Exchange magnon spin transport in the magnetic insulator yttrium iron garnet

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Magnon Spintronics

Magnon spintronics, at GHz frequencies

Connecting magnonics and spintronics, without frequency selection
Exciting magnons by spin-flip scattering

- Localized magnon injection (at Metal|YIG interface)
- Spin accumulation generates magnon accumulation
- Linear process

Conduction electron spin-up -> spin-down + magnon

Spin-down + magnon -> spin-up
Non-local experiment

Electrical magnon injection

Current $I$ is AC
Measure $V(\omega)$

Linear regime
Non-local resistance

: $I(\omega) = A \sin \omega t$
: 1\textsuperscript{st} harmonic $V(1\omega) \propto I$
: 2\textsuperscript{nd} harmonic $V(2\omega) \propto I^2$
: $V \propto I$
: $R_{nl} = \frac{V}{I}$
Devices

Long distances
2.5µm < d < 160µm
Device length 100µm

Short distances
200nm < d < 5µm
Device length 12.5µm

Pt
Ti/Au
Electrical magnon generation

Injector: $\mu^\parallel$ generates magnons $\rightarrow \cos \alpha$
Detector: $\mu_d$ contributes to $V_c \rightarrow \cos \alpha$
1$\omega$ signal is product of the two: $\cos^2 \alpha$
Distance dependence

1D spin diffusion equation:
\[ \frac{d^2 n_m}{dx^2} = \frac{n_m}{\lambda^2} \]

+ B.C. yields:
\[ R_{\text{non-local}} (d) = \frac{A}{\lambda} \cdot \frac{\exp(d/\lambda)}{1-\exp(2d/\lambda)} \]

\[ \lambda = 9.4 \pm 0.6 \ \mu m \]

Relaxation regime -> exponential decay
Diffusive regime -> 1/d decay
Parameters of the magnon system

Does not work!

- $\kappa_m$ several orders of magnitude too small
- $\lambda_{m-ph}$ several orders of magnitude too small

*J. Xiao et al., PRB 81, 214418 (2010)
Magnon chemical potential

> Out of equilibrium parameters for the system
  - $\mu_m$
  - $T_m$

> Conservation of magnon number ($\mu_m$)
  - Timescale limited by magnon-relaxation

> Conservation of energy ($T_m$)
  - Timescale limited by magnon-relaxation and magnon-phonon scattering
Magnon chemical potential

Modeling the experiments

\( \text{Linear response transport theory}^1 \)

\[
\begin{pmatrix}
\frac{2e}{\hbar} j_m \\
\frac{\hbar L}{2e} j_{Q,m}
\end{pmatrix}
= -
\begin{pmatrix}
\sigma_m & L/T \\
\hbar L/2e & \kappa_m
\end{pmatrix}
\begin{pmatrix}
\nabla \mu_m \\
\nabla T_m
\end{pmatrix}
\]

- \( j_m \) Magnon spin current density,
- \( \sigma_m \) Magnon spin conductivity,
- \( L \) Bulk spin Seebeck coefficient,
- \( \mu_m \) Magnon chemical potential,
- \( j_{Q,m} \) Magnon heat current density
- \( \kappa_m \) Magnon heat conductivity
- \( T \) Ambient temperature
- \( T_m \) Magnon temperature
Finite element model

- FEM gives the magnon chemical potential profile

- Find the spin current into the contacts:
  \[ j^\text{int}_s = g_s (\mu_m - \mu_s) \]
FEM results

Good agreement with experiments, for electrical generation

However, does not predict YIG thickness dependence of the signal correctly


We extract:

\[ \sigma_m = 5 \times 10^5 \text{ S/m} \]
\[ g_s = 0.96 \times 10^{13} \text{ S/m}^2 \]
Effect of temperature
Electrical magnon injection

- T-dependence agrees qualitatively with other observations*
- Distance dependence and FEM can be used to find:
  - $\lambda_m(T)$
  - $\sigma_m(T)$

*S.T.B. Goennenwein et al., APL **107**, 172405 (2015)
Vélez et al., arxiv:1606.02968 (2016)
Wu et al., PRB **93** 060403(R) (2016)
$\lambda_m(T)$ and $\sigma_m(T)$

Thermal magnon generation

Temperature gradient causes magnon spin current

\[ \left( \frac{2e}{\hbar} \mathbf{j}_m \right) = - \begin{pmatrix} \sigma_m & \frac{L}{T} \\ \frac{\hbar L}{2e} & \kappa_m \end{pmatrix} \begin{pmatrix} \nabla \mu_m \\ \nabla T_m \end{pmatrix} \]

Joule heating in device causes magnon accumulation

Electrical

Thermal
Non-local experiment
Thermal magnon injection

Injection relies on spin Seebeck effect
\[ \frac{2e}{\hbar} j_m = -\frac{L_m}{T} \nabla T_m \]

And
\[ \nabla T_m \propto I^2 \]

With:
- \( L_m \): bulk spin Seebeck coefficient
- \( T_m \): magnon temperature
- \( j_m \): magnon spin current
Angle dependent measurements: $2\omega$

- Injector: $I^2$ generates heat $\rightarrow$ const.
- Detector: $\mu_d$ contributes to $V_c$ $\rightarrow$ $\cos \alpha$
- $2\omega$ signal $\rightarrow$ $\cos \alpha$
Electrical vs thermal injection
Long distances

$1\omega$ (Electrical)

$2\omega$ (Thermal)

$\lambda^{1\omega} = 9.4 \pm 0.6 \, \mu m$

$\lambda^{2\omega} = 8.7 \pm 0.8 \, \mu m$
Model for thermal generation

- Heat current flows outward from detector
- SSE generates magnon spin current
- Magnon current cannot enter GGG
- Magnon accumulation at interface

Electrical vs thermal injection
Short distances

1ω

![Graph showing R_{ni1}^1 vs distance (μm)]

- 1/d decay indicates diffusive transport, for d < λ
- Thermally excited magnons behave differently for d ≈ t_{YIG} -> injector not a localized source for thermal magnons.

2ω

![Graph showing R_{ni2}^2 vs distance (μm)]
Effect of temperature

Electrical vs thermal magnon injection

- Complex T-dependence of $2\omega$ is not yet understood
Summary (I)

- Conversion between charge, electronic spin and magnonic spin currents

  Electrical magnon injection
  Thermal magnon injection

- YIG is a good conductor for diffuse spin currents, long spin diffusion length $\lambda_m = 9.4 \pm 0.6 \mu m$ at low fields and RT
Summary (II)

- Magnon chemical potential is an essential parameter in describing the magnon spin transport.

Temperature dependencies for electrical and thermal injection are completely different, but spin diffusion lengths agree.

1ω

2ω

λ
Thank you!

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