Massachusetts Institute of Technology

Nonreciprocal transport and topological band structure through magnon-magnon interaction

June 15th, 2022

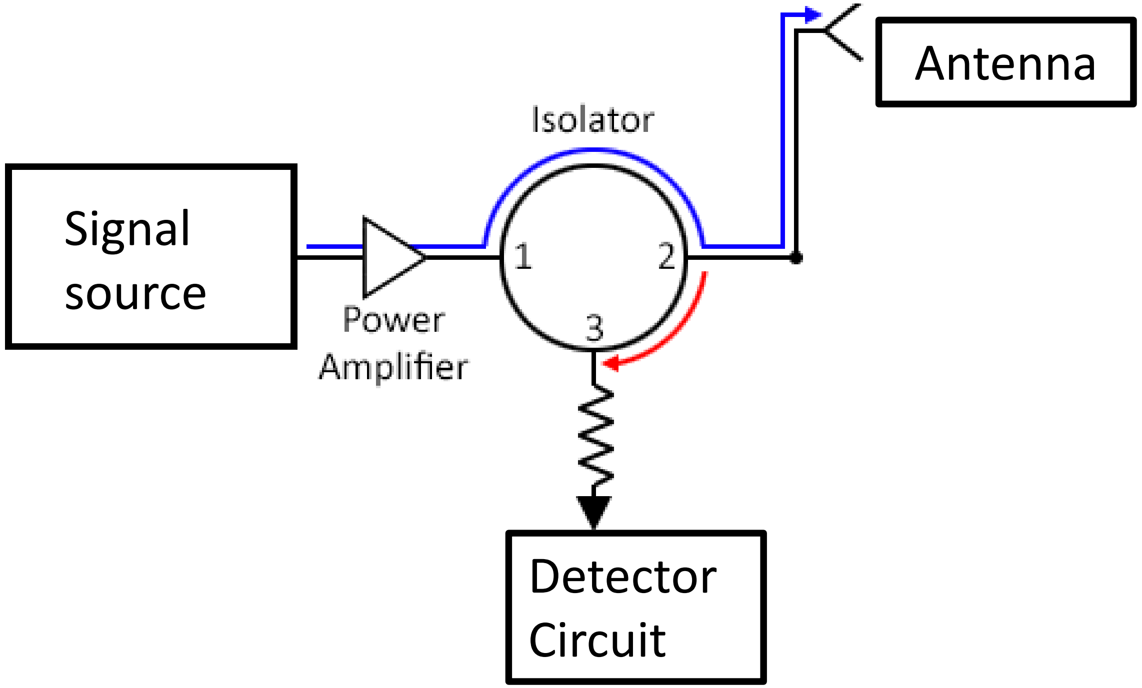
Luqiao Liu

Department of Electrical Engineering and Computer Science

Massachusetts Institute of Technology

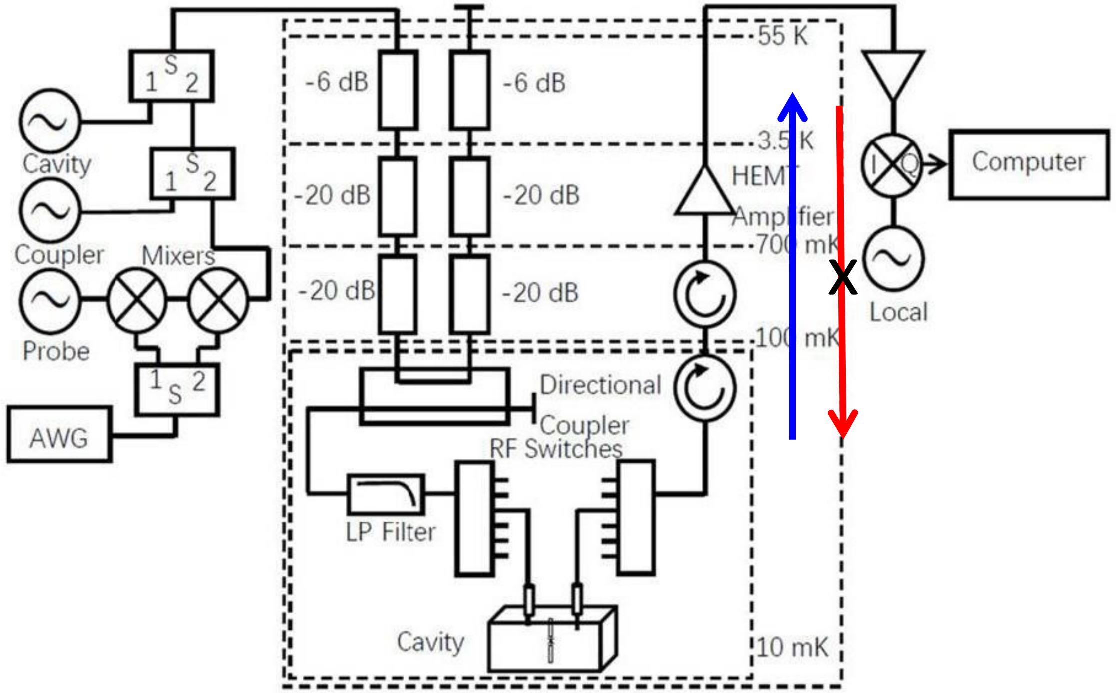
Non-reciprocal Transmission of Signals

Transmitter/receiver Isolation in Radar



From https://www.rfwireless-world.com/

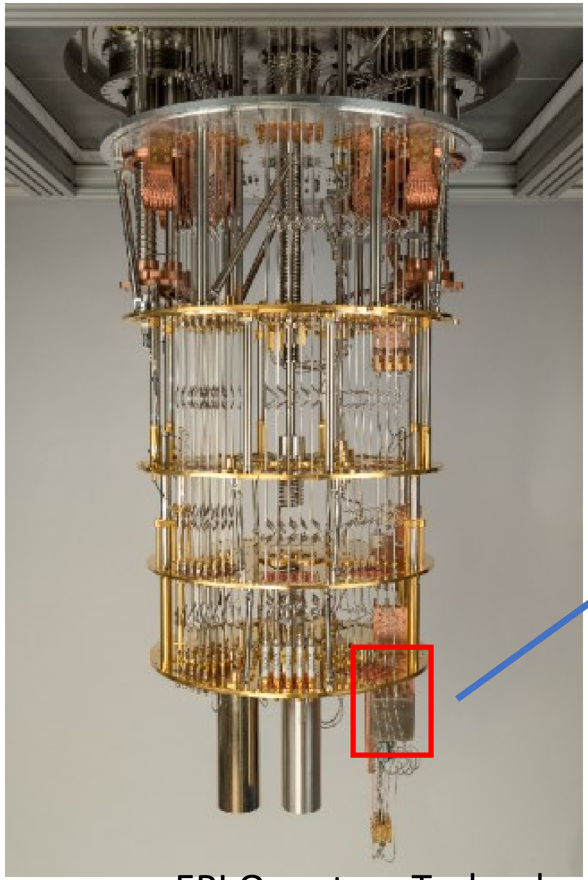
Noise Isolation for Quantum Computation



From https://www.oxinst.com/applications/quantum-computing

- Signal isolation devices are important for both classical and quantum applications
- Separating forward and backward signals is useful for protecting electronic devices, and prevent thermal noise to influence the sensitive state

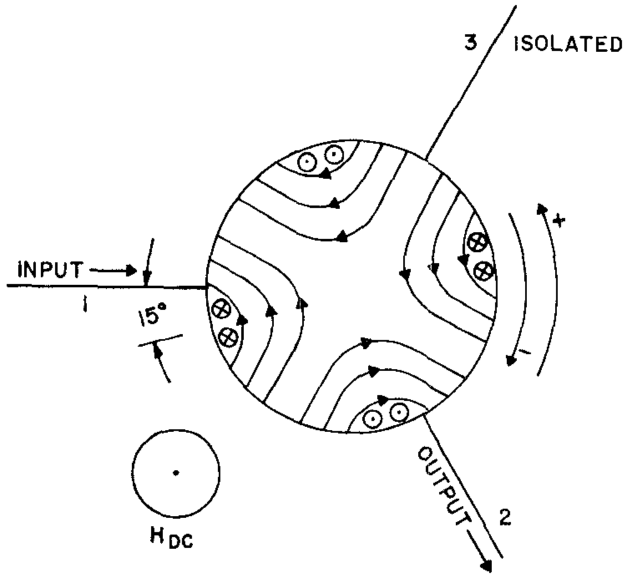
Magnetic Components for Signal Isolation



EPJ Quantum Technologies **6**, 2 (2019)

Circulator or Isolator

http://www.ketemicro.com

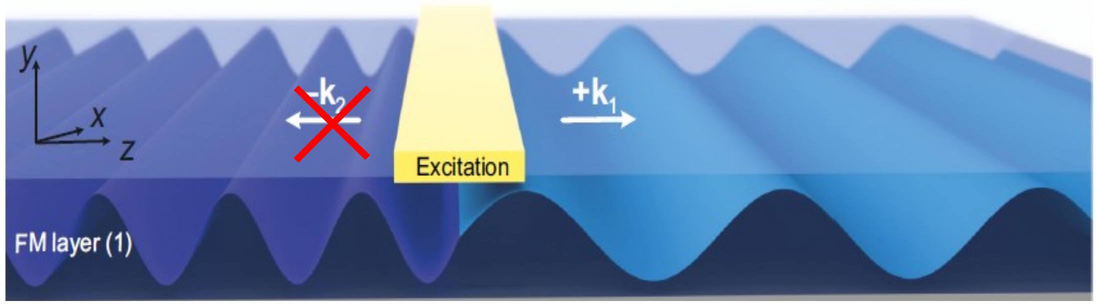


DOI: 10.1109/TMTT.1965.1125923

- Passive signal isolation device employs magnetic material for breaking time reversal symmetry
- Classical Circulator/Isolator is based on Faraday effect in microwave domain
- Constructive or destructive interference of two opposite mode
- Work in the frequency away from magnetic resonance, Usually bulky

Non-Reciprocity of Spin Wave

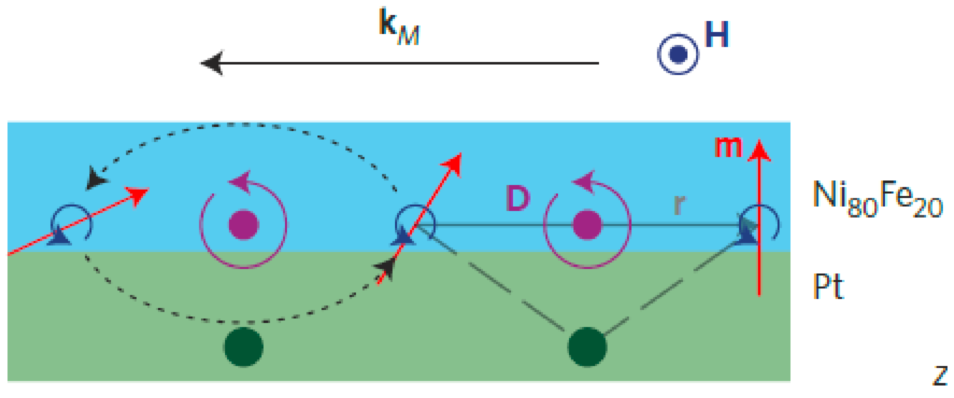
Directional Transmission of Spin Wave

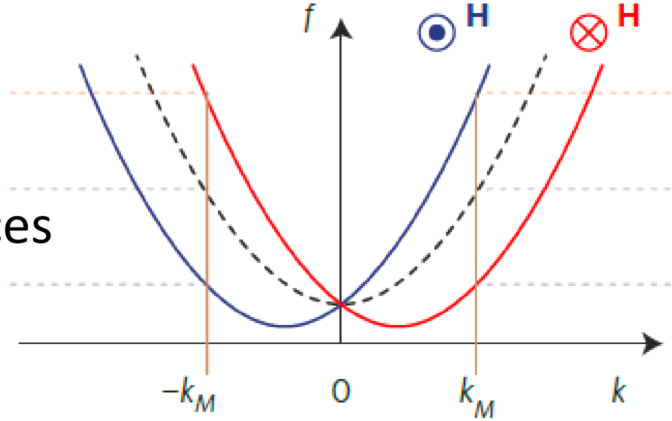


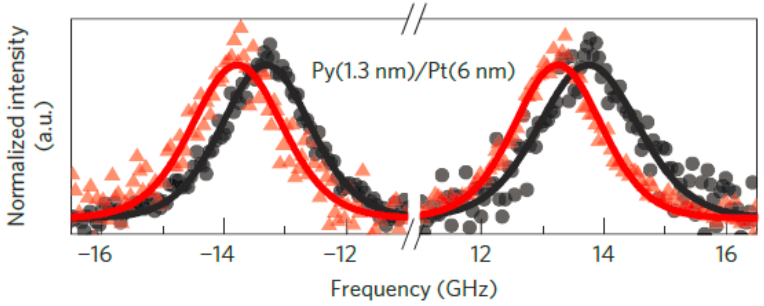
PHYS. REV. APPLIED **12,** 034012 (2019)

- Spin wave exhibits non-reciprocal transmission under certain circumstances
- Candidates for nanoscale on-chip circulator, isolator, etc

non-reciprocity from Dzyaloshinskii–Moriya interaction





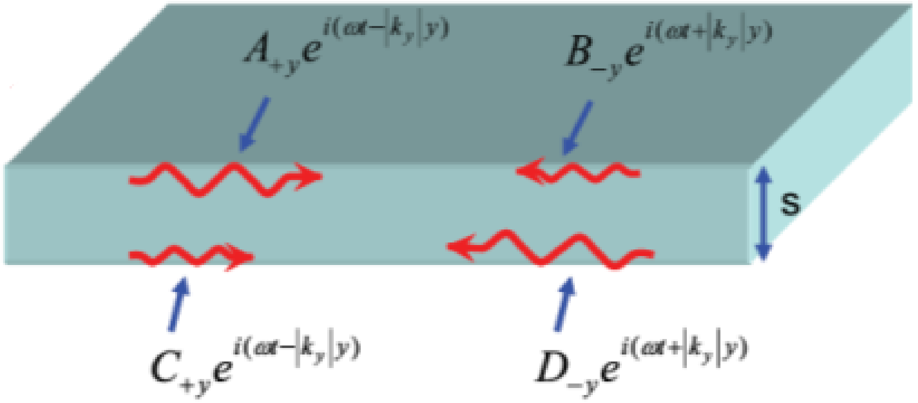


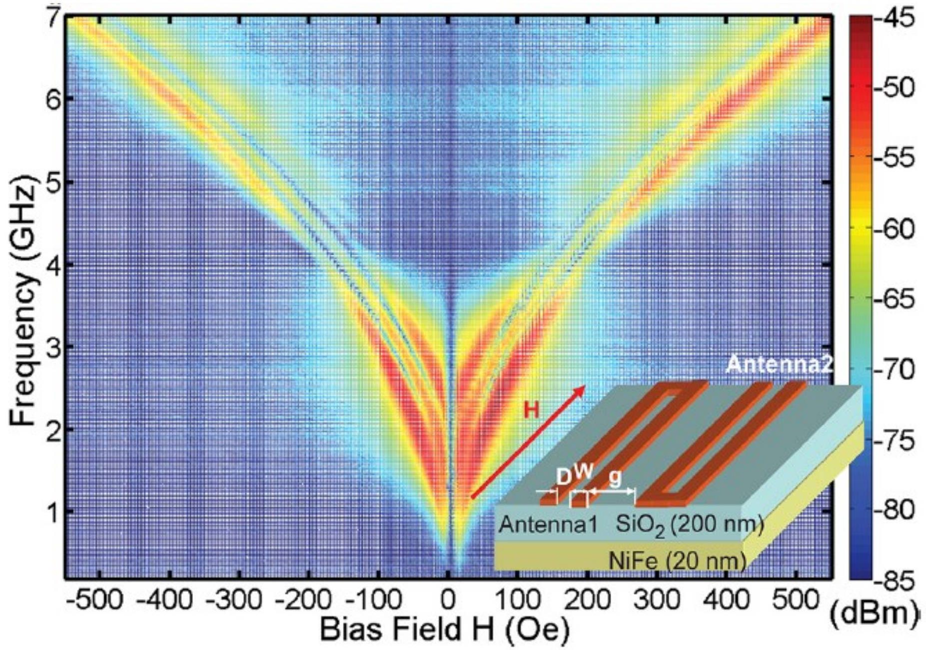
e.g., DOI: 10.1038/NPHYS3418

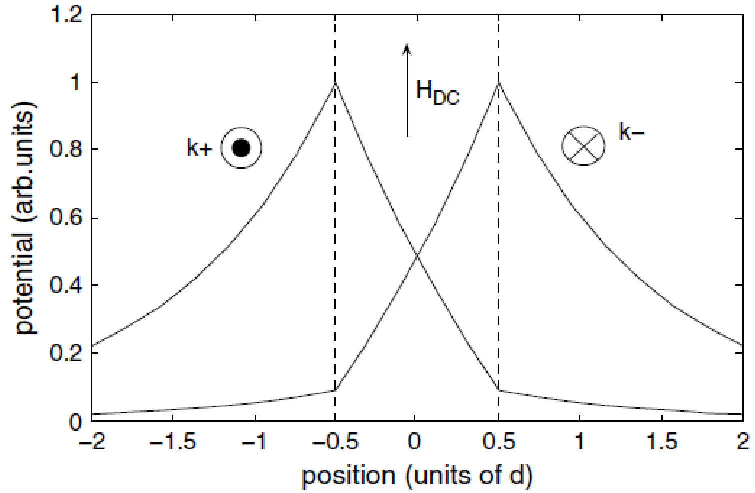
DMI: $H_{\mathrm{DMI}} = -\mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$ → Frequency shift for oppositely travelling waves

Non-Reciprocity from Dipolar Interaction

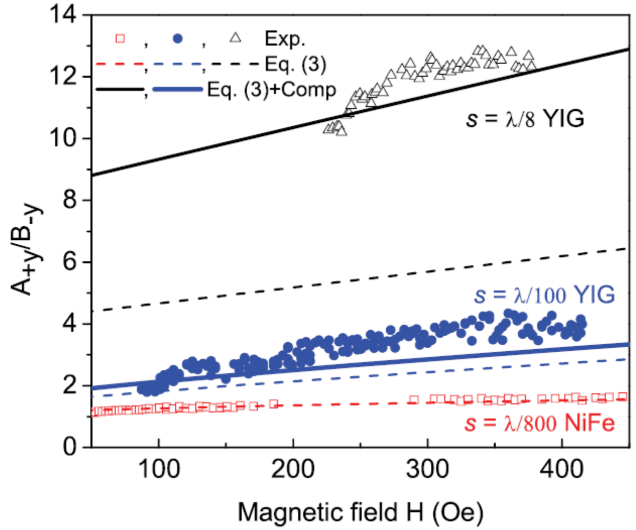
Surface mode of Magnetostatic wave







Spin waves: theory and applications, Stancil, Prabhakar, springer (2008)

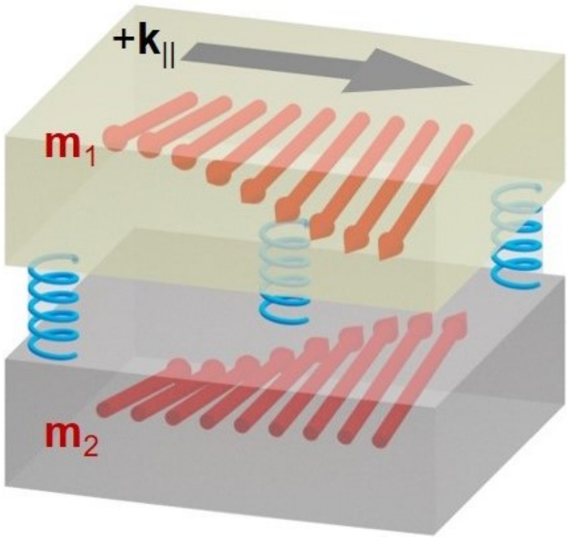


APL, 105, 232403 (2014)

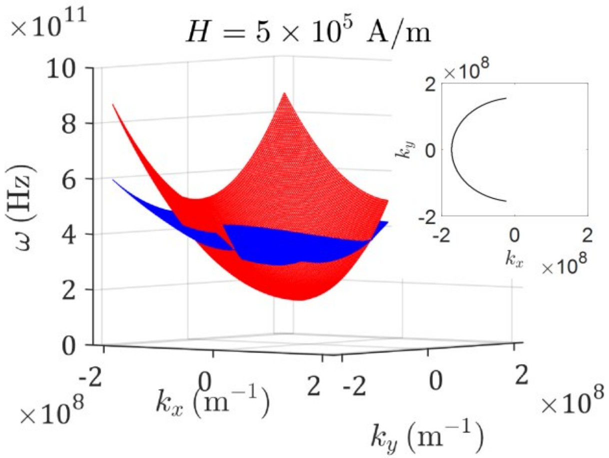
- Surface mode (Damon-Eshbach) is dominated by waves along opposite directions at opposite surfaces

Content

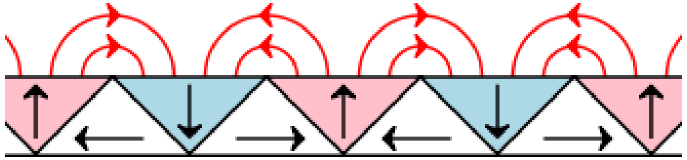
- Chiral dipolar interaction induced non-reciprocal magnon diffusion in a magnetic bilayer



- Tunable chern bands and chiral spin currents in magnetic multilayers

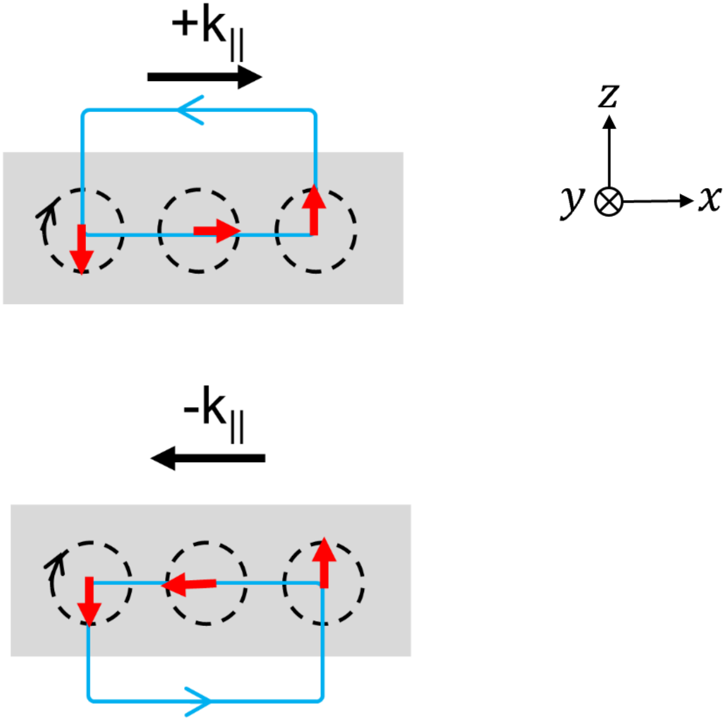


Chiral Dipolar Fields from Spin Wave



https://engineerdog.com/2015/03/12/**why-do-refrigerator-magnets-only-stick-on-one-side/**

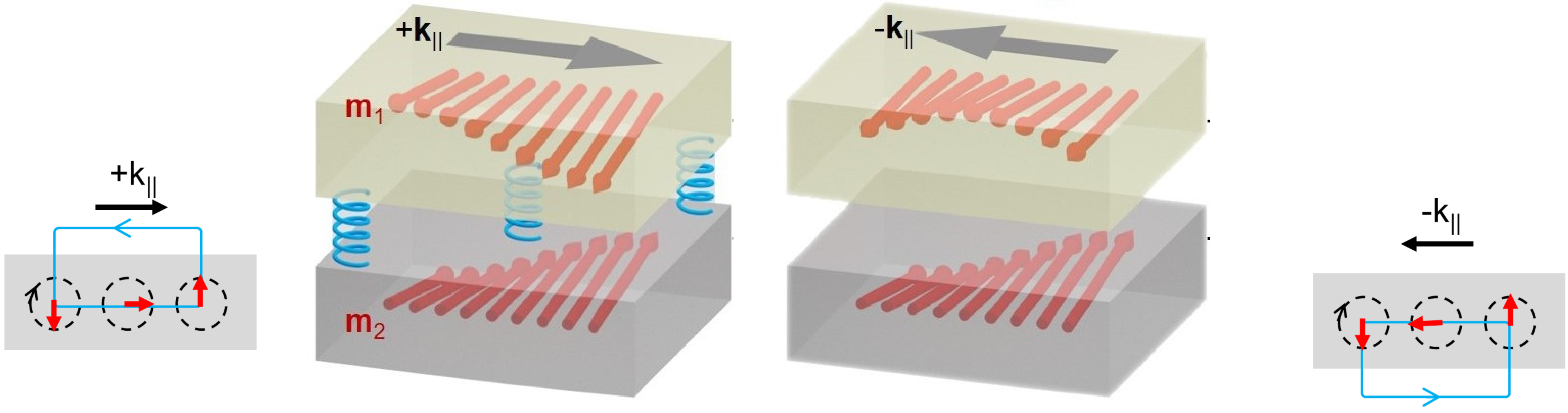
Snapshot on propagating spin wave



・The dipolar field generated from traveling magnons are single sided and circularly polarized, depending on the **k** direction → **chirality**

Phys. Rev. Lett. 123, 247202 (2019)

Chiral Coupling in Magnetic Bilayers

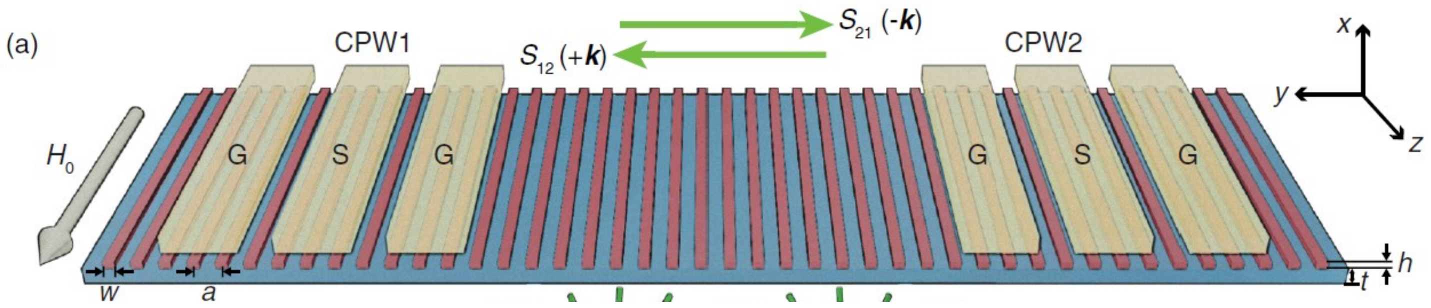


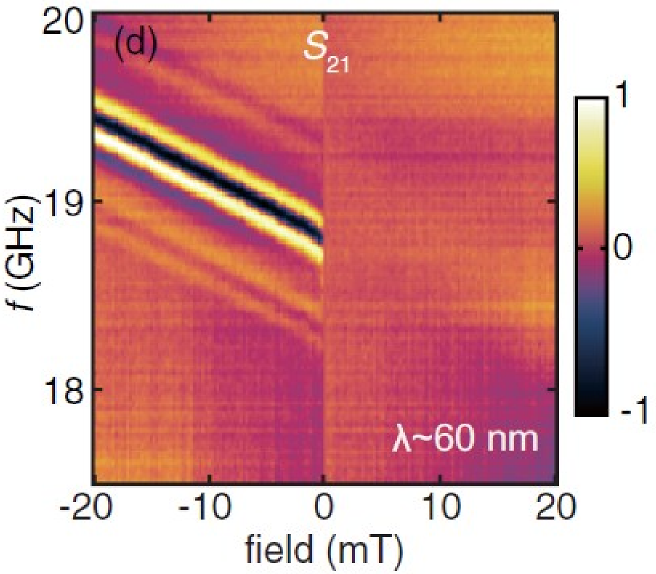
Coupled **Not Coupled**

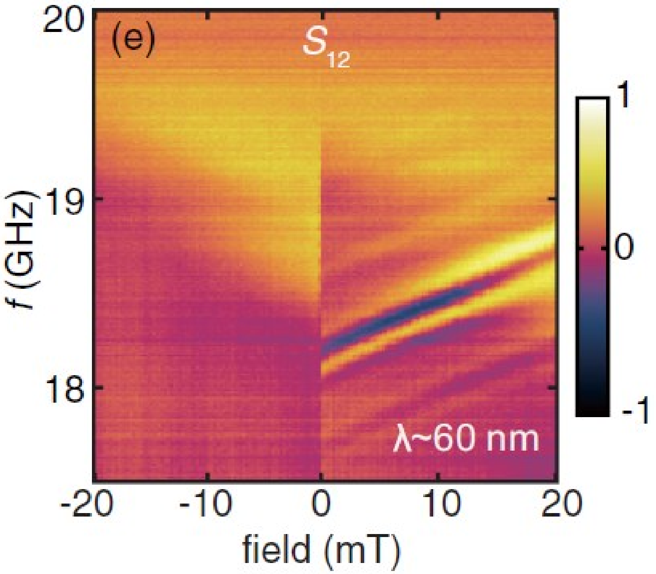
- Depending on propagation direction, spin waves in two neighboring layers get coupled or not→ **Asymmetric coupling**

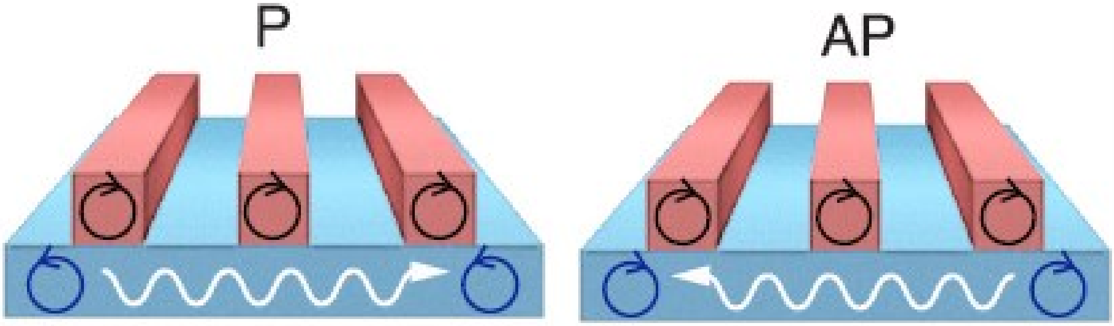
Non-Reciprocity in Magnetic Bilayers

Cobalt nanowires on YIG thin film







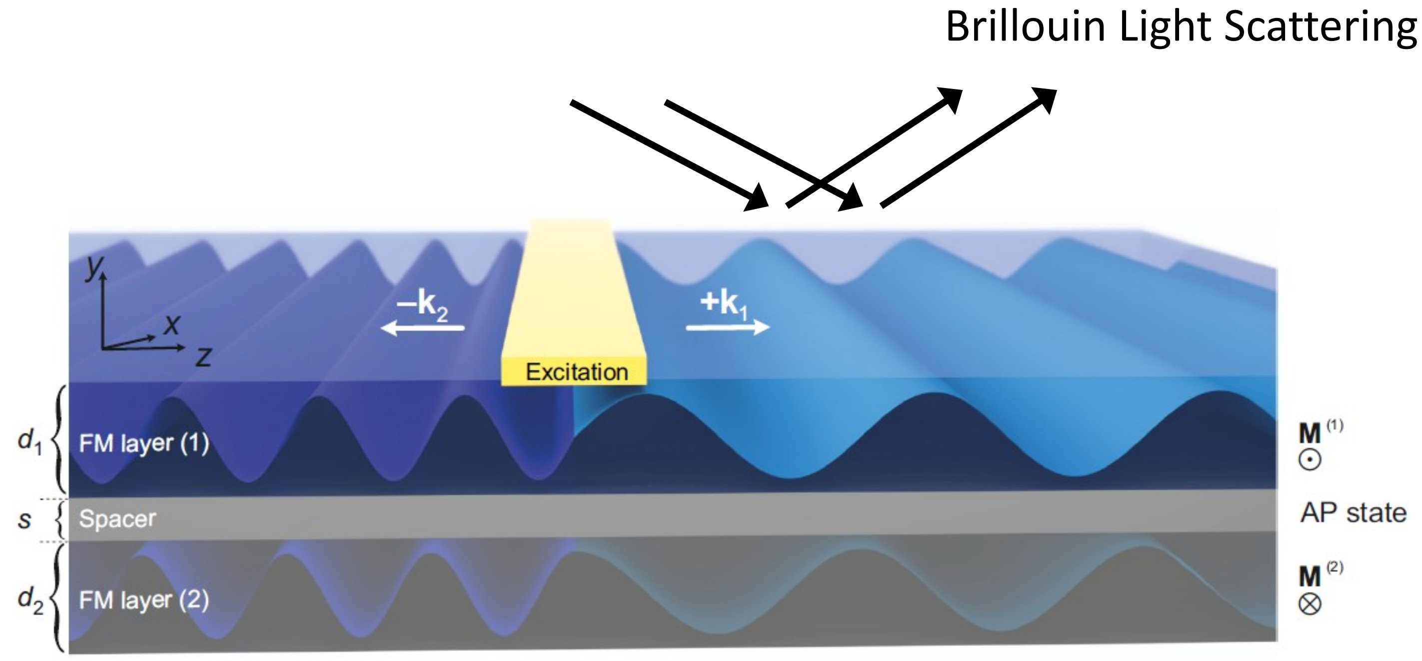


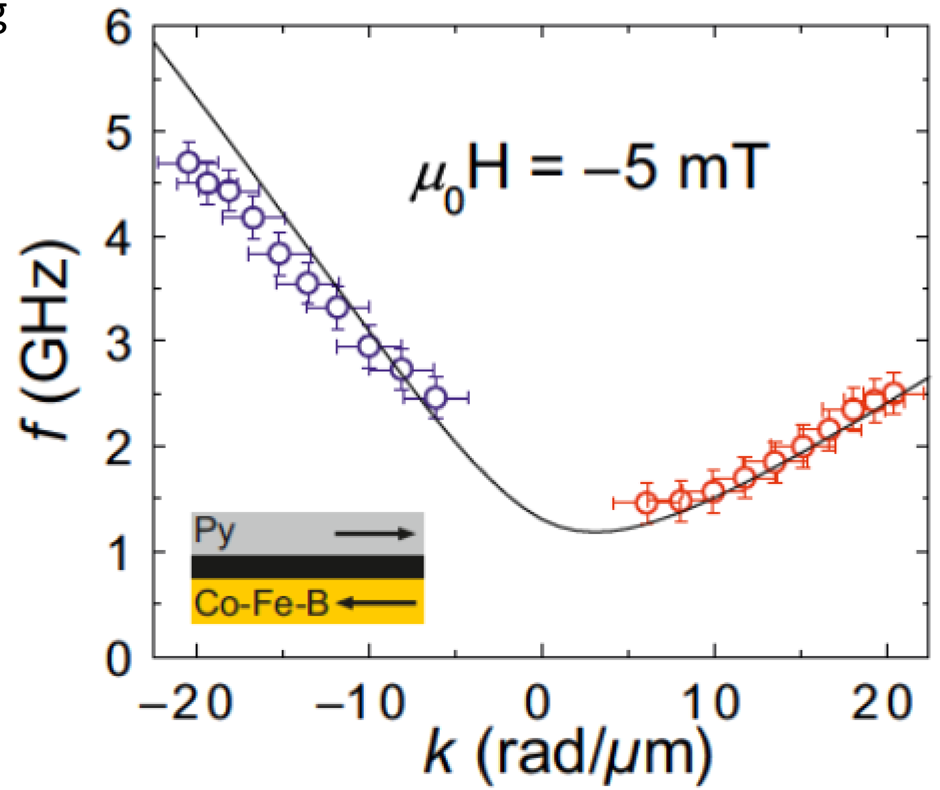
JILEI CHEN *et al.* PHYSICAL REVIEW B **100**, 104427 (2019)

- Cobalt nanowire gratings only excite spin wave in YIG along a fixed direction, depending on the Co magnetic moment orientation.

Non-Reciprocity in Magnetic Bilayers

Synthetic Antiferromagnet with Peralloy/CoFeB

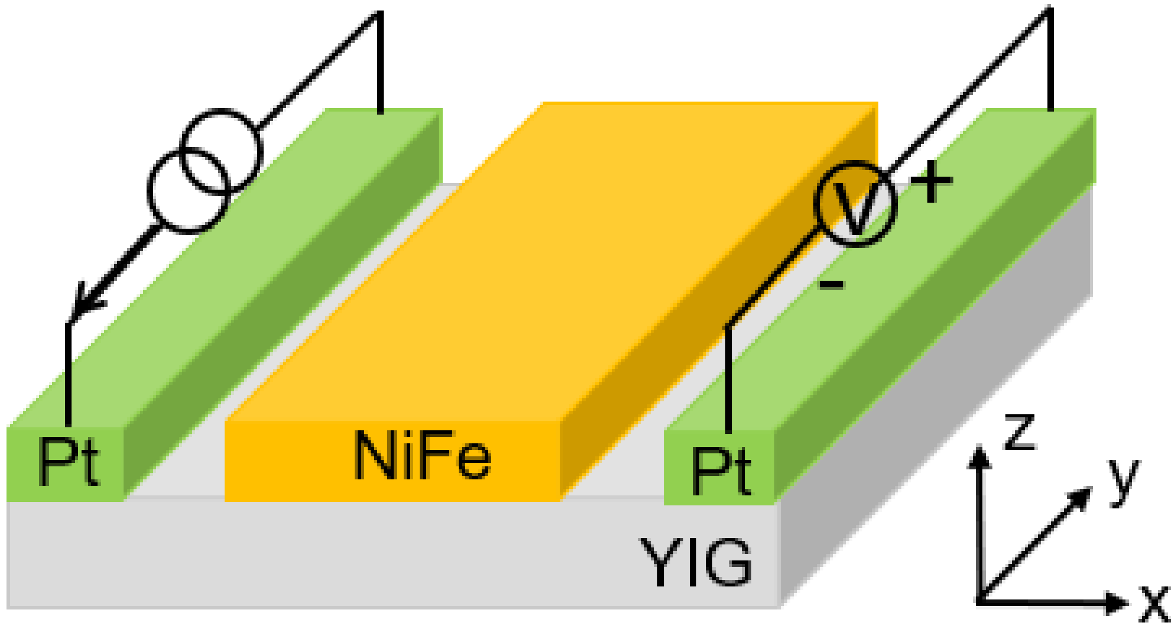


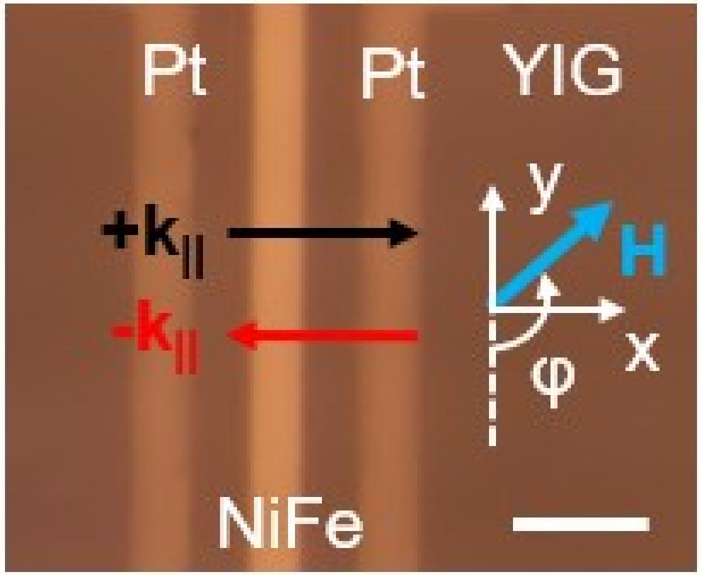


R.A. GALLARDO *et al.* PHYS. REV. APPLIED **12,** 034012 (2019)

- The dipolar interaction in antiparallel aligned magnetic bilayers modify magnon energy $\Delta E(k)$, depending on k's direction → frequency asymmetry

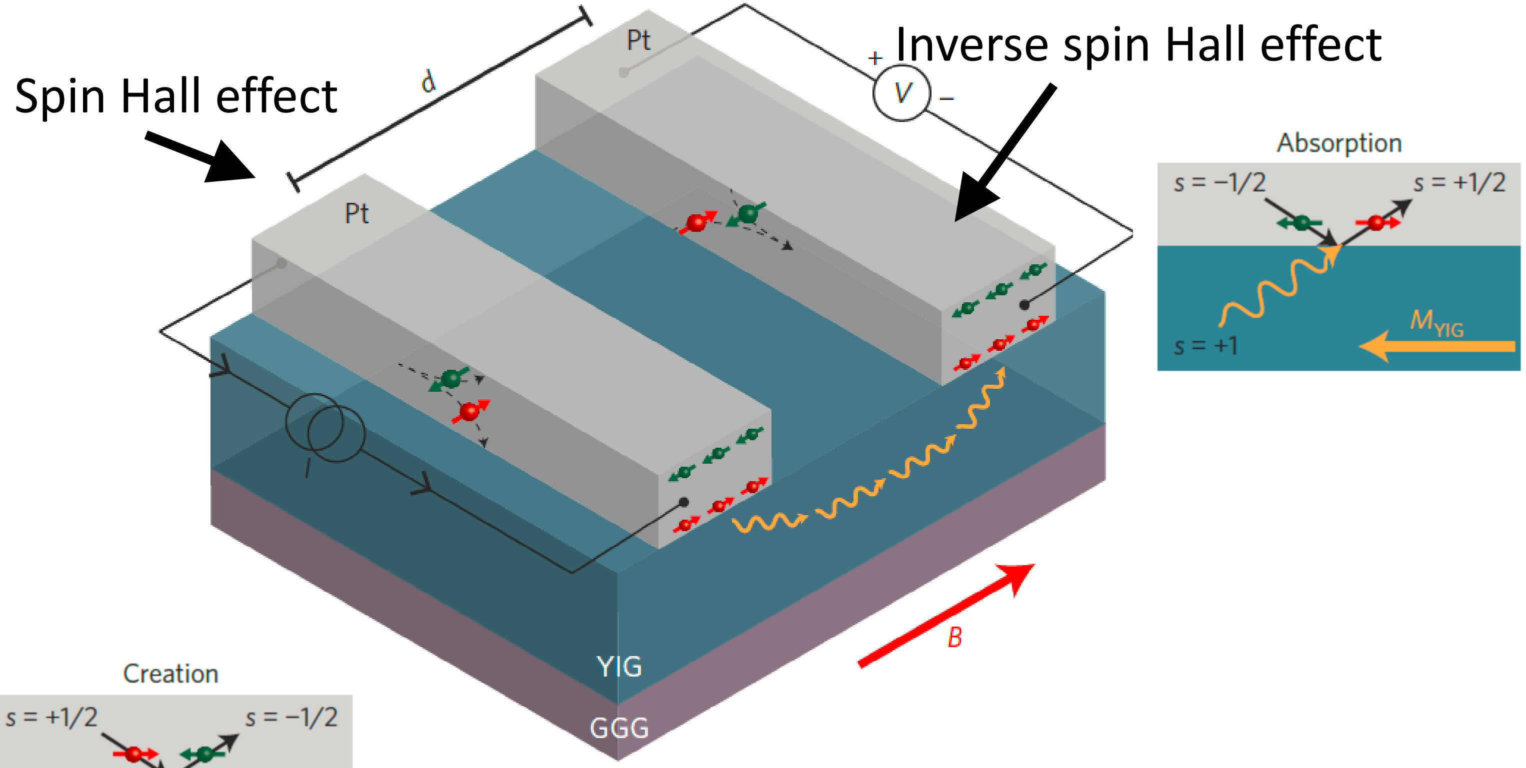
Magnon Non-Reciprocity in Diffusion Domain

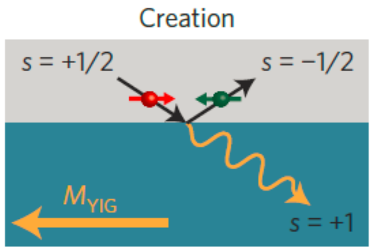




- Non-equilibrium magnons in YIG are excited and detected via spin Hall effect (broad band excitation)
- NiFe layer as a gate to control the magnon diffusion
- Magnon non-reciprocity are checked by swapping the transmitting/receiving electrodes

Non-local Charge Transfer Mediated by Magnon Diffusion

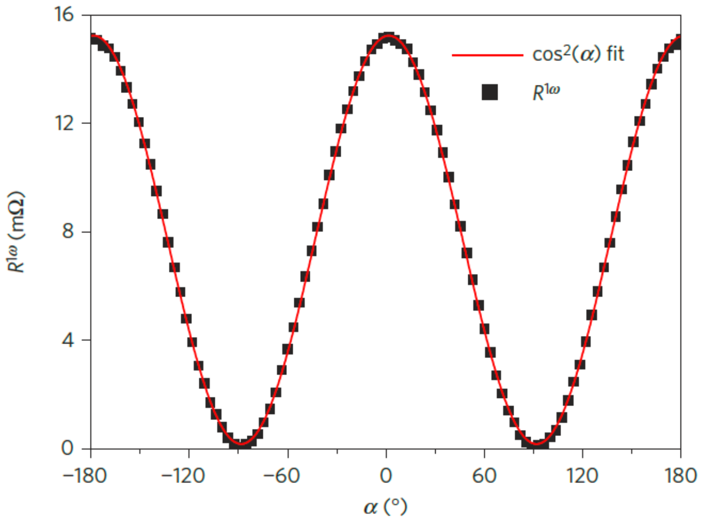




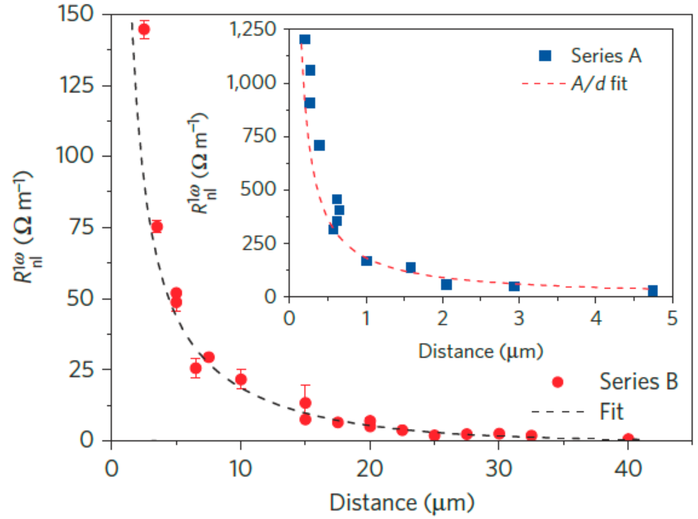
Cornelissen, Nature PHYS, **11**, 1022 (2015)
Lebrun, Nature **561**, 222 (2018)
Han et al. Liu, Nature Nano. **15**, 563 (2020)

- Spin Hall effect injects spins into magnetic insulator, modifies the magnon chemical potential **μ**.
- Non-local charge transfer through an insulator through magnon diffusion.

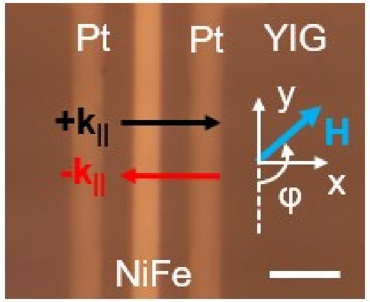
1^{st} Harmonic Readout

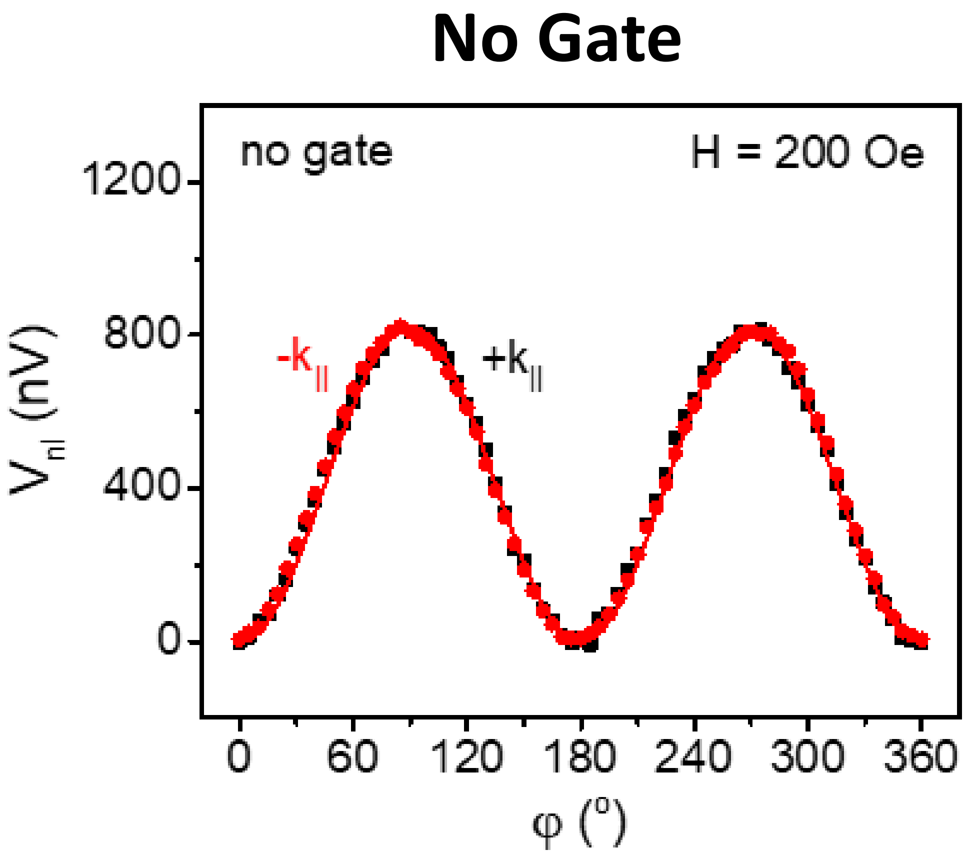


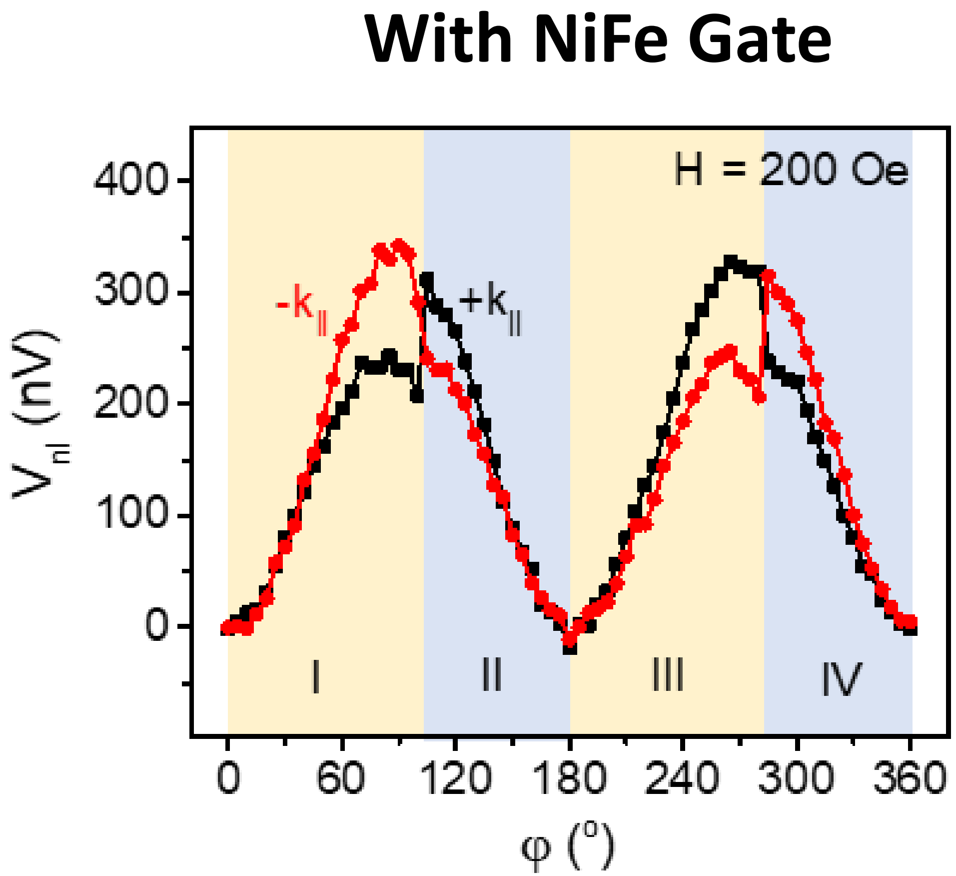
Exponential decay



Non-Reciprocal Spin Diffusion with Magnetic Gating

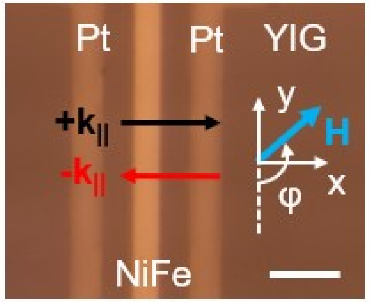


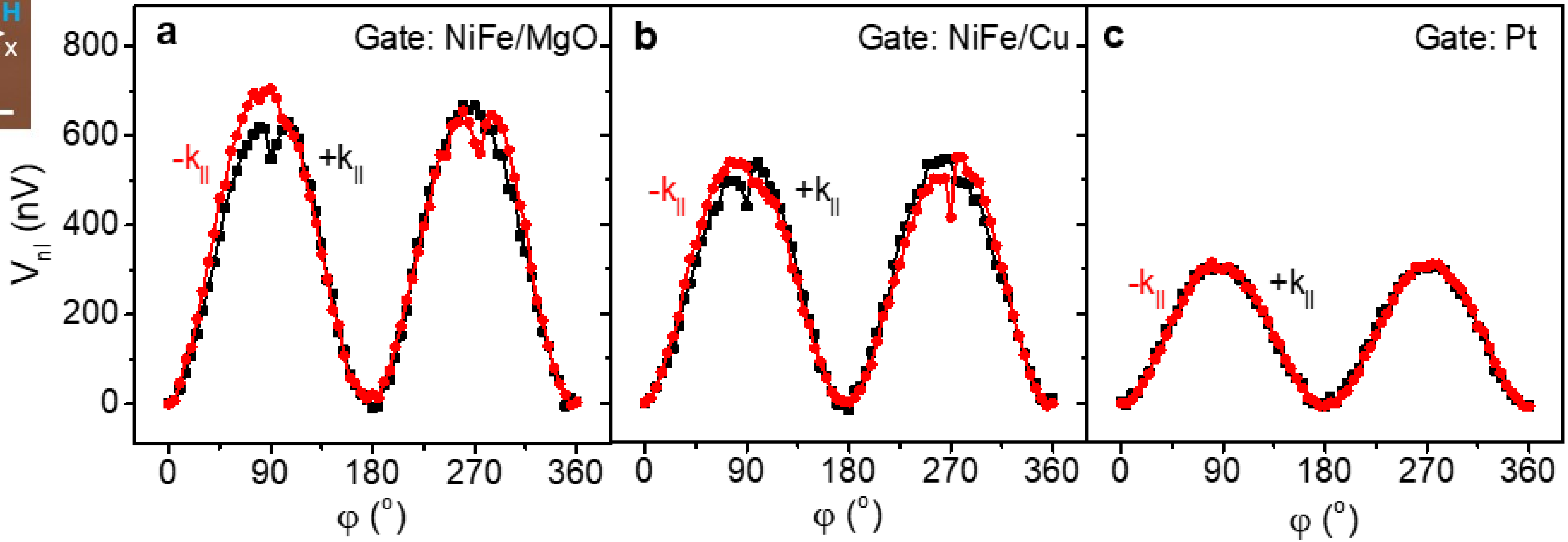




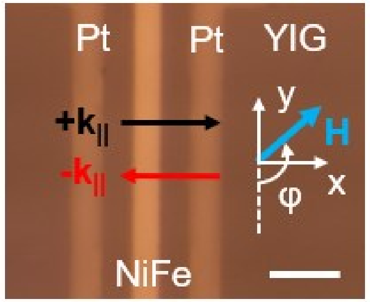
- NiFe gate causes significant deviation from a perfect sinusoidal angle dependence
- Under the same field condition, **left- and right-going spin waves** have different transmission rate

Control Samples with Different YIG/Metal Interfaces





- Despite of differences in magnitude, non-reciprocity exists in samples without direct contact between YIG and NiFe → ruling out standard or asymmetric (DMI) exchange, spin current, pointing to long range interaction (dipolar)

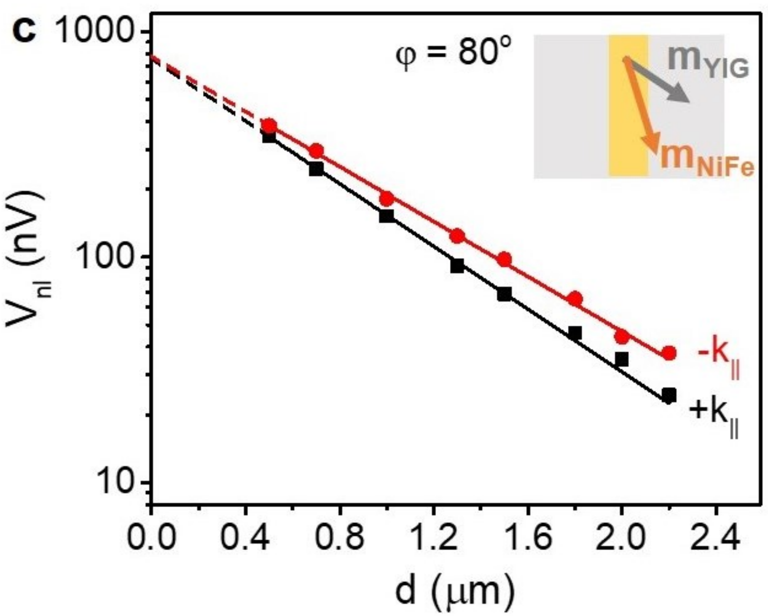


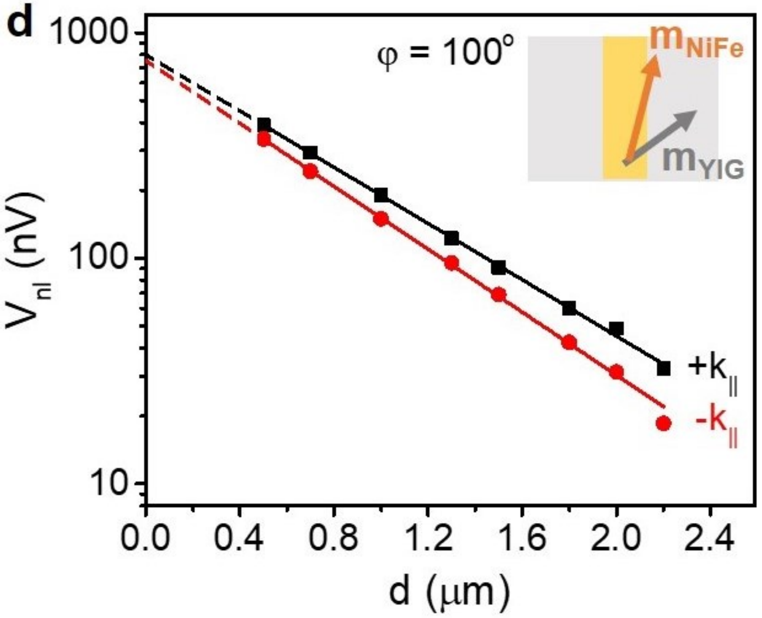
Unequal Diffusion Lengths for Opposite Directions

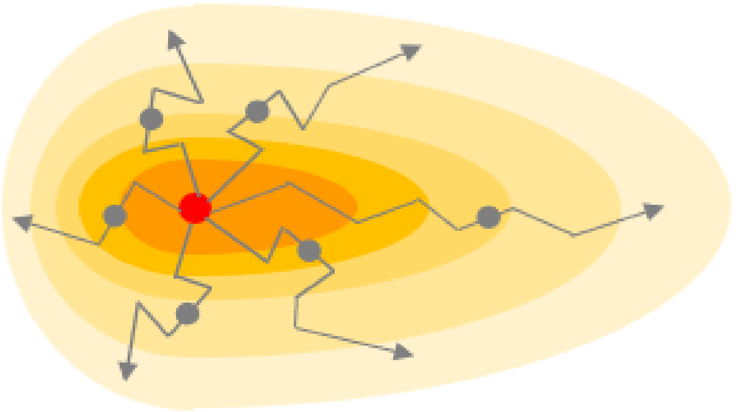
Field angle 80°

Field angle 100°

Asymmetric Magnon Diffusions



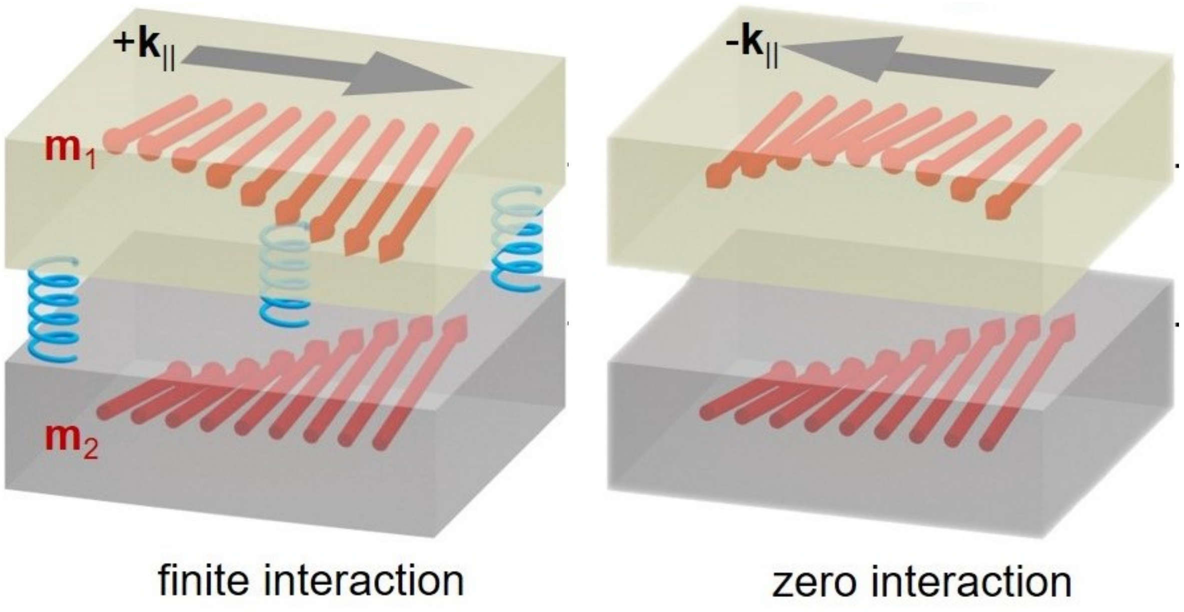




J.Han, et al, L. Liu, Nano Lett (2021)
10.1021/acs.nanolett.1c02575

- Opposite to the standard picture on electrons, phonons and magnons, magnons in the bilayer diffuse anisotropically, which is controlled by the equilibrium magnetic orientation.

Chiral Dipolar Coupling between Two Neighboring Layers

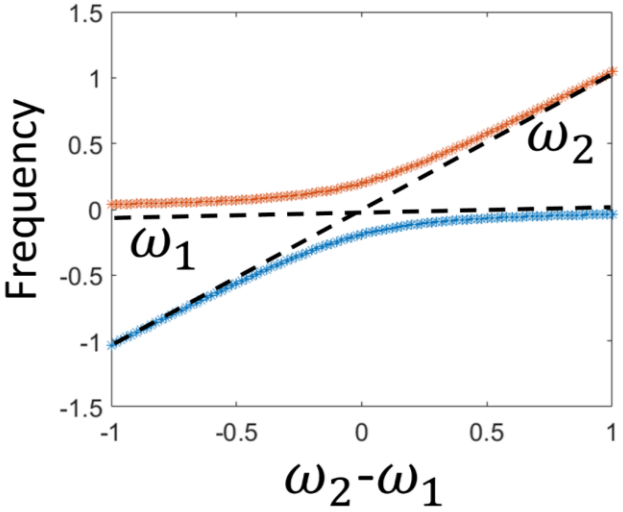


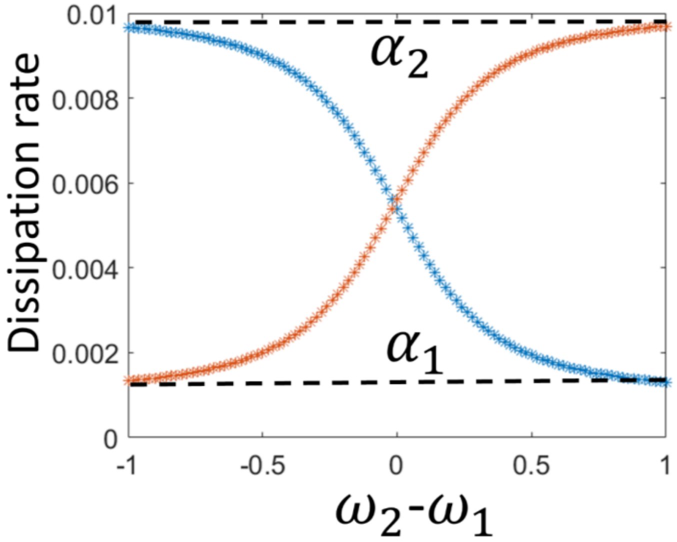
NiFe frequency

Magnon-magnon coupling

$$\begin{pmatrix} (1 - i\alpha_1)\omega_1(k_\parallel) & \Delta_{12} \\ \Delta_{21} & (1 - i\alpha_2)\omega_2(k_\parallel) \end{pmatrix}$$

YIG frequency

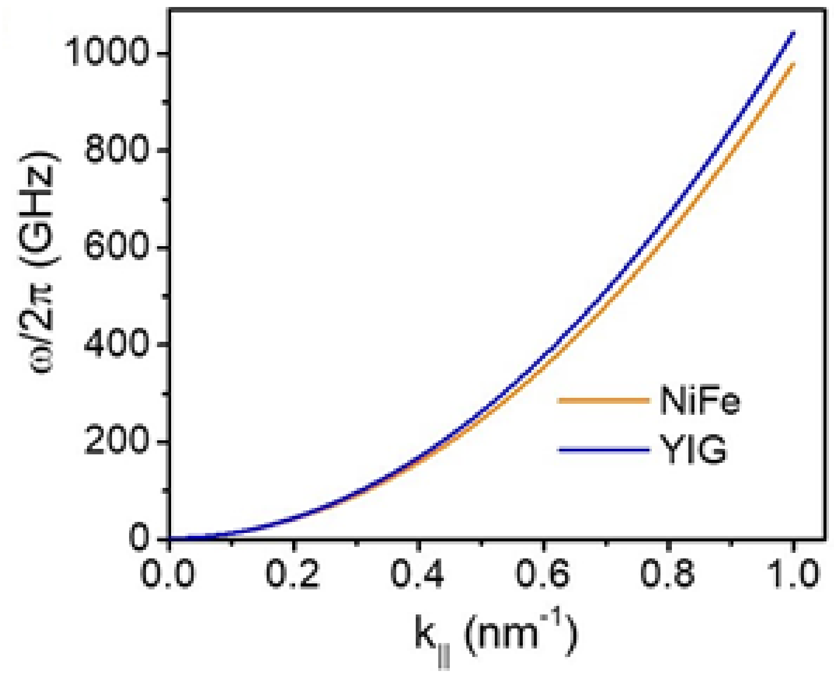




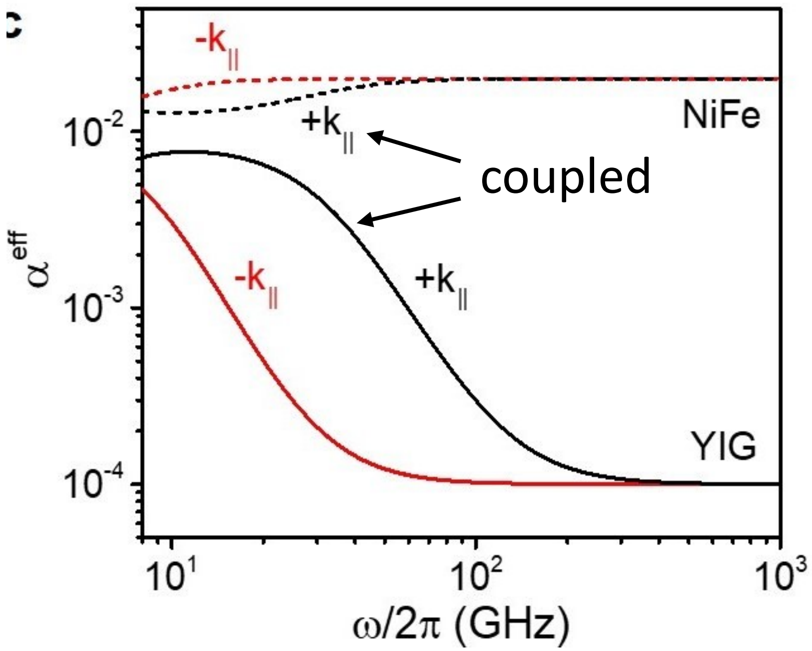
- Depending on the magnon propagation direction, the spin waves in the two layers couples together or remains intact→ **Asymmetric coupling**
- The coupling modifies both the real (frequency) and imaginary (damping) part of magnon dispersion.

Asymmetric Magnon Relaxation via Chiral Dipolar Coupling

Magnon dispersion

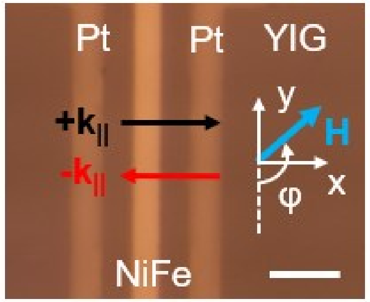


Asymmetric magnon relaxation



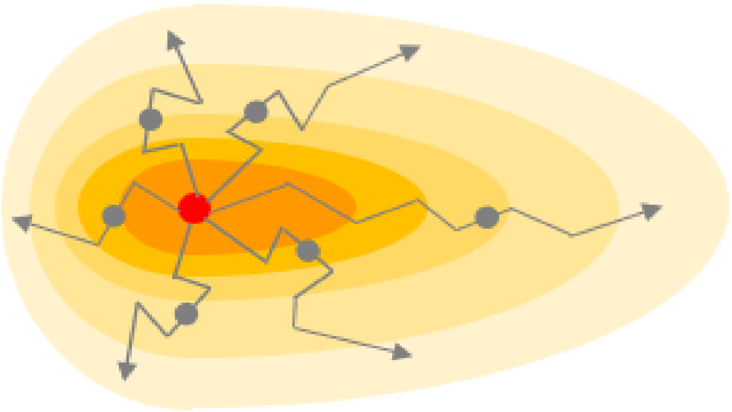
$\alpha^{\text{eff}}(+k_{\|}) \neq \alpha^{\text{eff}}(-k_{\|})$.

- When coupled, Permalloy tends to drag down the quality factor of YIG, due to the hybridization.
- Considering the realistic magnon dispersion in YIG and NiFe, and using their damping coefficients, α^{eff} of the two is calculated



Non-reciprocal Diffusion

Boltzmann Transport equation



$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \nabla_{\boldsymbol{r}} f + \frac{\mathrm{d}\boldsymbol{k}}{\mathrm{d}t} \cdot \nabla_{\boldsymbol{k}} f = -\frac{\delta f_{\mathrm{A}}}{\tau_0} - \frac{\delta f_{\mathrm{A}} + \delta f_{\mathrm{S}}}{\tau_{\mathrm{M}}}.$$

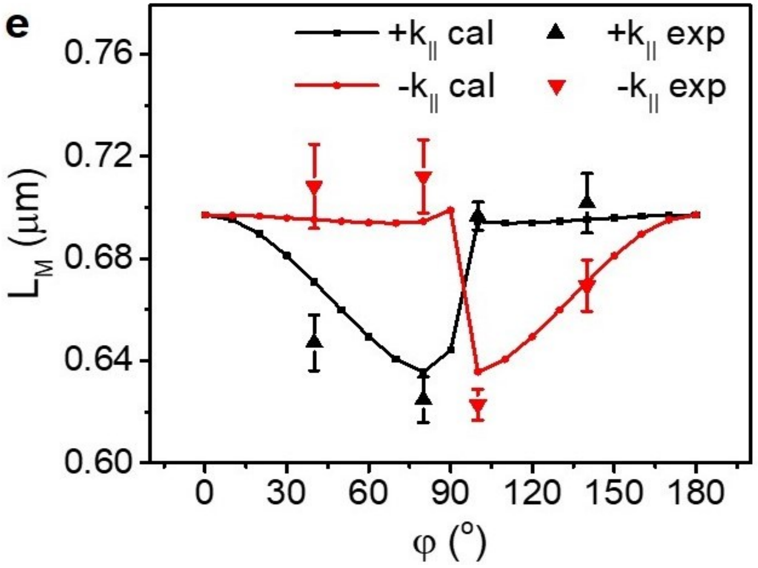
Spin conserving scattering (τ_0)

Spin non-conserving scattering (τ_{M})

$$1/\tau_{\mathrm{M}} \propto \alpha(\boldsymbol{k})$$

f_{A}: out-of-equilibrium distribution that is asymmetric with k.

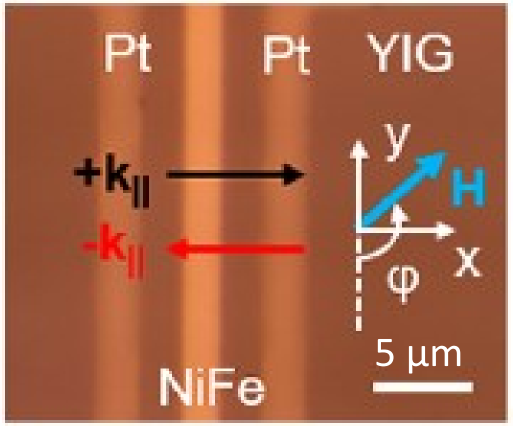
f_{S}: out-of-equilibrium distribution that is symmetric with k.

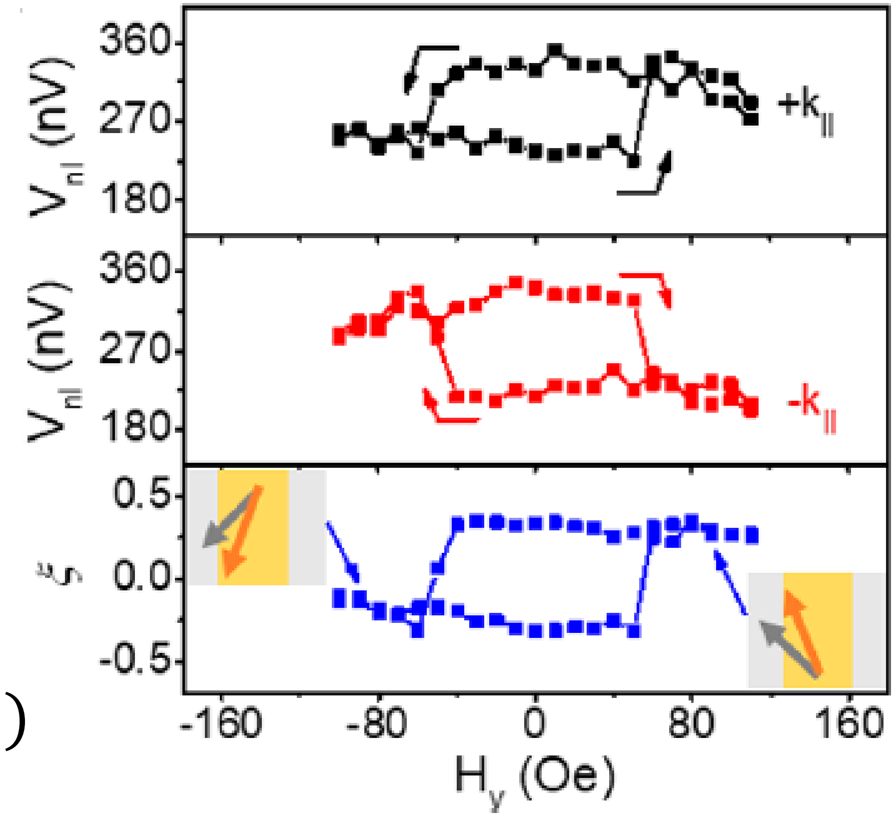


- $l_{sf} \sim \sqrt{\tau_0 \tau_M}$: spin diffusion length reflects the asymmetry in magnon relaxation rate under chiral dipolar coupling

Gate Tunable nonreciprocal magnon transport

- Nonvolatile, passive, nonreciprocal magnon transistor



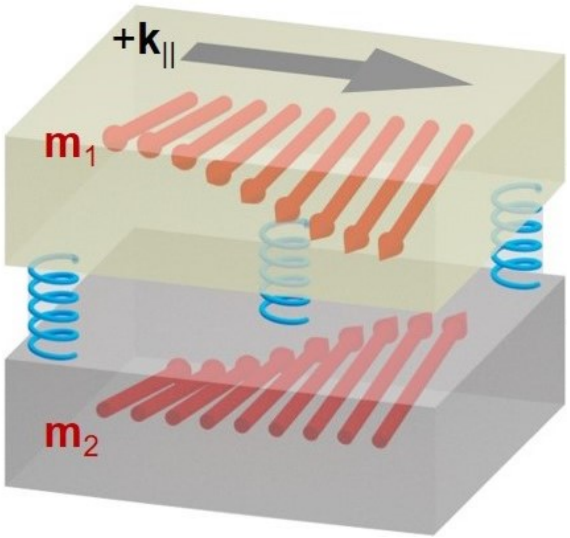


$$\xi = [V_{\mathrm{nl}}(+k_{\parallel}) - V_{\mathrm{nl}}(-k_{\parallel})]/\mathrm{max}(V_{\mathrm{nl}})$$

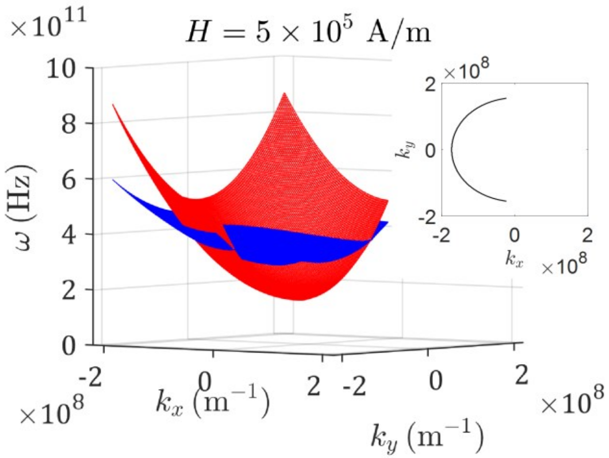
- To further increase the nonreciprocity ratio ξ:
  increase the difference in magnetic damping,
  have stronger degeneracy between the dispersion curves of the two materials

Content

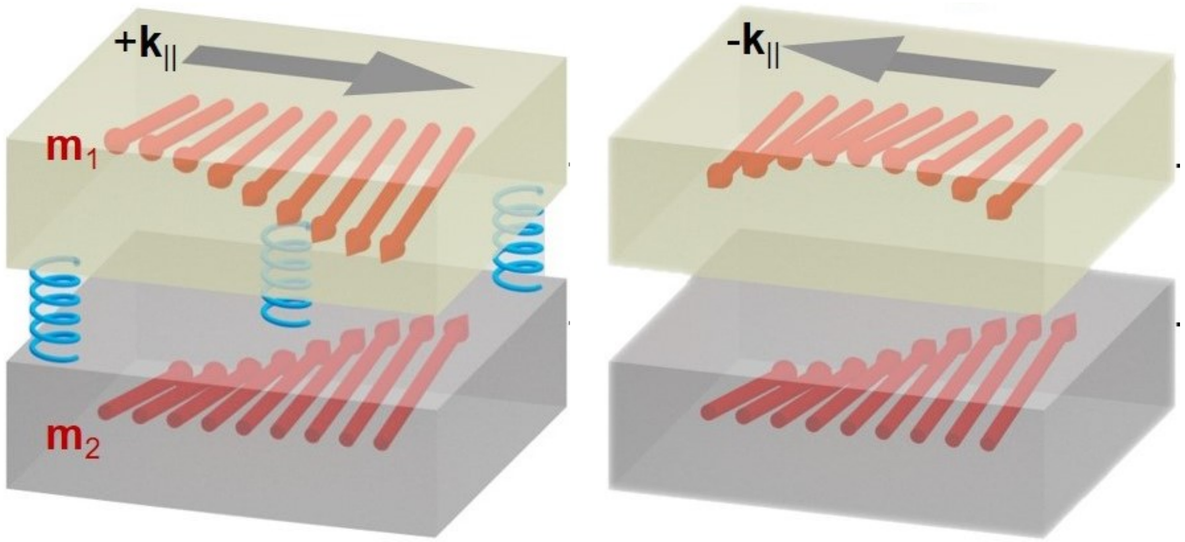
- Chiral dipolar interaction induced non-reciprocal magnon diffusion in bilayer heterostructure



- Tunable Chern bands and chiral spin currents in magnetic multilayers



Chiral Dipolar Coupling between Two Neighboring Layers



Magnon-magnon coupling

$$\begin{pmatrix} (1-i\alpha_1)\omega_1(k_\parallel) & \Delta_{12} \\ \Delta_{21} & (1-i\alpha_2)\omega_2(k_\parallel) \end{pmatrix}$$

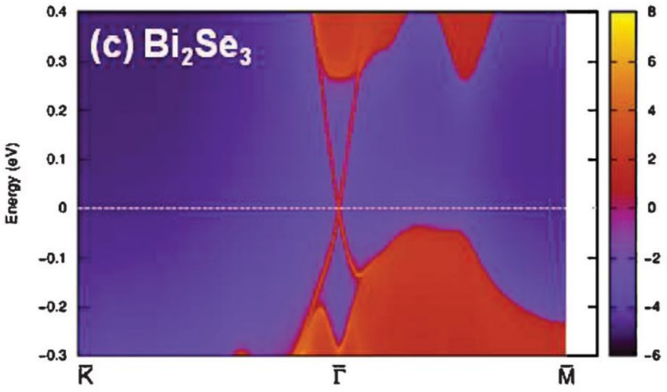
$$\Delta_{12} = B\left(|k_\parallel| \pm k_\parallel\right)$$

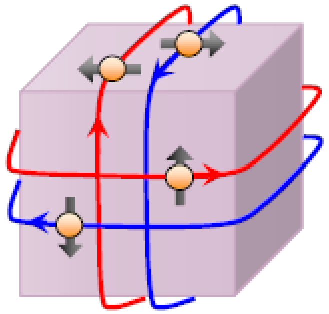
With $B = \gamma\mu_0 N_1 N_2 \sqrt{M_1 M_2 d_1 d_2}$,

$$N_{1(2)} = \frac{1-e^{-|k_\parallel| d_{1(2)}}}{|k_\parallel| d_{1(2)}}$$

- The interlayer dipolar coupling plays a similar role as spin-orbit coupling for electrons: magnon precession polarity*k *vs* spin orientation * k
- Can one use dipolar coupling to realize topological magnon band?

From (Electronic) Topological Insulator to Magnonic Topological Insulator

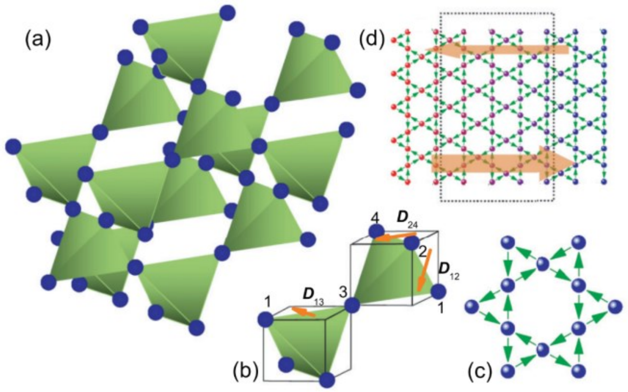




Topological insulators

Rev. Mod. Phys. **83**, 1057 (2011)

via DMI

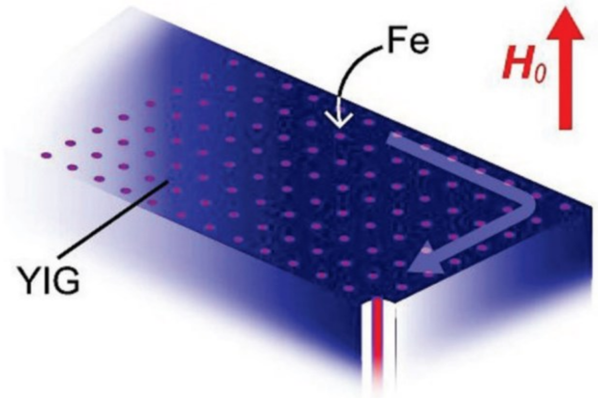


pyrochlore lattice ($Lu_2V_2O_7$)

$$H_{\mathrm{DMI}} = -\mathbf{D}_{ij} \cdot \left(\mathbf{S}_i \times \mathbf{S}_j\right).$$

Physical Review B 87, 144101 (2013)

via dipolar interaction



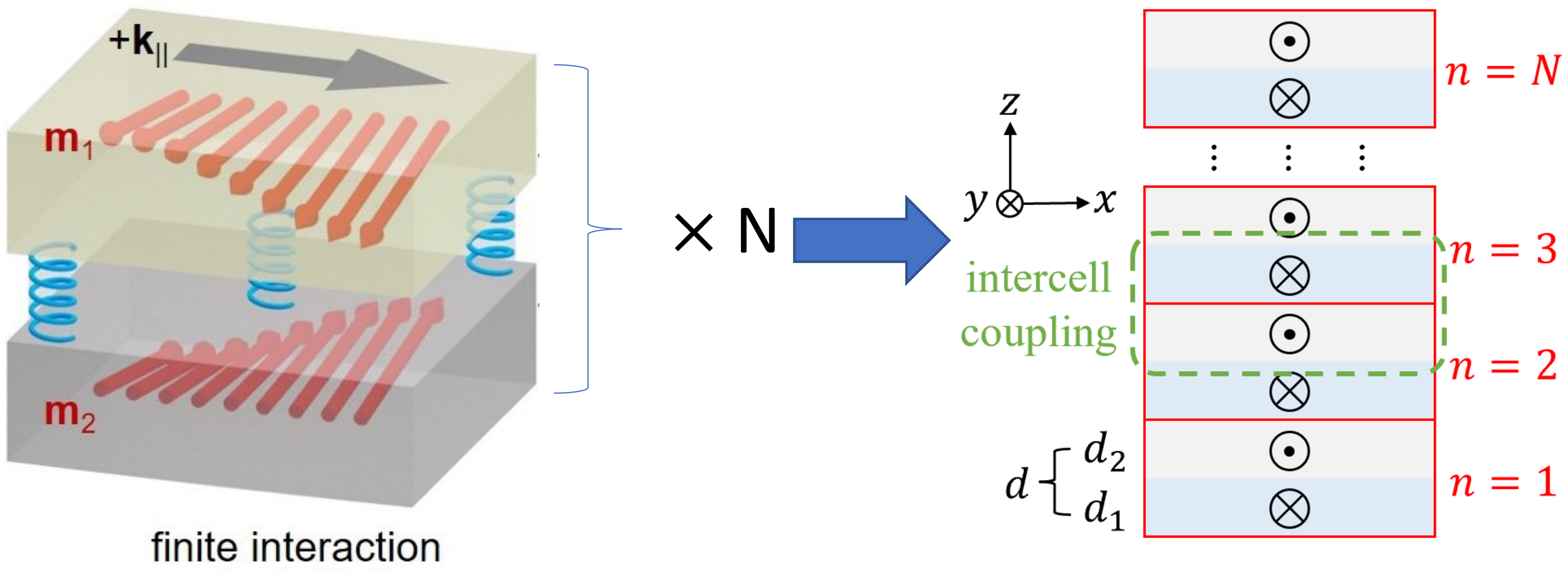
Artificial crystals

(periodic arrays of Fe pillars in YIG)

Physical Review B 87, 174427 (2013)

- Topological protection with suppressed scattering
- Spin orbit like mechanisms employed for magnon version of topological states
- Can lead to long coherence length of spin waves
- Existing approaches require materials with either special crystal symmetries or artificially nanostructures that demand advanced nanofabrication techniques

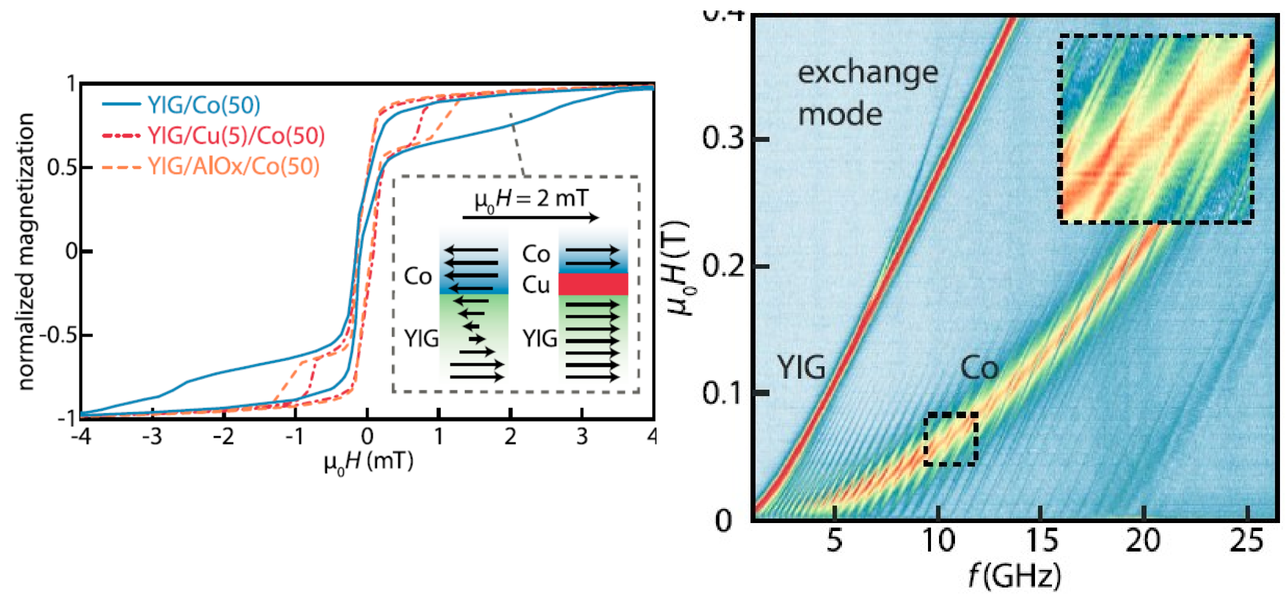
Antiparallelly Aligned Magnetic Multilayers



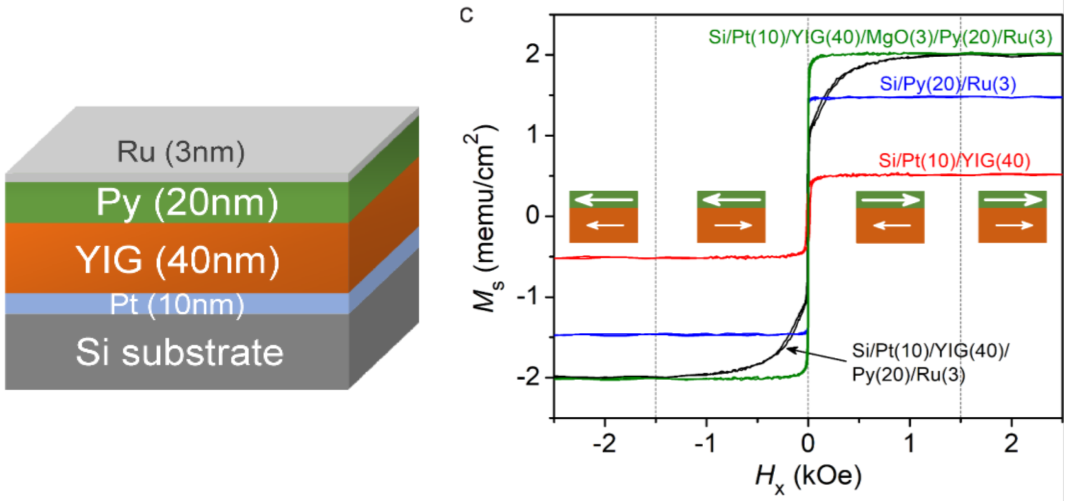
- Alternating magnetic layers with antiparallel magnetization
- Neighboring two layers (red boxes) form a unit cell
- Intrinsic exchange-dipolar magnons in each layer
- Dipolar interaction between propagating magnons lead to both intracell and intercell coupling

How to Achieve Antiparallel Alignment?

Antiparallel alignment between YIG and Ferromagnetic metal



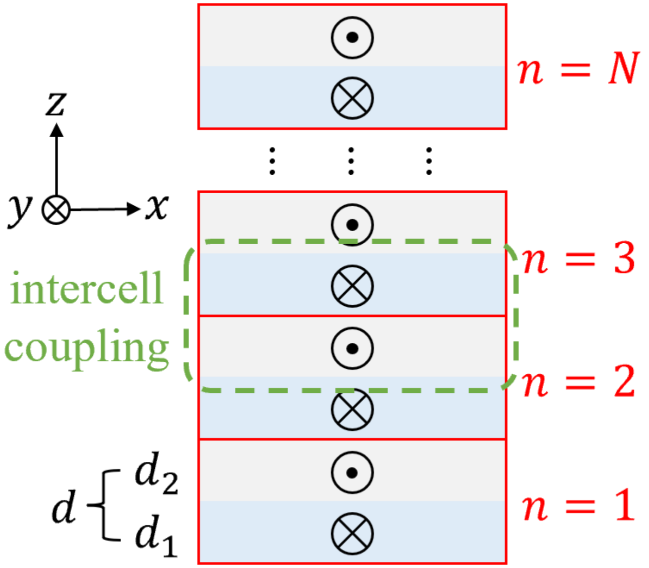
Klingler et al., PHYSICAL REVIEW LETTERS 120, 127201 (2018)



Y. Fan, et al, L. Liu, Physical Review Applied **13**, 061002 (2020)

- Antiparallel alignment achievable through natural interfacial exchange between magnetic metal and insulator (e.g., YIG/Py)
- Other possible approaches include synthetic antiferromagnet through RKKY exchange, shape anisotropy, etc

Hamiltonian of magnetic multilayer



$$\boldsymbol{H}_{\text{bulk}}(\boldsymbol{k}) = \begin{bmatrix} \omega_1 & \Delta_{\text{S}} + \Delta_{\text{D}} e^{-ik_z d} \\ \Delta_{\text{S}} + \Delta_{\text{D}} e^{ik_z d} & \omega_2 \end{bmatrix}$$

SSH like

Intrinsic frequency:

$$\omega_1 = \gamma\left(B_{ex1} - B_{app}\right) + A_1 {k_x}^2 \qquad \omega_2 = \gamma\left(B_{ex2} + B_{app}\right) + A_2 {k_x}^2$$

Interlayer exchange

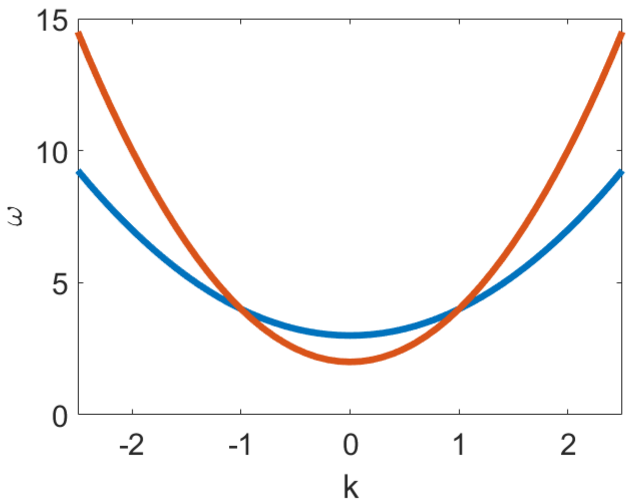
Applied field

Exchange within same layer

Choose $A_1 > A_2$(e.g., Py vs YIG)

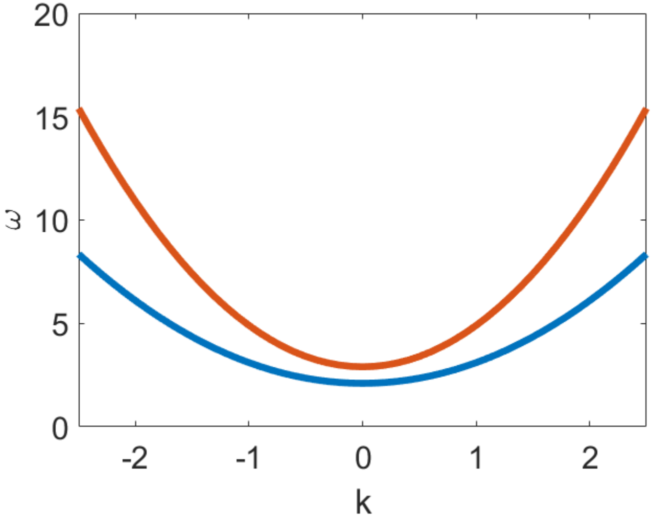
Band Inversion

$$B_{app} > \frac{1}{2}(B_{ex1} - B_{ex2})$$

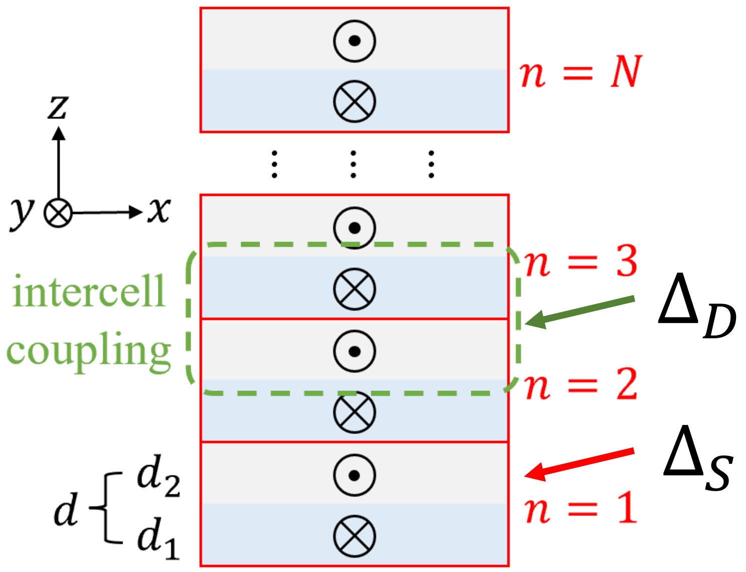


No Inversion

$$B_{app} < \frac{1}{2}(B_{ex1} - B_{ex2})$$



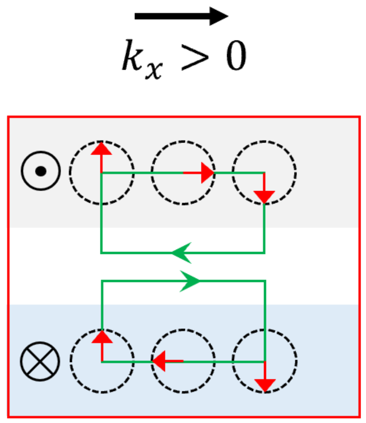
Gap Opening: Intracell *vs* Intercell Coupling



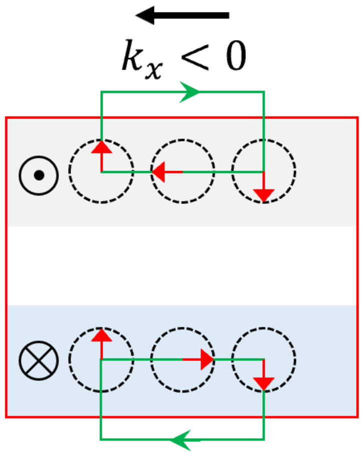
$$\boldsymbol{H}_{\text{bulk}}(\boldsymbol{k}) = \begin{bmatrix} \omega_1 & \Delta_S + \Delta_D e^{-ik_z d} \\ \Delta_S + \Delta_D e^{ik_z d} & \omega_2 \end{bmatrix}.$$

Intracell coupling : $\Delta_S = \text{const} \cdot (|k_x| + k_x)$

Intercell coupling: $\Delta_D = \text{const} \cdot (|k_x| - k_x)$



$\Delta_S > 0,\ \Delta_D = 0$

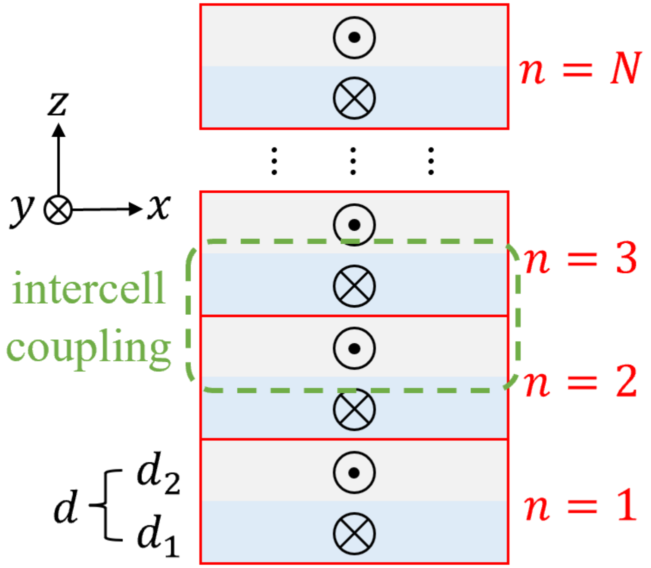


$\Delta_S = 0,\ \Delta_D > 0$

For $k_x > 0$: $\Delta_S > 0$ and $\Delta_D = 0$

For $k_x < 0$: $\Delta_S = 0$ and $\Delta_D > 0$

Magnonic Topological Band Structure



$$\begin{bmatrix} \omega_1 & \Delta_{\mathrm{S}} + \Delta_{\mathrm{D}} e^{-ik_z d} \\ \Delta_{\mathrm{S}} + \Delta_{\mathrm{D}} e^{ik_z d} & \omega_2 \end{bmatrix}$$

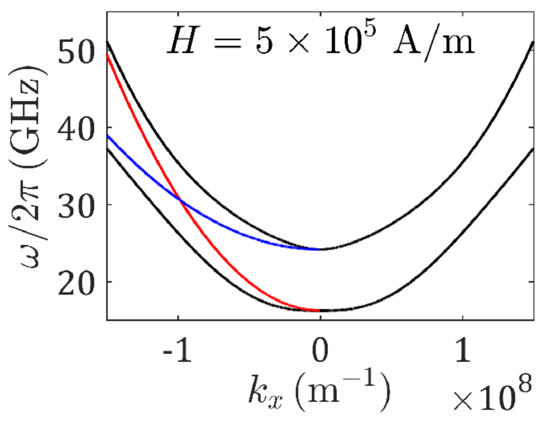
Chern integer (lower band):

$$Ch_- = \frac{1}{2\pi} \iint_{\mathrm{B.Z.}} \Omega_-(\boldsymbol{k}) dk_x dk_z = \begin{cases} 1 & (A_1 > A_2,\ B_{app} > \frac{1}{2}(B_{ex1} - B_{ex2})) \\ -1 & (A_1 < A_2,\ B_{app} < \frac{1}{2}(B_{ex1} - B_{ex2})) \\ 0 & (\text{otherwise}) \end{cases}$$

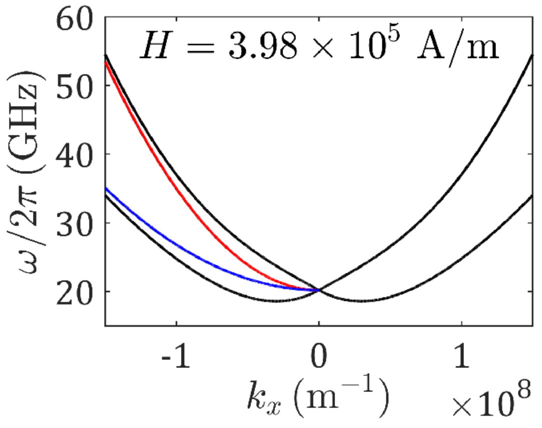
Inversion (first two cases)

Normal band (otherwise)

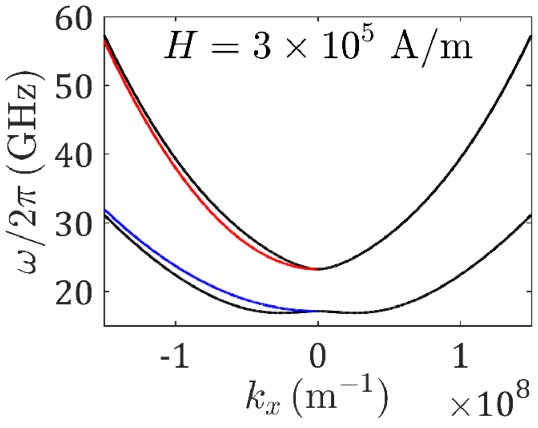
Magnonic band structure [10 nm YIG + 10 nm Py]$_N$



Ch = 1



Semi-metallic

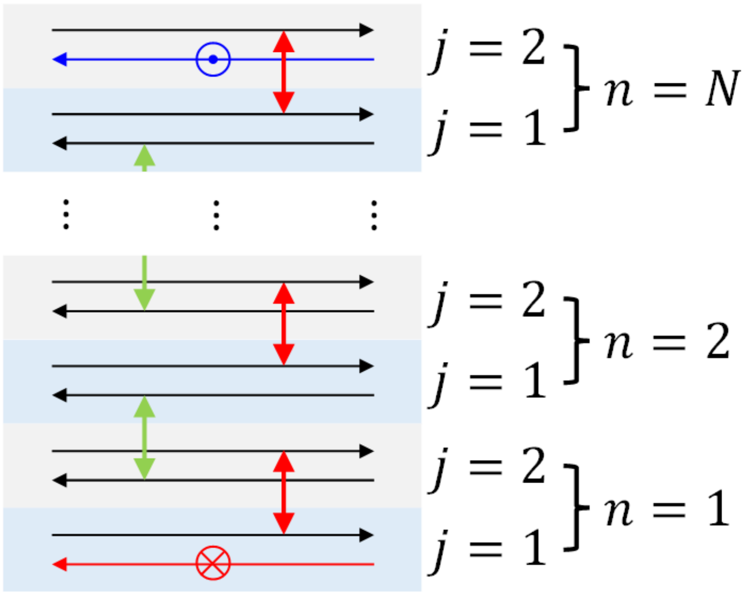


Ch = 0

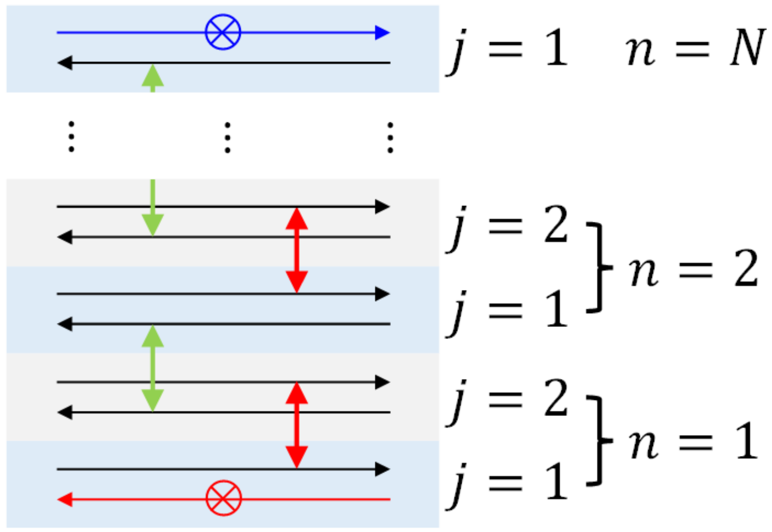
Red and blue lines: surface states at the top and bottom of multilayers.

Dirac point of surface state only shows up in one half of the B.Z.

Surface Mode in Topological Non-Trivial Case (coupled wire construction)



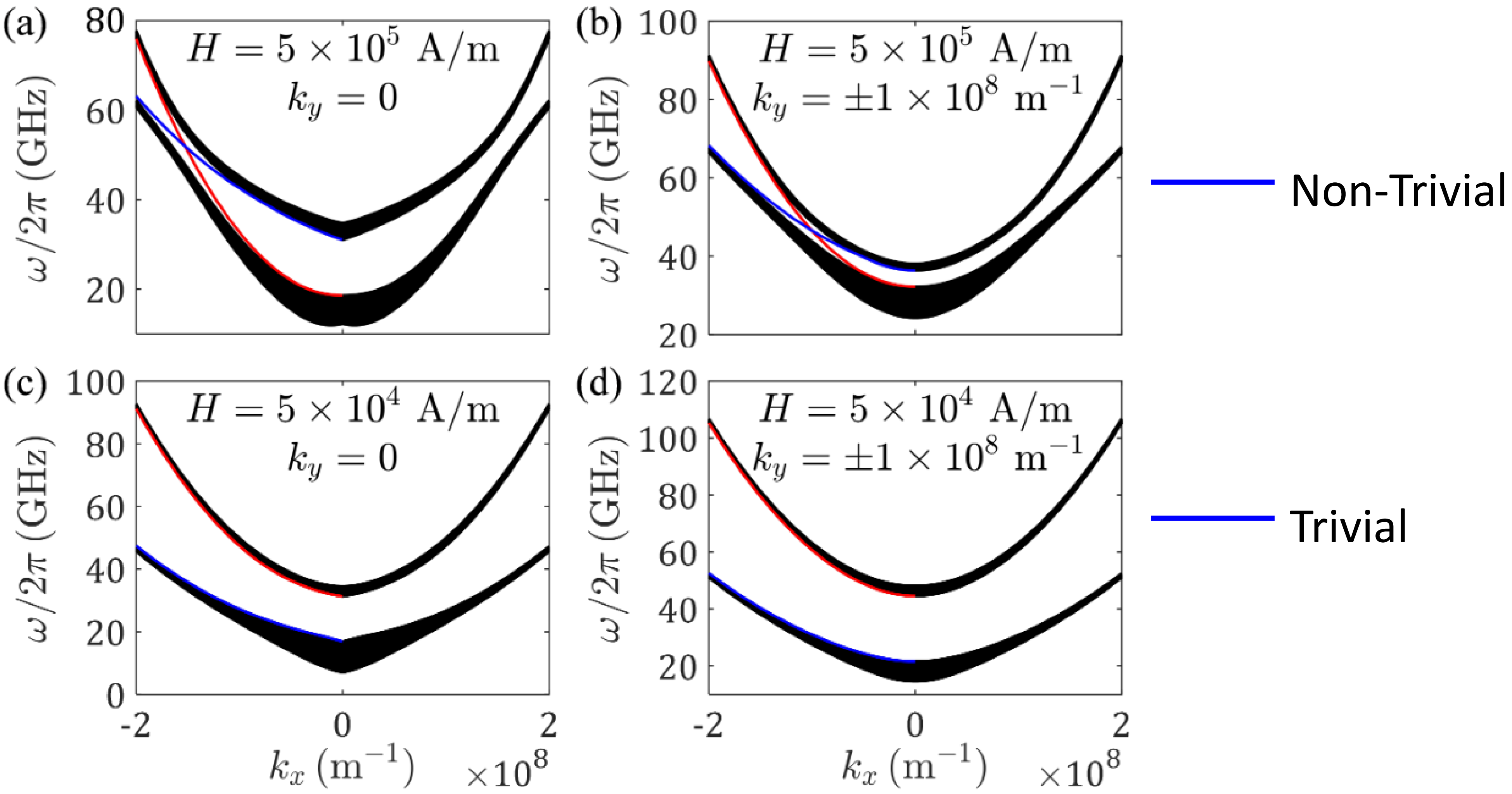
Total 2N individual layers

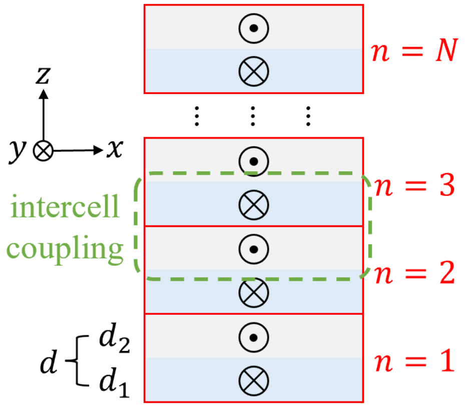


Total 2N-1 individual layers

- Right-moving ($k_x > 0$): $\Delta_S > 0$ and $\Delta_D = 0$, coupled through intracell interaction (red)
- Left-moving ($k_x < 0$): $\Delta_S = 0$ and $\Delta_D > 0$, coupled through intercell interaction (green)
- A pair of surface states are left uncoupled, carrying spin currents with opposite direction
- Chiral surface spin currents still exist for odd number of total layers

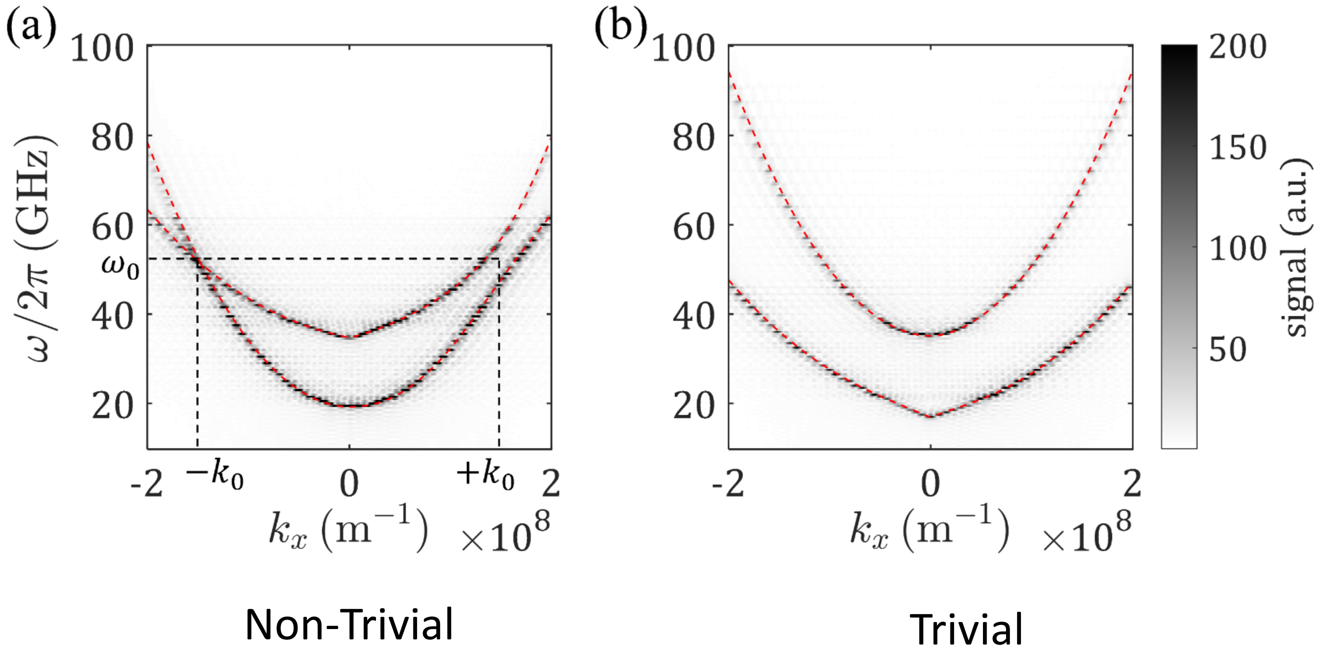
A More Generalized System with finite k_y





- Including finite k_y, dipolar interaction within each layer, exchange interaction at the interface, the band structure remains qualitatively the same.
- Topological phases still tunable through H

Micromagnetic Simulation

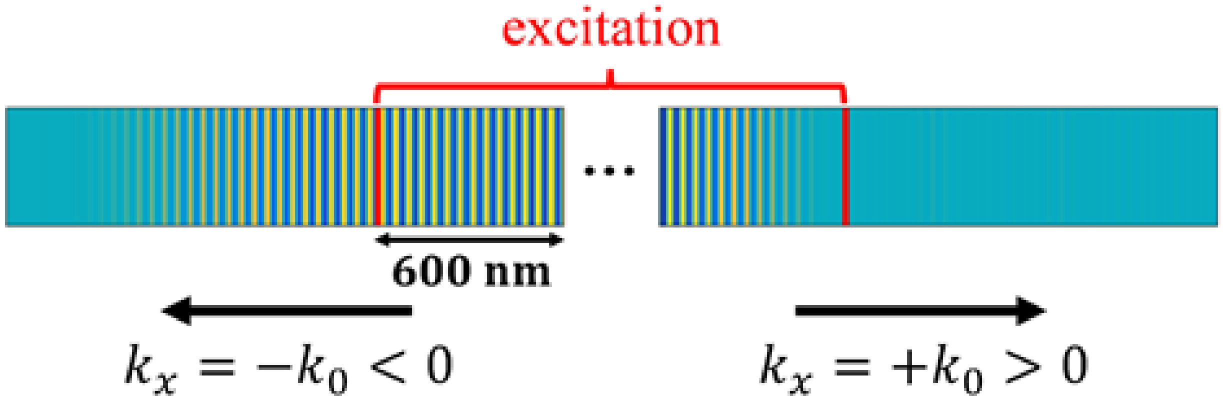


- Simplest structure:

  bilayer (YIG 10 nm + Py 10 nm)
- Pulse excitation:

$$h(x,t) = h_0 \mathrm{sinc}(k_c x)\,\mathrm{sinc}[\omega_c (t - t_0)]\,\hat{z}$$

- Consistent with Analytical Results



- At frequency ω_0, unidirectional propagation

$k_x < 0$ half-space: at Dirac point, two available states

$k_x > 0$ half-space: no available state, within the gap.

Summary

- Nonreciprocal transmission of the spin Hall effect-excited diffusive magnons in a NiFe gated YIG channel.
- Nonreciprocity switchable via magnetic moment orientation of the gate.
- Hyridization between two magnon modes via chiral dipolar coupling leads to asymmetric relaxation rate and magnon diffusion length.
- Topological magnonic state can be constructed in antiparallel magnetic multilayers via dipolar coupling, characterized by Chern number.
- Trivial or non-trivial states toggled via external field strength.
- Robust, long coherence, unidirectional surface spin current can be achieved with topological protection.

J. Han, et al. L. Liu, "Nonreciprocal Transmission of Incoherent Magnons with Asymmetric Diffusion Length" Nano Lett. 21, 7037 (2021).
Z. Hu, L. Fu, L. Liu, "Tunable Magnonic Chern Bands and Chiral Spin Currents in Magnetic Multilayers," arXiv:2201.00312 (2022).