Magnon supercurrents in a room temperature magnon condensate

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CMOS is coming to the end of Moore’s law
- Waste energy production
- End of scaling

Beyond current CMOS:
- Faster computing, less energy consumption
- Same technology for logic and data
- Logic circuits with reduced footprint and/or 3D

Novel paradigm: wave computing

Proposal:
use waves /wave packets instead of particles (electrons) for bit representation
Magnon computing

Why spin waves/magnons?

- wavelength down to nanometer, frequency up to several THz
- interference effects easily accessible
- efficient nonlinear effects
- room temperature
- no Joule heat, “insulatronics”
- wave-based computing: smaller footprint, all-wave logic
- good converters to CMOS

→ “magnon spintronics”

Achievements:

Logic gates

Magnon source
Input 2
Output

Andrii Chumak, Kaiserslautern
Magnon computing

Achievements:

- Logic gates
- Magnon transistor

Why spin waves?

- Wavelength down to **nanometer**, frequency up to **several THz**
- Interference effects easily accessible
- Efficient **nonlinear effects**
- Room temperature
- No Joule heat, “insulatronics”
- Wave-based computing: smaller footprint, all-wave logic
- Good converters to CMOS

→ “magnon spintronics”
Concept of magnon spintronics

- Magnon packet computing: go to deep exchange regime → THz computing, small feature size
- Develop efficient converters
- Engineering of interactions
- New materials
  - low damping
  - compatibility with CMOS
  - compatibility with existing production equipment
- Macroscopic magnonic quantum states computing

### Spin-wave device architectures

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![Diagram](image-url)

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Burkard Hillebrands  | Quantum Spintronics  | Mainz, September 21, 2016
Benchmarking

Hybrid CMOS-Spin Wave Device Circuits Compared to 10nm CMOS

The list includes adders, multipliers, a divider, and a cyclic redundancy check module

* Area-Delay-Power-Product (ADPP)

Benchmarking

Hybrid CMOS-Spin Wave Device Circuits Compared to 10nm CMOS

Area: 3.5x smaller
Delay: 10-20x slower
Power consumption: 100x lower
ADPP: 50-100x better!

* Area-Delay-Power-Product (ADPP)

Zografos, et al., Proceedings of the 15th IEEE International Conference on Nanotechnology
July 27-30, 2015, Rome, Italy
Novel magnon states

Main idea:
find novel magnon states useful for information transfer and processing

Here:
- macroscopic magnonic quantum states for information transfer and processing

A. Serga upcoming talk:
- magnon-phonon states at minimum energy and with large group velocity

Macroscopic magnonic quantum states:
- 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)
- prominent example: magnonic Bose Einstein condensate
Magnon spectrum of in-plane magnetized ferrimagnetic YIG film

Landau-Lifshitz equation:
\[
\frac{\partial \overrightarrow{M}}{\partial t} = -\gamma \overrightarrow{M} \times \overrightarrow{H}_{\text{eff}}
\]

\[
\overrightarrow{H}_{\text{eff}}(r) = \overrightarrow{H}_0 + \int \overrightarrow{G}(r,r') \cdot \overrightarrow{M}(r') \, dr^3 + \frac{\eta}{\gamma M_S} \nabla^2 \overrightarrow{M} + \ldots
\]

dipolar interaction  \hspace{1cm}  exchange interaction

\[Y_3Fe_5O_{12} (YIG)\]

\[H_0 = 1710 \text{ Oe}\]

Frequency \(f\) (GHz)

Wavenumber \(q\) (\(\times 10^5\) rad/cm)
(Non-)linear Processes

- Linear process
- Nonlinear processes

### Linear process

**Four-magnon scattering**

### Nonlinear processes

- **Two-magnon scattering**
- **Three-magnon decay**
- **Three-magnon confluence**
- **Four-magnon scattering**

**Magnon gas of interacting quasiparticles**

*Number of particles is conserved*
Magnons are **bosons** \((s=1)\) and thus, as any quasi-particles, described by a Bose-Einstein distribution with zero chemical potential.

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

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

Energy and momentum conservation laws

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

Parametric pumping by electromagnetic wave at microwave frequency

Bose-Einstein distribution

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

\(\mu\): chemical potential

\(\mu = 0\)

\(\vec{q} \perp \vec{H}\) at \(f_p/2\)

\(\vec{q} \parallel \vec{H}\)

\(\vec{H}_0\)
Control of magnon gas density by parametric pumping

Energy and momentum conservation laws:

\[ \mathbf{q}_{sw} + \mathbf{q}^\prime_{sw} = \mathbf{q}_p \approx 0 \]
\[ f_{sw} + f^\prime_{sw} = f_p \]

Parametric pumping by electromagnetic wave at microwave frequency.

Bose-Einstein distribution:

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

\( \mu \): 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

\[
\begin{align*}
\vec{q}_{\text{sw}} + \vec{q}_{\text{sw}}' &= \vec{q}_p \approx 0 \\
\left. f \right|_{\text{sw}} + \left. f \right|_{\text{sw}}' &= f_p
\end{align*}
\]

Parametric pumping by electromagnetic wave at microwave frequency


Bose-Einstein condensate of magnons

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

\[ \mu = E_{\text{min}} \]

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

\( \mu \): chemical potential

\( Y_3Fe_5O_{12} (YIG) \)

\( \vec{h}_p \)

\( \vec{H}_0 \)
Brillouin light scattering (BLS) spectroscopy

- Inelastic scattering of photons from spin waves:
  \[
  f_{\text{scattered}} = f_L \pm f_{\text{sw}} \\
  \vec{q}_{\text{scattered}} = \vec{q}_L \pm \vec{q}_{\text{sw}}
  \]

- Intensity of the scattered light is proportional to magnon density
Time- and wavevector-resolved Brillouin light scattering spectroscopy

**Resolution**
- Time: 1 ns
- Frequency: 50 MHz
- Wavenumber: $2 \times 10^3$ rad/cm

(111) LPE YIG films
- Width of the pumping area: 50 µm
- Length of the pumping area: 1 mm
- Max microwave power: 100 W
Time- and wavenumber-resolved BLS measurements of magnon BEC

BEC is formed during the pumping pulse is on

A. A. Serga et al., Nat. Commun. 5, 4452 (2014)
Time- and wavenumber-resolved BLS measurements of magnon BEC

BEC is formed during the pumping pulse is on

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

BEC is formed after the pumping pulse is switched off due to decrease of effective temperature of a magnon gas

A. A. Serga et al., Nat. Commun. 5, 4452 (2014)
Time-resolved measurements of parametric magnons, gaseous phase, and magnon BEC

Decrease of density of parametric magnons and gaseous magnon phase
Sharp increase of intensity of pumping free BEC of magnons

- Pumping pulse
  - Parametrically injected magnons
  - $T_{\text{fall}} = 10\ \text{ns}$

- Gaseous phase
  - $T_{\text{fall}} = 75\ \text{ns}$

- Bose-Einstein condensate
  - Rise time of the BEC-peak $T_{\text{BEC}}^{\text{rise}} = 70\ \text{ns}$
  - Decay time of the BEC $T_{\text{BEC}}^{\text{decay}} = 400\ \text{ns}$
Parametric magnons, gaseous phase, and magnon BEC

Cooling of strongly overheated low energy area of the magnon gas

A. A. Serga et al., Nat. Commun. 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 might shift down the magnon dispersion curves

**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
Magnon BEC dynamics for uniform temperatures

Pump pulse 2 μs
Low power probing laser beam
Air heating 27-45°C
Decrease in the steady-state magnon density due to higher magnon damping and lower efficiency of the parametric pumping.
Magnon BEC dynamics for uniform temperatures

No influence of uniform heating on the decrease of population of magnon BEC
Magnon BEC dynamics for uniform temperatures

No influence of uniform heating on the decrease of population of magnon BEC

Pump pulse 2 µs

Low power probing laser beam

Air heating 27-45°C

BLS intensity (counts)

τ_p = 2 µs

27°C

35°C

40°C

45°C

Time (µs)
Dynamics of condensed magnons in thermal gradient

D. A. Bozhko et al., Nature Physics, DOI: 10.1038/NPHYS3838 (2016)
Dynamics of condensed magnons in thermal gradient

D. A. Bozhko et al., Nature Physics, DOI: 10.1038/NPHYS3838 (2016)
Magnonic supercurrents

Particle current: BEC 1
- Temperature $T_1$
- Phase $\phi_1$

BEC 2
- Temperature $T_2$
- Phase $\phi_2$

Phase gradient leads to the formation of magnonic supercurrents

$T_1 > T_2$ \Rightarrow $\phi_1 \neq \phi_2$
Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations

$$\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_p N_p e^{-\Gamma_\sigma t} - A_{gb} N_g^3 + A_{bg} N_b^3$$

$$\frac{\partial N_b}{\partial t} = -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr})$$

$$\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr})$$

$N_{cr}$ — a critical number of magnons at which the chemical potential $\mu$ of the magnon gas reaches $\omega_{\text{min}}$.
Dynamics of condensed magnons in thermal gradient - theory

Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations.

With thermal gradient

Supercurrent

Supercurrent $\vec{J}(\vec{r},t) = \frac{\hbar}{m} N_c \nabla \phi$ gradient

BEC density: $N_c = |\psi|^2$

BEC phase: $\phi = \text{arg}(\psi)$

Magnon mass: $m = \hbar / \left\langle \frac{\partial^2 \omega(q)}{\partial q^2} \right\rangle$

Complex BEC wave function: $\psi(\vec{r},t)$

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $\vec{J}(\vec{r},t)$

V. L’vov, A. Pomyalov
Dynamics of condensed magnons in thermal gradient - theory

Dynamics of condensed magnons \( N_c(t) \), magnons in gaseous states \( N_g(t) \) and gaseous magnons at the bottom of SW spectrum \( N_b(t) \) was described using balance equations

\[
\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_g N_p e^{-\Gamma_g t} - A_{gb} N_g^3 + A_{bg} N_b^3
\]

\[
\frac{\partial N_b}{\partial t} = -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr})
\]

\[
\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr}) - \frac{\partial J_x}{\partial x} - \frac{\partial J_y}{\partial y}
\]

\[J_x = N_c D_x \frac{\partial \varphi}{\partial x}\]

\[J_y = N_c D_y \frac{\partial \varphi}{\partial y}\]

Anisotropic dispersion coefficients:

\[D_x = \frac{1}{2} \frac{d^2 \omega(q)}{dq_x^2}\]

\[D_y = \frac{1}{2} \frac{d^2 \omega(q)}{dq_y^2}\]

In experiment:

\[D_x \approx 21 D_y\]

\[J_T = J_x \gg J_y\]
Dynamics of condensed magnons in thermal gradient - theory

Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations

\[
\begin{align*}
\frac{\partial N_g}{\partial t} &= -\Gamma_g N_g + \Gamma_p N_p e^{-\Gamma_0 t} - A_{gb} N_g^3 + A_{bg} N_b^3 \\
\frac{\partial N_b}{\partial t} &= -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr}) \\
\frac{\partial N_c}{\partial t} &= -\Gamma_c N_c + A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr}) - \frac{\partial J_T}{\partial x}
\end{align*}
\]

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $J_T(x,t)$

With thermal gradient

1D thermally driven supercurrent

\[J_T = N_c D_x \frac{\partial \varphi}{\partial x}\]

\[\delta \varphi = \delta \omega_c(x) t\]

weak frequency shift of the magnon BEC due to temperature change

V. L’vov, A. Pomyalov
Dynamics of condensed magnons in thermal gradient - theory

Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations

\[
\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_g N_p e^{-\Gamma_d t} - A_{gb} N_g^3 + A_{bg} N_b^3
\]

\[
\frac{\partial N_b}{\partial t} = -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr})
\]

\[
\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr}) - \frac{\partial J_T}{\partial x} + \frac{\partial J_{\text{dis}}}{\partial x}
\]

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $J_x(x)$

1D thermally driven supercurrent

\[ J_T = N_c D_x \frac{\partial \phi}{\partial x} \]

\[ \delta \phi = \delta \omega_c(x) t \]

1D dispersive supercurrent

\[ J_{\text{dis}} = -D_x \frac{\partial N_c}{\partial x} \]

V. L’vov, A. Pomyalov
Dynamics of condensed magnons in thermal gradient - theory

Dynamics of condensed magnons $N_c(t)$, magnons in gaseous states $N_g(t)$ and gaseous magnons at the bottom of SW spectrum $N_b(t)$ was described using balance equations:

\[
\frac{\partial N_g}{\partial t} = -\Gamma_g N_g + \Gamma_p N_p e^{-\Gamma_0 t} - A_{gb} N_g^3 + A_{bg} N_b^3
\]

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\frac{\partial N_b}{\partial t} = -\Gamma_b N_b + A_{gb} N_g^3 - A_{bg} N_b^3 - A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr})
\]

\[
\frac{\partial N_c}{\partial t} = -\Gamma_c N_c + A_{bc} (N_b^3 - N_{cr}^3) \Theta(N_b - N_{cr}) - \frac{\partial J_T}{\partial x} + \frac{\partial J_{dis}}{\partial x}
\]

Additional decrease of population of condensed magnons $N_c(t)$ due to magnon supercurrent $J_x(x)$

1D thermally driven supercurrent

\[ J_T = N_c D_x \frac{\partial \varphi}{\partial x} \]

1D dispersive supercurrent

\[ J_{dis} = -D_x \frac{\partial N_c}{\partial x} \]

Total supercurrent

\[ J = -B_s N_c \delta \omega_c t + B_{dis} (N_c^0 - N_c) \]

\[ B_s \sim B_{dis} \sim -\frac{D_x}{R} \]

V. L'vov, A. Pomyalov
Dynamics of condensed magnons in thermal gradient - comparison with theory

\[ \delta \phi = \delta \omega_c (T) t \]

Thermally induced frequency shift of the magnon BEC

\[ \frac{\delta \omega_c (T)}{2\pi} \]

- 0 kHz
- 25 kHz
- 100 kHz
- 198 kHz
- 550 kHz

Corresponding maximal temperature change

4.7 K

D. A. Bozhko et al., Nature Physics, DOI: 10.1038/NPHYS3838 (2016)
Dynamics of condensed magnons in thermal gradient - comparison with theory

\[ \delta \varphi = \delta \omega_c(T) t \]

Thermally induced frequency shift of the magnon BEC, \( \delta \omega_c(T) / 2\pi \)

- 0 kHz
- 25 kHz
- 100 kHz
- 198 kHz
- 550 kHz

COMSOL simulation using 3D heat-transfer model

5.7 K

Observed dynamics of a room-temperature magnon condensate in a ferromagnetic film subject to a thermal gradient can be understood both quantitatively and qualitatively taking into account magnon supercurrents.

D. A. Bozhko et al., Nature Physics, DOI: 10.1038/NPHYS3838 (2016)
1. Magnonics provides model system for macroscopic quantum phenomena
   - Room temperature experiments
   - Tool: Brillouin light scattering
2. First evidence for magnon supercurrent in magnonic Bose Einstein condensate found
3. Supercurrent depends on phase gradient
4. Phase gradient induced by lateral temperature gradient