Spintronic operation in antiferromagnets

Takahiro Moriyama

Institute for Chemical Research, Kyoto University

Highlights

1. Spin pumping in FM/AFM
2. Terahertz spin pumping in AFM
3. Fabrication of chiral antiferromagnet Mn_3Ir

KYOTO UNIVERSITY

Nano spin conversion

CSRN
@Osaka Univ.

CSRN
@Tohoku Univ.

科研費 KAKENHI

Possibility of antiferromagnetic spintronics

	Magnetic susceptibility	Resonant frequency
FM	~ 10^3 *	A few 10 GHz
AFM	~ 10^{-2} **	A few THz

* Typical value of Fe
** Typical value of MnF_2

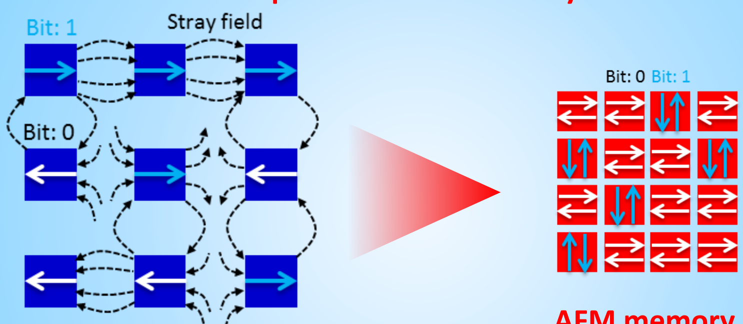
Small susceptibility

Ultra high density memory
Tolerance to field disturbance

THz dynamics

High speed magnetization switching
THz emission

Close packed memory bits



FM memory
Bit interference
due to stray field

AFM memory
No stray field allows 100 times more packed bits*

*S. Loth *et al.*, *Science* **335**, 196 (2012).

THz emission

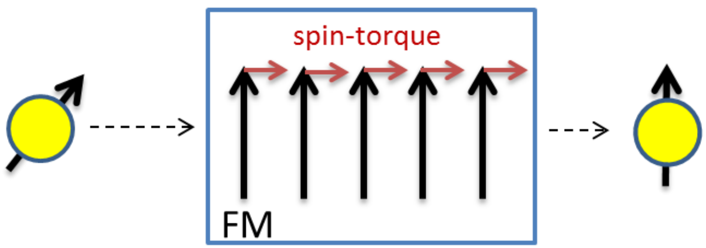
THz emission using antiferromagnetic resonance excited by spin current

See reviews in: Jungwirth et al., Nat. Nanotechnol., 11, 231 (2016), and Baltz, TM, et al., RPM 90, 015005 (2018)

Spin current interaction in AFM

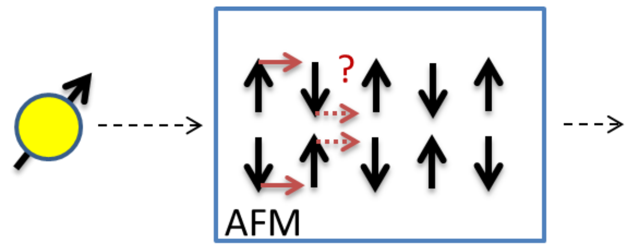
How is the spin torque exerting in antiferromagnets?

(a) Case of FM



Well known

(b) Case of AFM



?

Spin current dissipation and spin torque

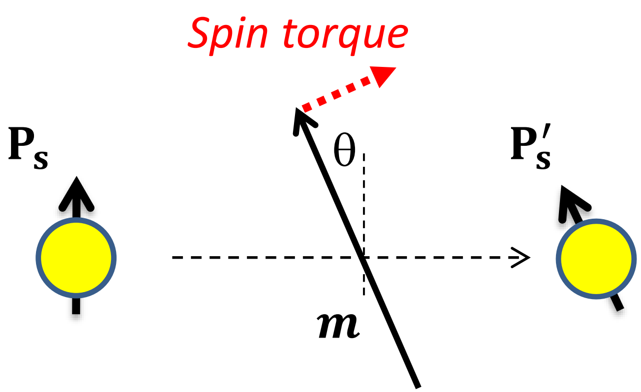
Ferromagnet

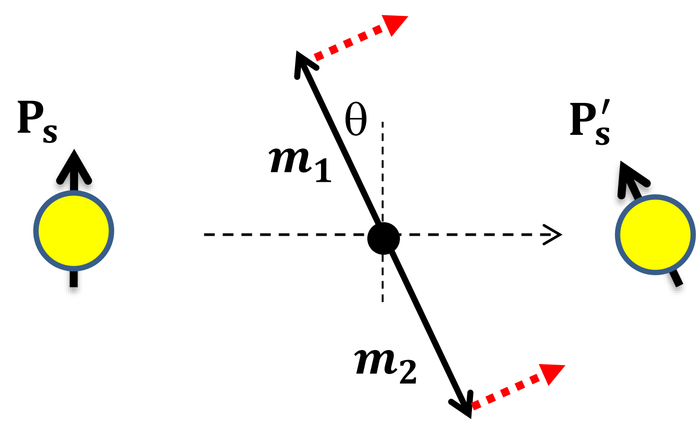
$$\left.\frac{d\mathbf{m}}{dt}\right|_{spin\ torque} \propto \mathbf{m} \times (\mathbf{m} \times \mathbf{P_s}) \Longrightarrow |\mathbf{P_s}|(\sin\theta)^2$$

Antiferromagnet

$$\left.\frac{d\mathbf{m}}{dt}\right|_{spin\ torque} \propto \mathbf{I} \times (\mathbf{I} \times \mathbf{P_s}) \Longrightarrow |\mathbf{P_s}|(\sin\theta)^2$$

* in a strong exchange limit
Gomonay, et al., *PRB* **81**, 144427 (2010)





$$\mathbf{I} = \boldsymbol{m_1} - \boldsymbol{m_2}$$

$\mathbf{P_s}$ = *spin torque* + $\mathbf{P_s'}$

||

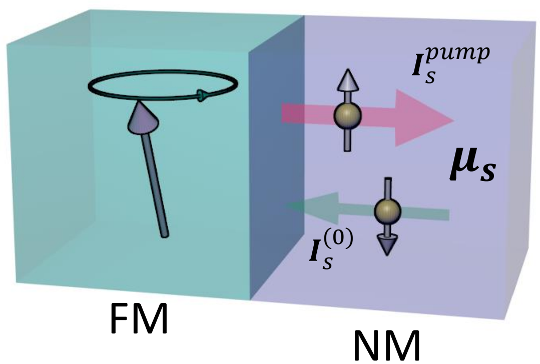
Spin dissipation in the spin current point of view

Moriyama, *PRL* 119, 267204 (2017)

Damping enhancement by spin pumping effect

Damping enhancement as a probe of spin torque effect.

FM/NM spin pumping



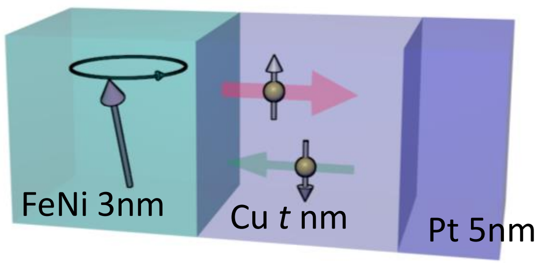
Damping α of the FM (FMR linewidth) is enhanced due to the spin current dissipation in NM.

$$\alpha \propto I_s^{pump} - I_s^{(0)}$$

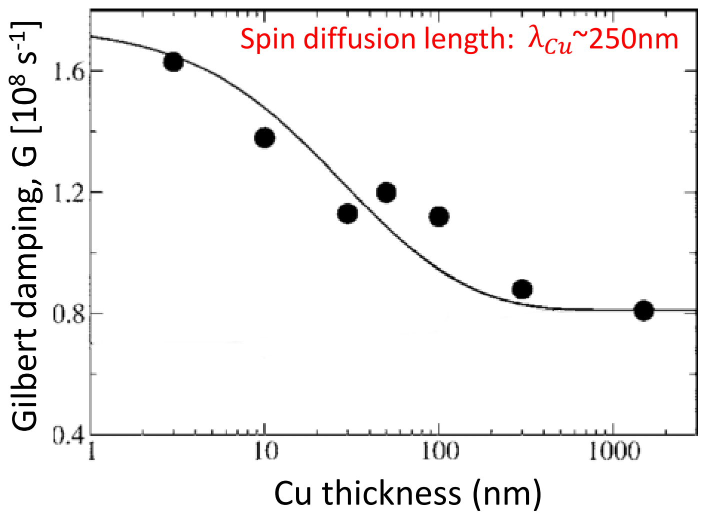
$$\begin{cases} I_s^{pump} = \dfrac{g_r^{\uparrow\downarrow}}{4\pi} m \times \dfrac{dm}{dt} \\ I_s^{(0)} = \dfrac{g_r^{\uparrow\downarrow}}{4\pi} m \times \mu_s \times m \end{cases}$$

Tserkovnyak, et al. *RMP* **77**, 1375 (2005)

Mizukami, *PRB* **66**, 104413 (2002)



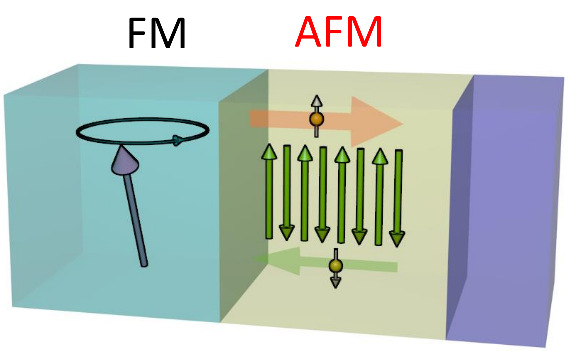
$$Damping\ enhancement \propto \left[1 + \tilde{g}_r^{\uparrow\downarrow} R_{sd} \frac{1 + \tanh(t_{Cu}/\lambda_{Cu})\tilde{g} R_{sd}}{\tanh(t_{Cu}/\lambda_{Cu}) + \tilde{g} R_{sd}}\right]^{-1}$$



Damping enhancement with AFM

Damping enhancement as a probe of spin dissipation in AFM.

FM/AFM spin pumping



FM dynamics

Spin pumping injection of I_s into AFM

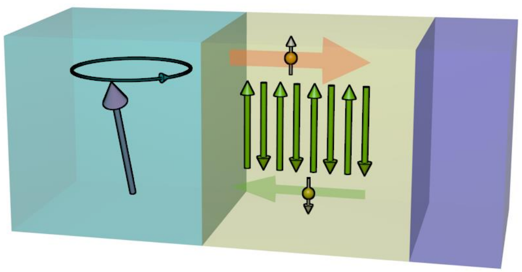
I_s dissipation in AFM

Damping change of FM

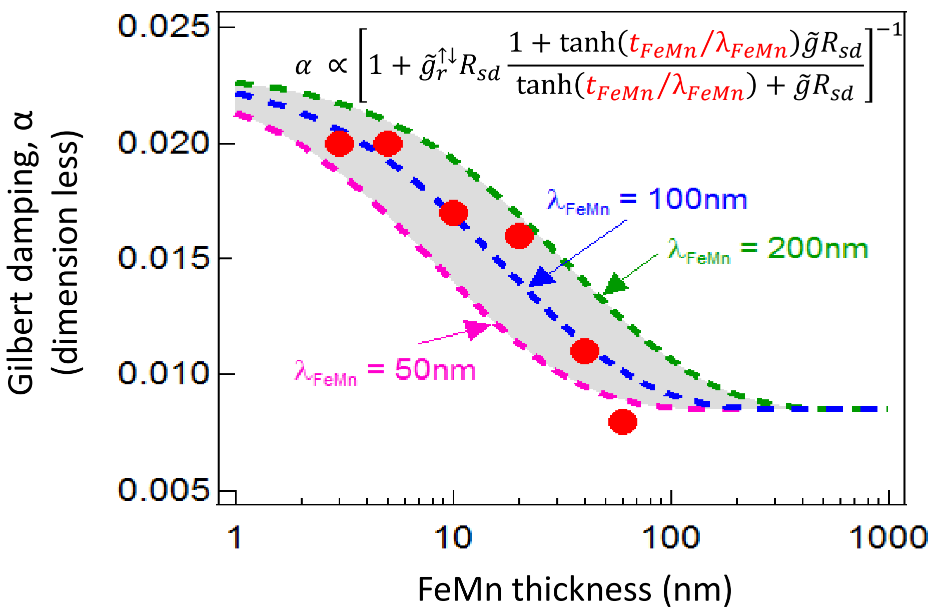
Can damping enhancement in FM tell the spin dissipation (spin torque) in AFM?

Damping vs. FeMn thickness

FeNi 4nm FeMn *t* nm Pt 5nm

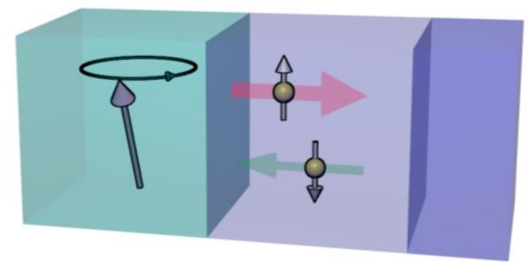


Our results

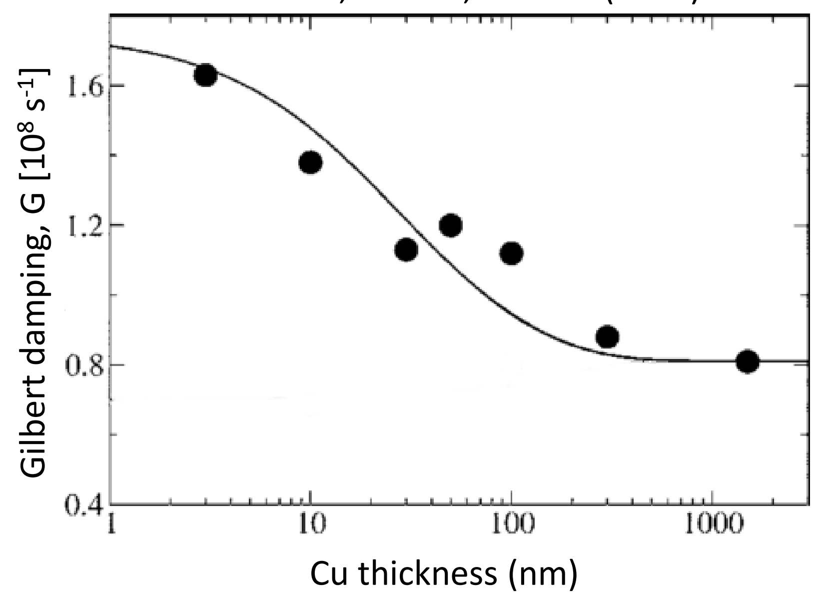


Spin diffusion length of FeMn ~100nm

FeNi 3nm Cu *t* nm Pt 5nm



Mizukami, PRB 66, 104413 (2002)



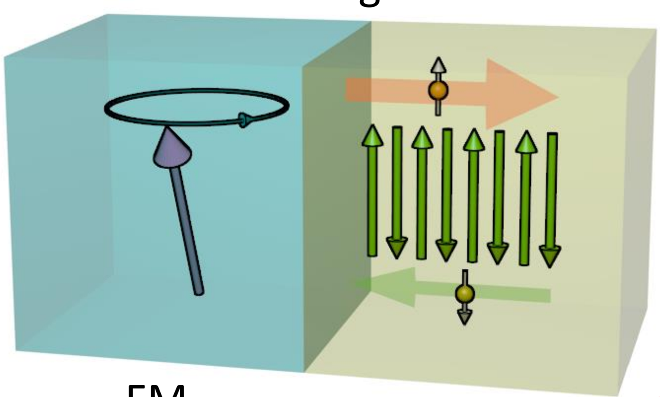
Spin diffusion length of Cu ~250nm

Spin current carried by spin fluctuation;

PRL **113**, 097202 (2014).; *APL* **106**, 162406 (2015); *PRB* **92**, 020409R (2015).; *PRL* **118**, 147202 (2017).

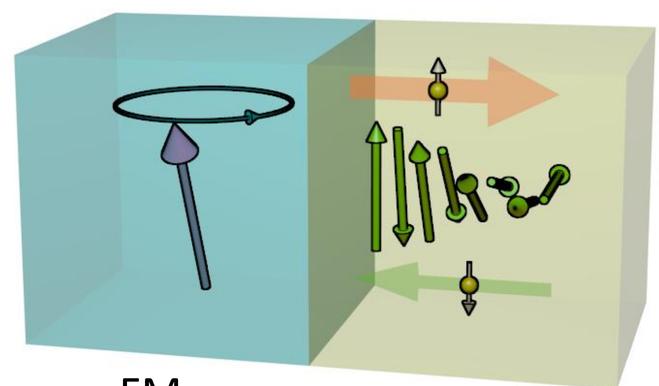
Damping enhancement vs. AFM magnetic structure

AFM aligned



Any change in spin current dissipation?

AFM twisted

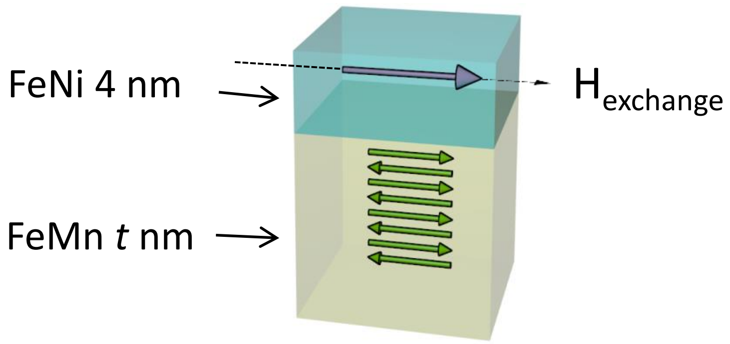


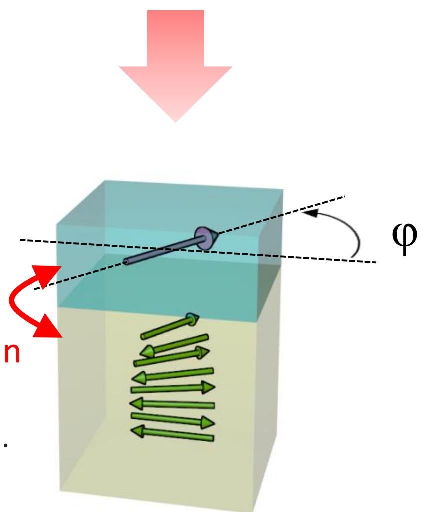
$$\left.\frac{d\mathbf{m}}{dt}\right|_{spin\ torque} \propto \mathbf{I}\times\mathbf{P_s}\times\mathbf{I}$$

Spin dissipation should depend on AFM magnetization direction.

Moriyama, *PRL* 119, 267204 (2017)

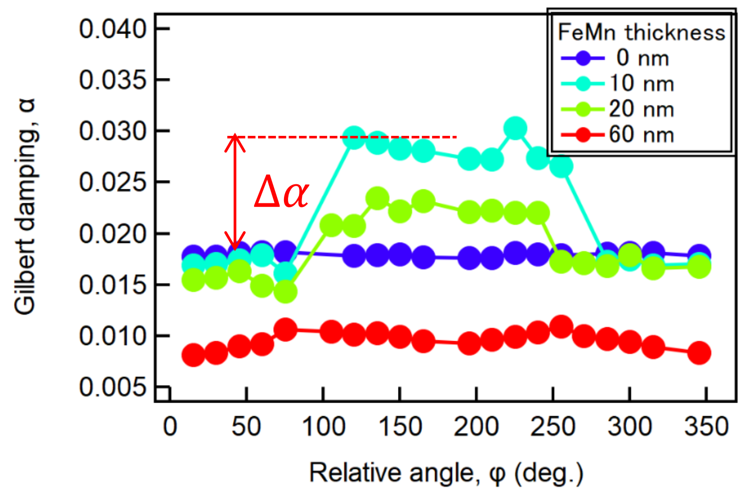
AFM twisting and damping enhancement

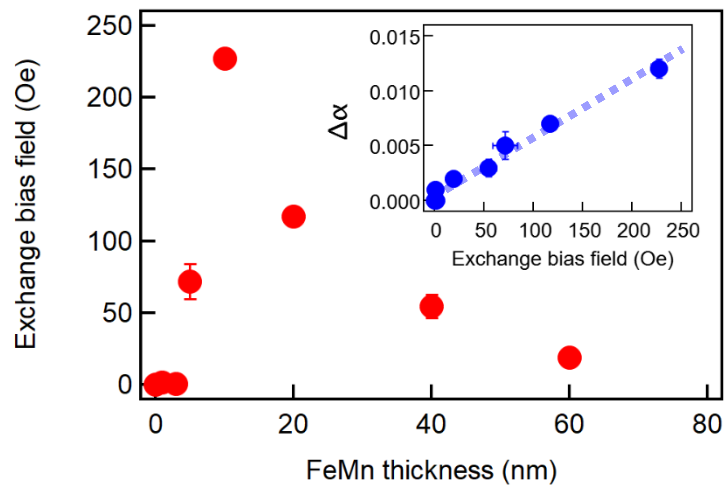




Exchange coupling
Induces a twisting in AFM.

e.g. *PRL* **92**, 24 (2004).

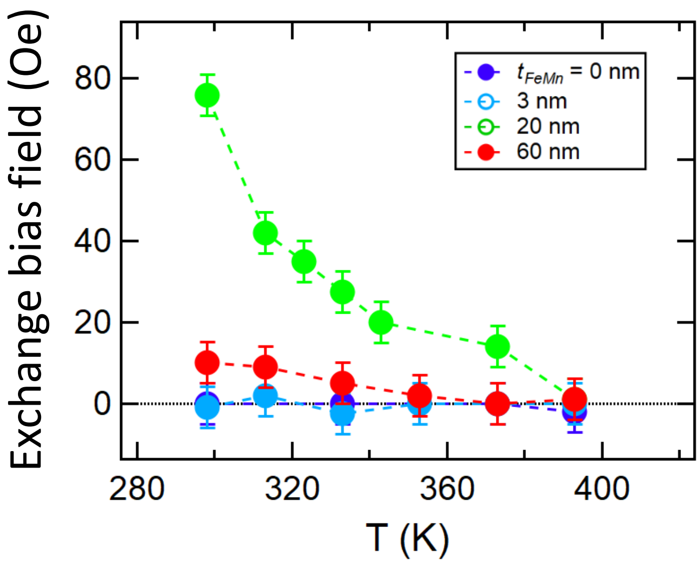


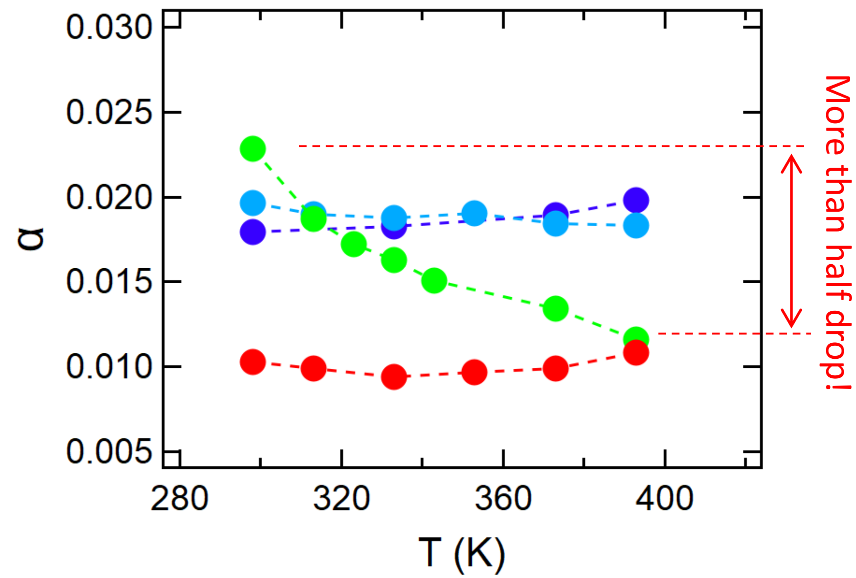


Damping is maximized at the relative angle ~180° at which the twisting is maximized.

Moriyama, *PRL* 119, 267204 (2017)

Damping control by temperature



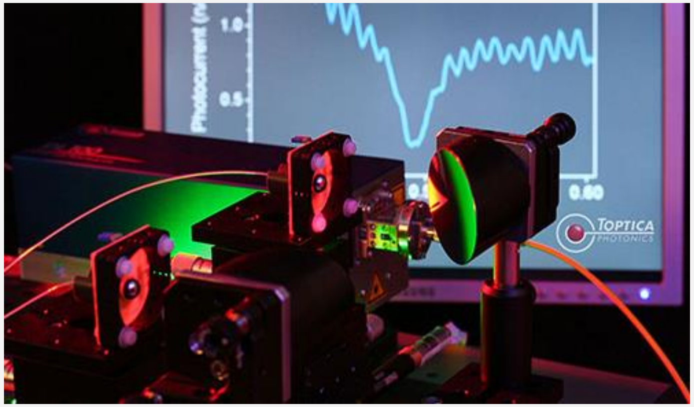


Damping drastically changes in the temperature range of 300 ~ 400 K.
→ Beneficial for spintronic devices where Joule heating is involved during the operation (*e.g.* STT-MRAM)

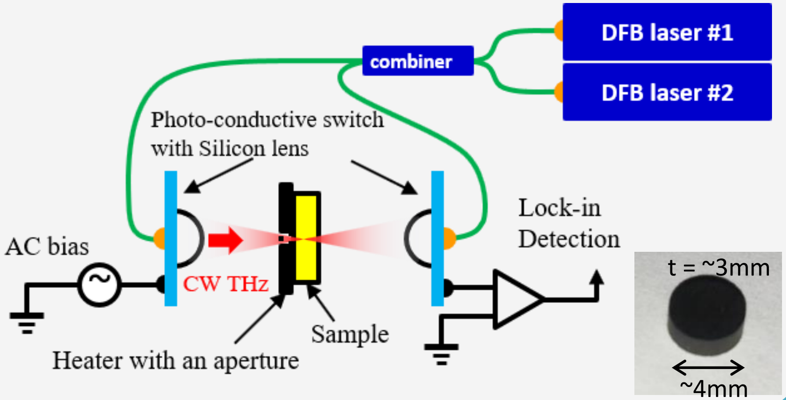
Moriyama, *PRApplied* 11, 011001 (2019)

Antiferromagnetic resonance

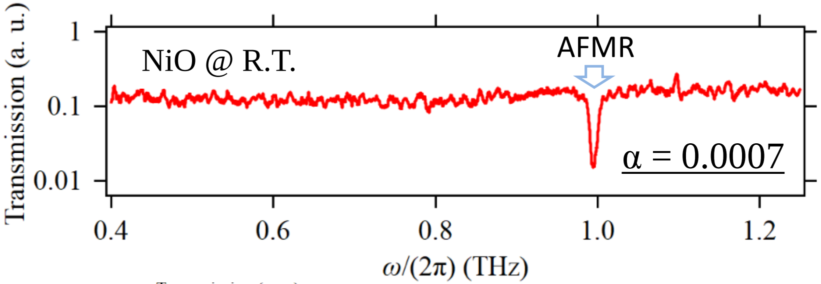
Broadband CW-frequency domain THz spectroscopy

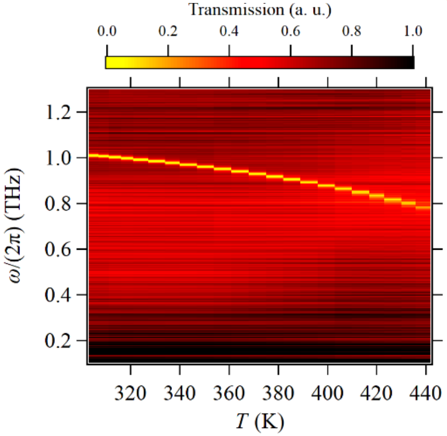


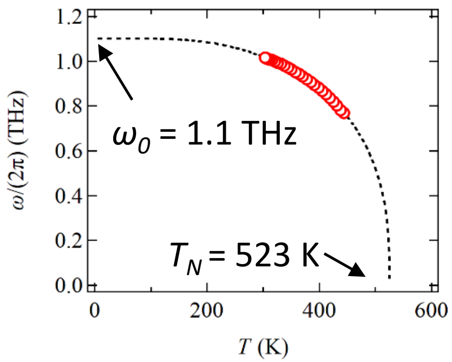
https://www.toptica.com/products/terahertz-systems/



AFMR of NiO bulk





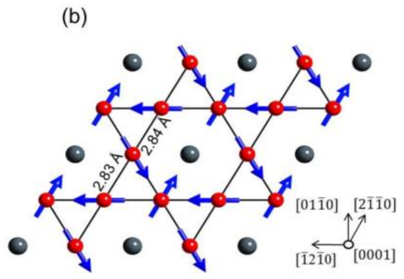


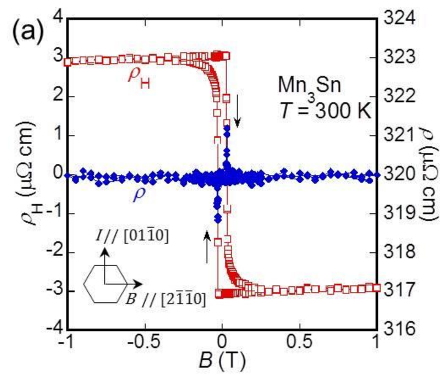
- High resolution AFMR measurements in THz range
  → Linewidth analysis = damping constant α
- Temperature dependence of the AFMR $\omega = \omega_0\left(M_0(T)\right)^n$
  → T_N and ω_0

T. Moriyama, Phys. Rev. Mater. **3**, 051402 (2019)

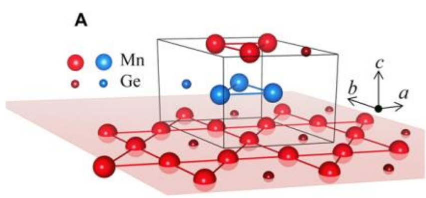
Chiral antiferromagnets: Mn_3X

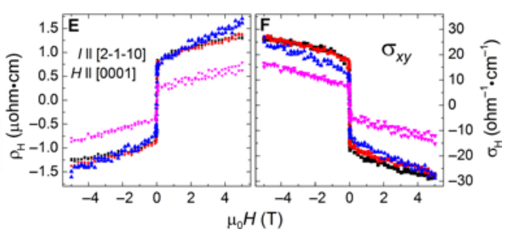
DO_{19} (hexagonal): Mn_3Sn, Mn_3Ga, Mn_3Ge





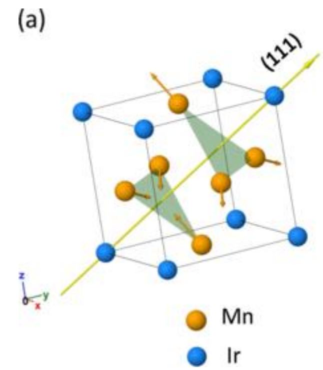
Nakatsuji, Nature **527**, 212 (2015).

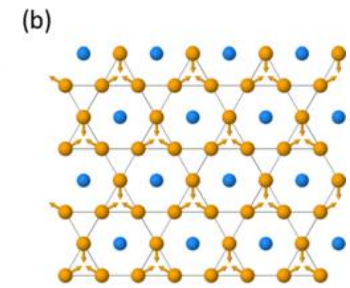




Ajaya K. Nayak, *et al.*, *Sci. Adv*. **2**, e1501870 (2016).

$L1_2$ (fcc): Mn_3Pt, Mn_3Rh, Mn_3Ir





e.g. Chen, PRL 112, 017205 (2014)

	AHC σ
symmetry-imposed tensor shape	$\begin{pmatrix} 0 & \sigma_{xy} & 0 \\ -\sigma_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Rh	$\begin{pmatrix} 0 & -284 & 0 \\ 284 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Ir	$\begin{pmatrix} 0 & -312 & 0 \\ 312 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Pt	$\begin{pmatrix} 0 & 98 & 0 \\ -98 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Zhang, PRB 95, 075128 (2017)

Measurements on Mn_3Ir?

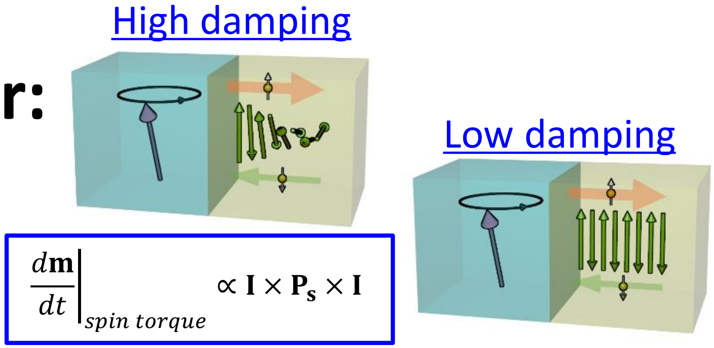
Summary

1. Spin pumping in AFM/FM bilayer:

→ Control spin dissipation by the AFM order

→ FM damping is controlled by AFM

APL **106**, 162406 (2015); *PRB* **92**, 020409R(2015);
PRL **119**, 267204 (2017); *APEX* **11**, 073003 (2018);
PRApplied **11**, 011001 (2019)



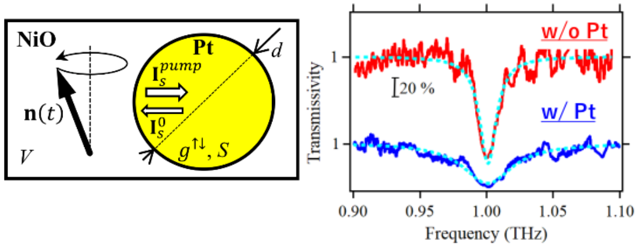
$$\left.\frac{d\mathbf{m}}{dt}\right|_{spin\ torque} \propto \mathbf{I} \times \mathbf{P_s} \times \mathbf{I}$$

2. Antiferromagnetic spin pumping:

→ Experimentally observed for the first time.

→ Large $g_{\uparrow\downarrow} = 43\ \mathrm{nm}^{-2}$ was determined.

PRMatererials **3**, 051402 (2019);
manuscript under review

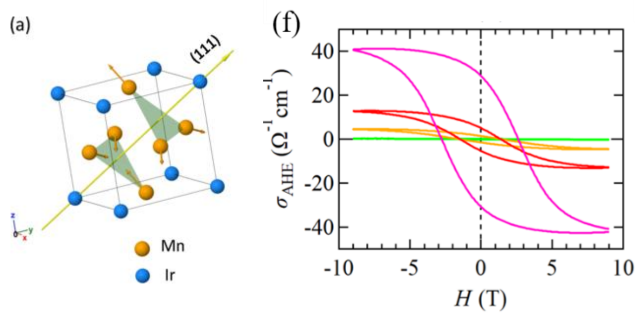


3. AHE in Mn_3Ir:

→ Positive correlation between *S* and AH conductivity

→ AH conductivity is ~40 $\Omega^{-1}\ \mathrm{cm}^{-1}$

manuscript under review



Collaborations & Acknowledgements

Kyoto Univ.

Mr. K. Oda
Mr. T. Ikebuchi
Prof. T. Ono

Tohoku Univ.

Prof. M. Kimata

U. S. A

Prof. Y. Tserkovnyak (UCLA)
Prof. S. Takei (CUNY)

SPring-8

Dr. T. Okouchi

Gifu Univ.

Mr. K. Hayashi
Prof. K. Yamada
Prof. M. Shima
Prof. Y. Ohya

Europe

Prof. G. Finocchio (Messina)
Prof. M. Carpentieri (Bari)

Thank you for your attention!