**³ – GPU accelerated micromagnetism


Electromagnetic FEM

COMSOL Multiphysics
COMSOL Multiphysics

mumax³
Pinned magnetization on the surface
M. Mruczkiewicz et al.,

**Influence of the Dzyaloshinskii-Moriya interactions**

**Magnonic band structure**

**FMR spectrum**

\[ \Delta f \approx \frac{4 \gamma D}{a M_S} \]
Reprogrammable magnonic band structure

M. Krawczyk and D. Grundler, 
Microwave transducer to generate SW beams

Dispersion relations of SWs

- Frequency (GHz) vs. Wavenumber (10^7 /m)
- FT amplitude (a.u.) vs. Wavenumber (10^7 /m)

Parameters:
- W = 1.5 μm
- s = 95 nm

Design elements:
- CPW1
- CPW2
- 10 nm
- 65 nm
- 260 nm

Legend:
- G
- S
- H
Nonreciprocal excitation of spin waves with CPW

Conclusions

- Nonreciprocity can be induced in various ways, we have shown influence of:
  - metal,
  - surface magnetocrystalline anisotropy and
  - DM interactions.

- Spin wave nonreciprocity can be exploited in nanoscale with oscillations in the GHz range.

Collaboration

- P. Gruszecki, J. Rychły, AMU, Poznań;
- M. Mruczkiewicz, Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia.
- R. Gieniusz, A. Maziewski, Uniwersity of Bialystok, Poland
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Thank you for attention!