Magnetization Dynamics II: Magnonics: Trends and Challenges

Burkard Hillebrands

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Coherent dynamics: spin waves

Landau-Lifshitz torque equation

\[
\frac{1}{|\gamma|} \frac{d\vec{M}(t)}{dt} = -\vec{M}(t) \times \vec{B}_{\text{eff}}(t) + \frac{\alpha}{M_s} \vec{M}(t) \times \frac{d\vec{M}(t)}{dt}
\]

\[
\vec{m}(\vec{r}, t) = \vec{m}_0(\vec{r}) e^{i(k \cdot \vec{r} - \omega t)}
\]

dynamic magnetization

Burkard Hillebrands  
IEEE Magnetics Society Summer School - Minneapolis  
June 14-19, 2015
Spin wave bus

Travelling magnons allow one to:

- **transfer** spin information over centimeter distances
- **process** the information (using wave nature of magnon)
- **operate** in insulator-based technology

Fundamental properties:

- Minimal wavelength is down to several nm
- Frequency is in GHz and up to the THz range
- **Energy**: $E_{\text{magnon}} \ll k_B T$
- **Lifetime**: up to several 100 ns
Magnonics: Trends

- Making magnons
- Moving magnons
- Detecting magnons

Materials for magnons

- Thermal excitation
- Microwave excitation
- Parametric pumping
- Spin Hall effect
- Spin torque oscillator
- Femtosecond laser pulses
- ...

Magnonics
“Magnonics” team

Kaiserslautern PI Team

A. Chumak  
V. Vasyuchka  
A. Serga  
B. Leven

Main External Collaborators

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A.N. Slavin (University of Rochester, Michigan, U.S.A.)
A. Karenowska (Oxford University, U.K.)
M. Kostylev (University of Western Australia)
AG Magnetismus in TU Kaiserslautern

D. A. Bozhko, Dr. M. Agrawal, T. Fischer, S. Klingler, Dr. B. Leven, S. Keller, P. Clausen, L. Mihalceanu, Dr. A. A. Serga, L. Gareis, T. Langner, J. Greser, Dr. P. Pirro, Dr. A. Conca Parra, Jun.-Prof. Dr. E. Th. Papaioannou, Dr. A. Ruiz Calaforra, Dr. T. Brächer, F. Heussner, T. Meyer, Dr. V. I. Vasyuchka, V. Lauer, Prof. Dr. B. Hillebrands + (Dr. A. V. Chumak).
Magnonics: Main trends

I. New materials for magnonics

II. Novel means for magnon detection

III. Data processing using magnons

IV. Magnonic supercurrents
I. New materials for magnonics

Main requirement: small damping parameter

Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
I. New materials for magnonics

- Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
- CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$

![Graph showing α vs. Ta (°C)]

Liu, et al. JAP 110, 033910 (2011)
I. New materials for magnonics

Main requirement: small damping parameter

- Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
- CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$
- Novel Heusler compounds: $\alpha = 3 \times 10^{-3}$
Spin-wave propagation in Co$_{2}$Fe$_{0.4}$Mn$_{0.6}$Si Heusler waveguides

Sebastian, et al., APL 100, 112402 (2012)
Spin-wave propagation in Co$_2$Fe$_{0.4}$Mn$_{0.6}$Si Heusler waveguides

Spin-wave propagation is observed over distance of more than 80 µm

Decay length: 10.6 µm
Damping $\alpha$: $4.7 \times 10^{-3}$

$I(x) = I_0 \exp(-\frac{2x}{\delta}) + b$

$\alpha = \frac{1}{\tau \gamma \mu_0 (H_{\text{eff}} + M_s)}$

$\tau = \frac{\delta}{v_G}$

Sebastian, et al., APL 100, 112402 (2012)
I. New materials for magnonics

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- Novel Heusler compounds: $\alpha = 3 \times 10^{-3}$
- Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$
Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG)

YIG:
- magnetic insulator
- smallest spin-wave damping

Preparation via:
- liquid phase epitaxy
- sputtering
- pulsed laser deposition

Sample fabrication

Multi-focused Brillouin Light Scattering setup was used for magnon detection

BLS intensity map: YIG thickness: 100 nm made by liquid phase epitaxy

For standard YIG quality: free path will be up to 1 mm

P. Pirro, et al., APL 104, 012402 (2014)
I. New materials for magnonics

- Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
- CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$
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- Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$
- Magnonic crystals: artificial magnetic materials (static and dynamic)
**What is a “magnonic crystal”?**

**Magnonic crystal** – magnetic meta-material:
- artificial medium with periodic lateral variation in magnetic properties

One-dimensional magnonic crystal:

![Diagram of magnonic crystal]

- analogous to photonic and sonic crystals but operates with spin waves in the GHz frequency range

**Magnonic-crystal are engineered to have properties that may not be found in nature**
Band gaps – regions of the spectrum over which waves are not allowed to propagate.

We analyze the case of the incident angle $\theta = 0$. 

$$n\lambda = 2a$$

We analyze the case of the incident angle $\theta = 0$. 

$\lambda$ rad/cm
Which magnetic property do we modulate?

Bias magnetic field

\[ f(k) = \gamma \left( H_0 + 4\pi M_0 \right) \frac{1 - \exp\left(-\sqrt{\frac{(\pi/w)^2 + k^2 d}}{\sqrt{(\pi/w)^2 + k^2 d}} \right)}{\sqrt{(\pi/w)^2 + k^2 d}} \]

Effective saturation magnetization

Chumak et al., PRB, 81, 140404 (2010)
Obry et al., APL, 102, 202403 (2013)

Waveguide thickness

Sykes et al., APL 29, 388 (1976)
Chumak et al., APL 93, (2008)

Input signal

Waveguide width

Chumak et al., APL 95, (2009)
Lee et al., PRL 102, 127202 (2009)
# Magnonic crystals - overview

<table>
<thead>
<tr>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave filter</td>
<td>Chumak et al., <em>APL</em> 93, 022508 (2008)</td>
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<td>Chumak et al., <em>APL</em> 94, 172511 (2009)</td>
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<td>Chumak et al., <em>JAP</em> 105, 083906 (2009)</td>
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<td>Stable microwave generator</td>
<td>Karenowska et al., <em>APL</em> 96, 082505 (2010)</td>
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<td>Micro-sized crystal</td>
<td>Chumak et al., <em>APL</em> 95, 262508 (2009)</td>
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<td>Obry et al., <em>APL</em>, 102, 202403 (2013)</td>
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<tr>
<td>Travelling crystal</td>
<td>Chumak et al., <em>PRB</em>, 81, 140404 (2010)</td>
</tr>
</tbody>
</table>
Localized ion implantation:

- Purely magnetic patterning
- No change in sample topography

State of the art studies (YIG):

G. Volluet, P. Hartemann,
*Reflection of magnetostatic forward volume waves by ion implanted gratings*,

R. L. Carter, J. M. Owens, C. V. Smith, Jr., K. W. Reed,
*Ion-implanted magnetostatic wave reflective array filters*,

Irradiation of Ni$_{81}$Fe$_{19}$ films with 30 keV Cr$^+$ ions:

Control saturation magnetization $M_S$ and Gilbert damping $\alpha$

Fassbender *et al.*, PRB 73, 184410 (2006)
Fabrication of microscopic metallic magnonic crystal with periodic change in saturation magnetization $M_S$

- Waveguides:
  - MBE evaporation
  - Lift-off techniques
Transmission spectrum

Spin-wave excitation spectra:

- Parameters:
  - \( \mu_0 H_{\text{ext}} = 27.3 \text{ mT} \)
  - \( w_{\text{eff}} = 4 \mu m \)
  - \( t = 16.8 \text{ nm} \)

- Two pronounced band gaps in transmission spectrum

Detection

\[ \mu_0 H_{\text{ext}} = 27.3 \text{ mT} \]

Obry et al., APL 102, 202403 (2013)
Dynamic magnonic crystal

Periodic modulation of the bias magnetic field by current-carrying wires

Lattice constant: \( a = 300 \, \mu \text{m} \)
Number of periods: \( N_g = 20 \)

Two modes with $k = \pi/a$ and $k = -\pi/a$ are coupled by periodic variation of field

Coupling provides a mechanism for energy transfer
Spin-wave mode coupling by dynamic magnonic crystal

Two modes with $k = \pi/a$ and $k = -\pi/a$ are coupled by periodic variation of field

Coupling provides a mechanism for energy transfer

Input signal:

\[ A_s(t) \sim \sum_{\Delta f} \exp(-i 2\pi \Delta f \cdot t) \]

\(\Delta f\) is a frequency shift from the Bragg frequency

Reflected signal:

\[ A_R(t) \sim \sum_{\Delta f} \exp(i 2\pi \Delta f \cdot t) \sim A_s(-t) \]

Classical reflection from mirror

Railway analog:

Spin-wave experiment:
Reflection via time reversal

Railway analog:

Spin-wave experiment:

Magnetic field
Reflection from a mirror

I. New materials for magnonics

- Commonly used material: Permalloy (Py, NiFe): $\alpha = 8 \times 10^{-3}$
- CoFeB: low damping (both am. and crystalline phase): $\alpha = 4 \times 10^{-3}$
- Novel Heusler compounds: $\alpha = 3 \times 10^{-3}$
- Micro-structured Yttrium Iron Garnet $Y_3Fe_5O_{12}$ (YIG): $\alpha = 4 \times 10^{-5}$
- Magnonic crystals: artificial magnetic materials (static and dynamic)
- Normally magnetized non-reciprocal materials
Sample configuration

Simulation of a perpendicular magnetized Permalloy discs (OOMMF)

Parameters

\[ \mu_0 M_s = 1 \text{ T} \]
\[ H_k = 0 \]
\[ \alpha = 0.007 \]
\[ \mu_0 H = 1.050 \text{ T} \]

Spin waves are exited by the dynamic Oersted field created by injecting an RF current through antenna.

Diameter of antenna: 500 nm

Side charges were added in order to have an uniform distribution of the internal field.

Internal field = 50 mT

![Graph showing internal field variation inside the disc](image)
Spin-wave boundary mode

- **f = 8 GHz**
  - $\lambda_v = 278\,\text{nm}$
  - $\lambda_e = 3.7\,\mu\text{m}$

- **f = 10 GHz**
  - $\lambda_v = 125\,\text{nm}$
  - $\lambda_e = 1.9\,\mu\text{m}$

- **f = 12 GHz**
  - $\lambda_v = 98\,\text{nm}$
  - $\lambda_e = 0.94\,\mu\text{m}$

**Effective thickness**
- $d = 55\,\text{nm}$ (??)
Spin-wave circuit

Thickness = 300 nm  
Excitation frequency = 10 GHz

The boundary mode propagates around the corners without changing its properties.
I. New materials for magnonics

II. Novel means for magnon detection

III. Data processing using magnons

IV. Magnonic supercurrents
II. Novel means for magnon detection

Spin pumping + inverse spin Hall effect
Magnon to charge current conversion

Detection of magnons by a combination of spin pumping and inverse spin Hall effect

**Spin pumping**

- Tserkovnyak et al., PRL (2002)
- Costache et al., PRL (2006)

**Inverse spin Hall effect (ISHE)**

- Saitoh et al., APL 88 182509 (2006)
Time resolved ISHE voltage

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

Magnetic field $B = -175.5 \text{ mT}$
Microwave frequency 7 GHz

Parameters:
YIG thickness: 2.1 µm
YIG/Pt width: 3 mm
Pt thickness: 10 nm

Jungfleisch et al., APL 99, 182512 (2011)
Time resolved ISHE voltage

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

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Microwave frequency 7 GHz

Parameters:
- YIG thickness: 2.1 \( \mu \text{m} \)
- YIG/Pt width: 3 mm
- Pt thickness: 10 nm

- ISHE pulse has a long rise and fall times
- Secondary magnons contribute to ISHE

Jungfleisch et al., APL 99, 182512 (2011)
Surface modes contribute to spin pumping

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

Magnetic field \( B = +175.5 \text{ mT} \)

Dipolar-exchange waves contribute to spin pumping!

- ISHE pulse has a long rise and fall times
- Secondary magnons contribute to ISHE

Jungfleisch et al., APL 99, 182512 (2011)
Surface modes contribute to spin pumping

Yttrium iron garnet (YIG) / platinum (Pt) bilayer was used

But dipolar-exchange waves have zero velocities → no spin transport

Spin pumping by propagating magnons?
Spin-wave source and Pt detector are separated in space

Parameters:
- YIG thickness: 2.1 μm
- Pt size: 3 x 0.2 mm
- Pt thickness: 10 nm
- Signal frequency: 7 GHz
Spin pumping by exchange magnons

Parametric pumping at 14 GHz

Sandweg et al., PRL 106, 216601 (2011)

Sandweg et al., PRL 106, 216601 (2011)

Kurebayashi, Dzyapko et al., APL 99, 162502 (2011)
Ando et al., APL 99, 092510 (2011)
III. Data processing using magnons

Spin-wave logic gates
Mach-Zehnder interferometer based spin-wave logic gate

Kostylev et al., APL 87, 153501 (2005)
Schneider et al., APL 92, 022505 (2008)
“Interferometer on a waveguide”
“Interferometer on a waveguide” – BLS measurement

No current applied to the wire

240 mA applied to the wire

Schneider et al., J. of Nanoelectronics and Optoelectronics 3, 69 (2008)
Mach-Zehnder interferometer based spin-wave logic gate

Inputs
\[ A (I_1) \quad B (I_2) \]

Output
\[ 0 (0) \quad 0 (0) \quad 1 \]
\[ 0 (0) \quad 1 (I_{\pi}) \quad 0 \]
\[ 1 (I_{\pi}) \quad 0 (0) \quad 0 \]
\[ 1 (I_{\pi}) \quad 1 (I_{\pi}) \quad 1 \]

Realization of XNOR gate

Input: DC pulses
Output: magnon packets

How to control one magnon by another?

Schneider et al., APL 92, 022505 (2008)
III. Data processing using magnons

- Spin-wave logic gates
- Magnon transistor
Magnon transistor

Semiconductor field-effect transistor:

All-magnon device:
source-to-drain magnon flow shift by magnons in the transistor

Magnonic crystal acts as an enhancer of non-linear effects

A.V. Chumak et al., Nat. Commun. 5:4700 (2014)
Magnon transistor

**Opened:** $R \rightarrow 0$
Gate magnon density $n_G = 0$

**Semi-closed:** $R > 0$
Gate magnon density $n_G > 0$

**Closed:** $R \rightarrow \infty$
Gate magnon density $n_G >> 0$

A.V. Chumak et al., Nat. Commun. 5:4700 (2014)
**Magnon transistor**

**Opened:** $R \rightarrow 0$

Gate magnon density

$n_G = 0$

**Semi-closed:** $R > 0$

Gate magnon density

$n_G > 0$

**Closed:** $R \rightarrow \infty$

Gate magnon density

$n_G \gg 0$

---

A.V. Chumak et al., Nat. Commun. 5:4700 (2014)
Magnon transistor

Opened: $R \rightarrow 0$

Semi-closed: $R > 0$

Closed: $R \rightarrow \infty$

A.V. Chumak et al., Nat. Commun. 5:4700 (2014)
Magnon transistor

\[ n_G = 0.1 \ n_S \]

“magnon control by magnon“ principle was realized: data can be processed on the same magnetic chip.

A.V. Chumak et al., Nat. Commun. 5:4700 (2014)
Logic operations

XOR logic gate

<table>
<thead>
<tr>
<th>I₁</th>
<th>I₂</th>
<th>O</th>
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</thead>
<tbody>
<tr>
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XOR gate requires 2 transistors instead of 8 FET in CMOS

Half adder

<table>
<thead>
<tr>
<th>I₁</th>
<th>I₂</th>
<th>C</th>
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III. Data processing using magnons

- Spin-wave logic gates
- Magnon transistor
- Magnon majority gate
**Majority gate**

**Phase Shifter**

**Parametric Amplifier**
- T. Brächer, et al., APL 103, 142415 (2013)

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**Diagram**
- **Magnon Source**
- **Magnon Processor**
- **Magnon Detector**
Majority gates: Design

Design of a spin-wave majority gate employing mode selection

S. Klingler, P. Pirro, T. Brächer, B. Leven, B. Hillebrands, and A. V. Chumak

Fachbereich Physik and Landesforschungszentrum OPTIMAS,
Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

(Dated: August 15, 2014)

Majority gate design:
100 nm YIG, Pirro et al., APL 104, 012402 (2014)

Truth-table:

<table>
<thead>
<tr>
<th>Input 1</th>
<th>Input 2</th>
<th>Input 3</th>
<th>Output</th>
</tr>
</thead>
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</tbody>
</table>

In CMOS 56 transistors (3 NOT, 4 AND, 3 OR) are needed for majority gate

Data is coded into spin-wave phase

S. Klinger et al., arXiv: 1408.3235
Majority gates: Simulations

(a) 2 µm width (inputs)
(b) 1 µm width (output)

- Frequency (GHz)
- Wavevector (rad/µm)

Excitation frequency

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
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<tr>
<td>110</td>
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<tr>
<td>101</td>
<td>&quot;1&quot;</td>
</tr>
<tr>
<td>111</td>
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</tbody>
</table>
Majority gates: Out-of-plane magnetization

Switch from the in-plane magnetization to the out-of-plane (see e.g. T. Schwarze, et al., Phys. Rev. B 85, 134448 (2012))

Forward volume spin waves are isotropic (always transverse to field)

but no parasitic generation of high-wavenumber magnons
Majority gates: Out-of-plane magnetization

How to increase this value?
Majority gates: Out-of-plane magnetization

Results of numerical simulation (MuMax 2)
III. Data processing using magnons

- Spin-wave logic gates
- Magnon transistor
- Magnon majority gate
- Magnon multiplexer
Spin-wave propagation path was controlled by a DC current

Computing principles

- Classical Computing
  - Scalar variable
  - Boolean logic
- Wave Computing
  - Vector variable
  - Special task data processing
- Quantum Computing
  - Vector state variable
  - Entanglement
IV. Magnonic supercurrents

Main idea: find macroscopic magnonic quantum states for information transfer and processing

- analogous to superconductivity (Josephson currents), and to superfluidity in $^3$He and $^4$He
- free of dissipation (apart from magnon-phonon and magnon-electron coupling)

- Bose-Einstein Condensation (BEC) of magnons
- Supercurrents in magnon condensates
Magnon gas

Magnon as a quanta of spin-wave

- Energy \( \epsilon = \hbar \omega = \frac{\eta}{\hbar} p^2 \)
- Momentum \( \vec{p} = \hbar \vec{q} \)
- Mass \( m = \hbar / (2\eta) \)
- Spin \( s = 1 \)
- Lifetime \( \sim 700 \text{ ns} \)!
( Yttrium Iron Garnet, \( Y_3Fe_5O_{12} \) )
Magnon scattering

TWO-MAGNON SCATTERING

\( \varepsilon_1, p_1 \rightarrow \varepsilon_1, p_2 \)

Magnon gas of interacting quasiparticles
Number of particles is conserved

FOUR-MAGNON SCATTERING

\( \varepsilon_1, p_1 \rightarrow \varepsilon_3, p_3 \)
\( \varepsilon_2, p_2 \rightarrow \varepsilon_4, p_4 \)
Magnons are **bosons** \((s=1)\) and thus as any quasi-particles are described by Bose-Einstein distribution with **zero chemical potential**.
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws

\[ \begin{align*}
\vec{q}_{SW} + \vec{q}'_{SW} &= \vec{q}_p \approx 0 \\
\vec{f}_{SW} + \vec{f}'_{SW} &= \vec{f}_p
\end{align*} \]

Parametric pumping by electromagnetic wave at microwave frequency

Bose-Einstein distribution

\[ \rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_B T}\right) - 1} \]

\( \mu \): chemical potential
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws:
\[
\begin{align*}
\vec{q}_{sw} + \vec{q} &= \vec{q}_p \approx 0 \\
f_{sw} + f'_{sw} &= f_p
\end{align*}
\]

Parametric pumping by electromagnetic wave at microwave frequency.

Bose-Einstein distribution:
\[
\rho(f) = \frac{D(f)}{\exp\left(\frac{hf - \mu}{k_B T}\right) - 1}
\]

µ: chemical potential

Magnon thermalization due to 4-particle scattering: incoherent magnon gas.
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws
\[
\begin{align*}
\mathbf{q}_{sw} + \mathbf{q}'_{sw} &= \mathbf{q}_p \approx 0 \\
\mathbf{f}_{sw} + \mathbf{f}'_{sw} &= \mathbf{f}_p
\end{align*}
\]

Parametric pumping by electromagnetic wave at microwave frequency

\[Y_3Fe_2O_{12}(YIG)\]

\[\hbar \vec{p} \rightarrow \vec{H}_0\]

Bose-Einstein distribution
\[\rho(f) = \frac{D(f)}{\exp\left(\frac{\hbar f - \mu}{k_B T}\right) - 1}\]

\[\mu: \text{chemical potential}\]

Bose-Einstein condensate of magnons

Magnon thermalization due to 4-particle scattering: incoherent magnon gas

\[\mu = E_{\text{min}}\]
Brillouin light scattering spectroscopy

Brillouin light scattering process
= inelastic scattering of photons from spin waves

\[ f_{\text{scattered}} = f_L \pm f \]
\[ q_{\text{scattered}} = \bar{q}_L \pm \bar{q} \]

incident photon \( f_L, \bar{q}_L \)
magnons \( f, \bar{q} \)
scattered photon \( f_L \pm f, \bar{q}_L \pm \bar{q} \)
Time-resolved Brillouin light scattering spectroscopy
Decrease of density of parametric magnons and gaseous magnon phase

Sharp increase of intensity of pumping free BEC of magnons

Parametric magnons, gaseous phase, and magnon BEC

- Pumping pulse
  - Parametrically injected magnons
    - $T_{\text{fall}} = 10 \text{ ns}$
- Gaseous phase
  - $T_{\text{fall}} = 75 \text{ ns}$
- Rise time of the BEC-peak
  - $T_{\text{BEC}}^{\text{rise}} = 70 \text{ ns}$
- Bose-Einstein condensate
- Decay time of the BEC
  - $T_{\text{BEC}}^{\text{decay}} = 400 \text{ ns}$
Evaporative supercooling of strongly overheated low energy area of the magnon gas

Serga et al., Nature Communications 5, 4452 (2014)
Influence of power of probing laser beam

Parametrically injected magnons
- No influence from laser power on temporal dynamics!
- Laser heating decreases magnetization and thus strongly shifts down the magnon dispersion branch

Bose-Einstein condensate
- Increasing laser power results in significant decrease of the BEC’s lifetime and amplitude!
- Only weak frequency shift of BEC due to temperature change

[Graphs showing normalized BLS intensity over time for different laser powers, highlighting the effects on magnon dispersion and Bose-Einstein condensation.]
Magnon supercurrents – magnon BEC dynamics in thermal gradient

BLS Intensity (a.u.)

Time (µs)

Pump pulse

Probing laser beam 2 mW

No influence of uniform heating

Air heating 22-50°C
Magnon supercurrents – magnon BEC dynamics in thermal gradient

BLS Intensity (a.u.)

Time (µs)

0 0.5 9.5 10.0 10.5 11.0 11.5 12.0

Pump pulse

Probing laser beam 250 mW

Strong influence of focused light

Air heating

22-50°C

50°C
Magnon supercurrents – magnon BEC dynamics in thermal gradient

BLS Intensity (a.u.)

Time (µs)

Pump pulse

Probing laser pulse

250 mW

16 µs

<< < 50°C

Pump pulse

Burkard Hillebrands

IEEE Magnetics Society Summer School - Minneapolis

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Magnon supercurrents – magnon BEC dynamics in thermal gradient

- Decrease of population of magnon BEC changes with temperature gradient
- Magnon supercurrent phase induced outflow of condensed magnons
- Relaxation of gaseous magnon phase no temperature dependence

Time (μs)

BLS Intensity (a.u.)

Pump pulse
Magnonic supercurrents

\[ \text{BEC 1} \]
Temperature \( T_1 \)
Phase \( \phi_1 \)

\[ \text{BEC 2} \]
Temperature \( T_2 \)
Phase \( \phi_2 \)

\[ T_1 > T_2 \rightarrow \phi_1 \neq \phi_2 \]
Sample of better quality: Magnon lifetime 700 ns
Probing laser power 0.8 mW ensures small BEC outflow

Why so long lifetime?

Long existence time of the magnon BEC in the probing point
Oscillations of the BEC lifetime

Sample of better quality: Magnon lifetime 700 ns

Probing laser power 0.8 mW ensures small BEC outflow

Long existence time of the magnon BEC in the probing point

Probing laser power 20 mW

Gaseous magnon phase
BEC in gradient of saturation magnetization

\[ J \propto \nabla \varphi \]

\[ \Delta \varphi = \Delta \omega t \]

\[ J \propto \sin(\Delta \omega t) \]

Outcoming supercurrent

\[ \varphi_1 = \varphi_2 - \pi/2 \]

Incoming supercurrent

\[ \varphi_1 = \varphi_2 + \pi/2 \]

No supercurrent for gaseous phase
Magnonics: Challenges

- New insulators
- Materials with controlled damping
- Novel artificial materials
- Materials with controlled spin-orbit coupling

- Magnon Bose (Einstein) condensates
- Spin Transfer Torque effect in insulators
- Miniaturization
- THz magnonics
- Single magnon generation and detection

- Magnon supercurrents
- Dzyaloshinskii-Moria interactions
- Electric field effects

- Enhancement of existing techniques
- TMR
- Quantum effects