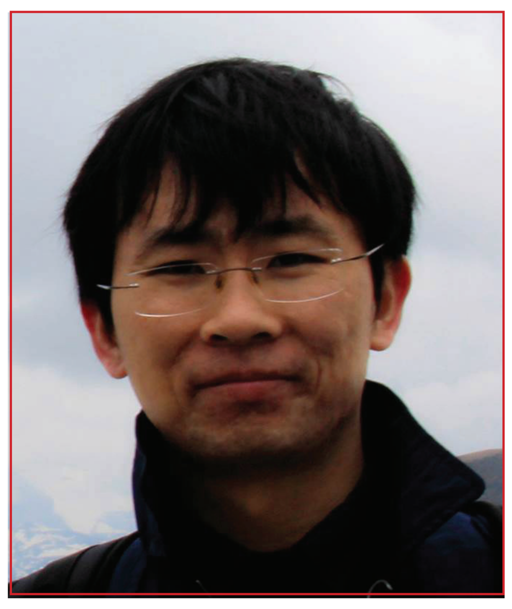

DI KAI

Achievements

Dr Di's research is focused on the study of spin waves in novel magnetic nanostructures by combined methods of experiment using laser Brillouin spectroscopy and micro magnetic simulation and analytical calculation. He has an excellent publication output which includes eight journals and have been published in Physical Review Letters, Scientific Reports, Applied Physics Letters, Physical Review B, Journal of Applied Physics and Nanoscales Research Letters. In addition, he has presented papers at the 2013 International Conference on Materials for Advances Technologies, Singapore and the European Materials Research Society 2014 Spring Meeting, France.

Awards

- ✓ Winner of the NUS FoS Best Graduate Researcher Award from Physics (2015)
- ✓ Winner for the Top Graduate Researcher Award in the Faculty of Science (2015)

Molding the Flow of Spin Waves

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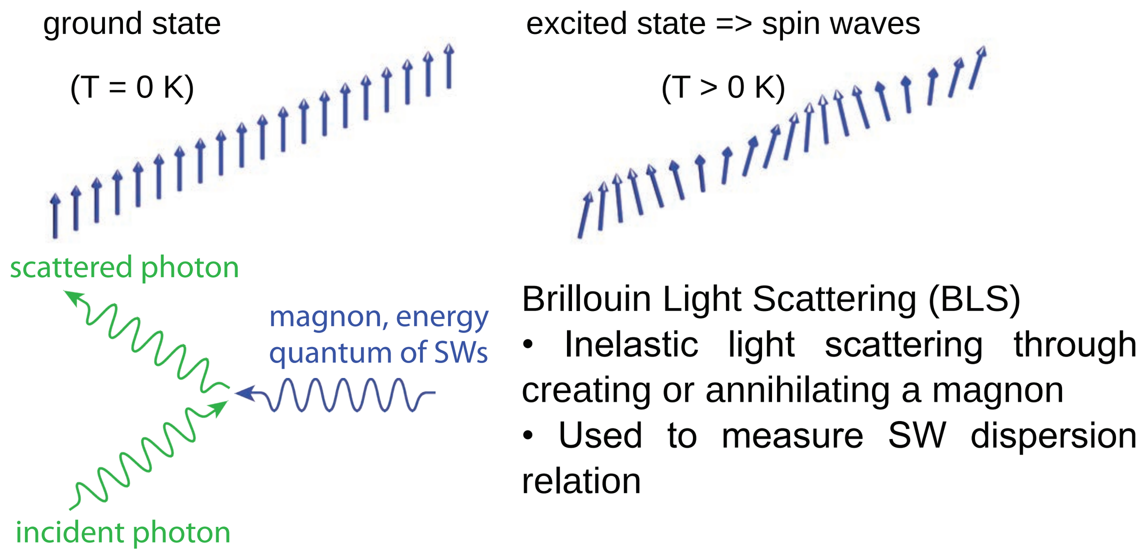
NUS National University of Singapore

Spin waves & Brillouin light scattering

Spin waves (SWs) are propagating wavelike disturbances in the ordering of magnetic materials [1].

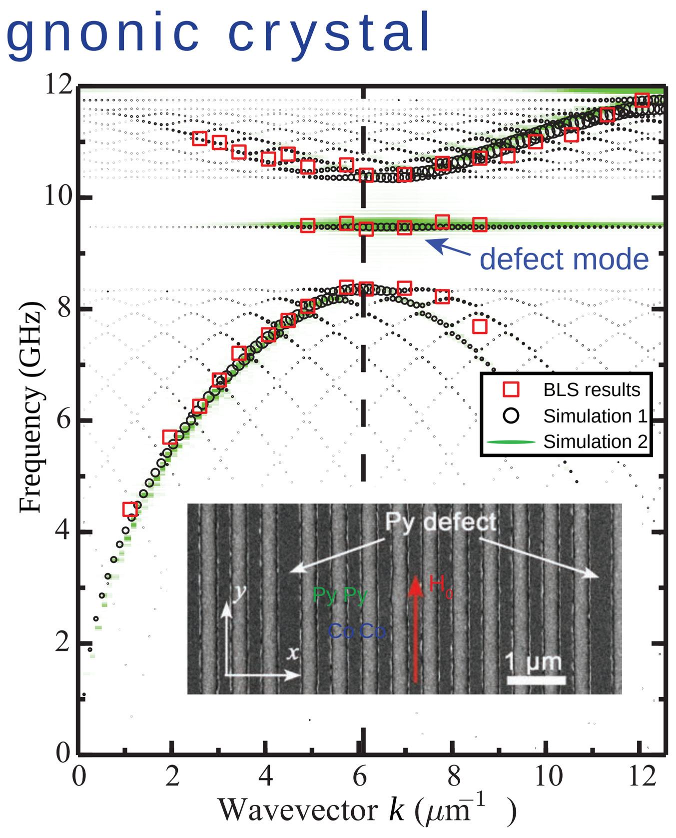


Brillouin Light Scattering (BLS)

- Inelastic light scattering through creating or annihilating a magnon
- Used to measure SW dispersion relation

Defect magnonic crystal

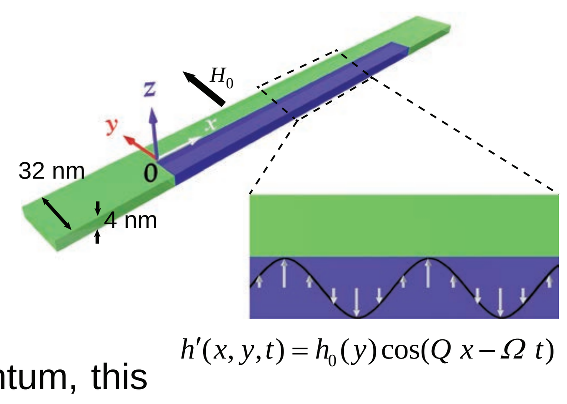
Magnonic crystals (MCs) are metamaterials with periodically alternating magnetic properties. Like electrons in periodic crystal potentials, the dispersion relation of magnons in MCs features interesting bandgaps, within which propagation of SWs is forbidden. We have made the first experimental observation of nanostructured MCs with artificial defects, which can be used for energy band engineering for various magnonic devices [2-4].

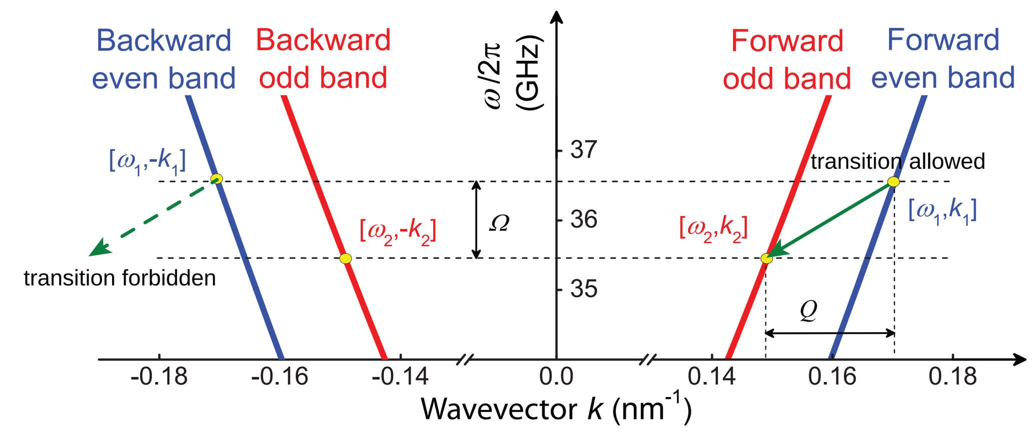


Measured SW band structure of a MC with artificial defects. Inset: SEM image of the thin-film-based MC showing defects.

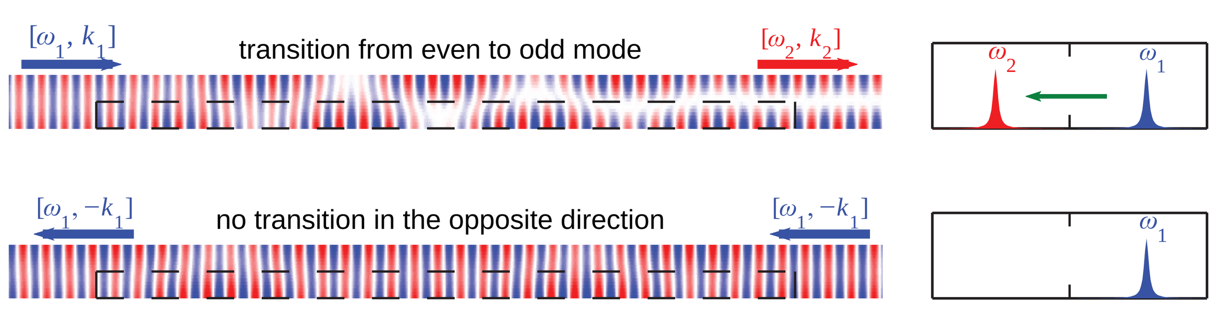
SW nonreciprocity by interband transition

Like photon-absorption induced indirect electronic transitions in semiconductors, magnons can undergo interband transitions when microwave photons with suitable symmetry are present, as shown by our simulations [5]. Due to the conservation of energy and momentum, this transition can happen in only one direction, leading to nonreciprocal magnonic transitions. Our finding is useful for stabilizing magnonic circuits.

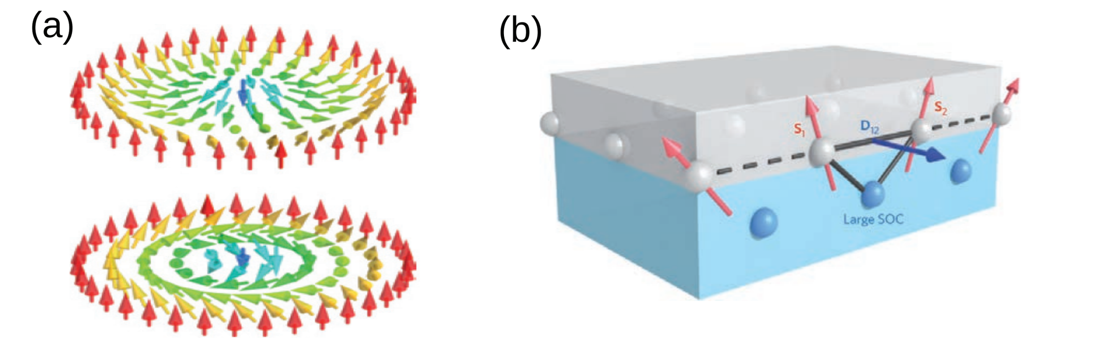




Band structure of the nano-stripe waveguide. Green arrows represent the enrgy and momentum of microwave photons showing possible transitions.



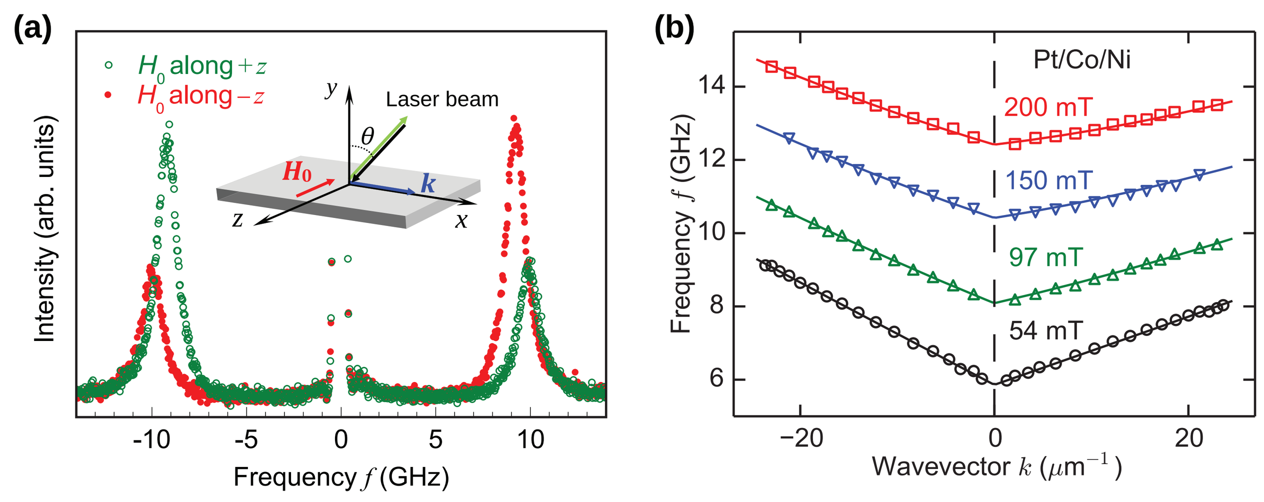
SW dynamics in the presence of Dzyaloshinskii-Moriya interaction (DMI)



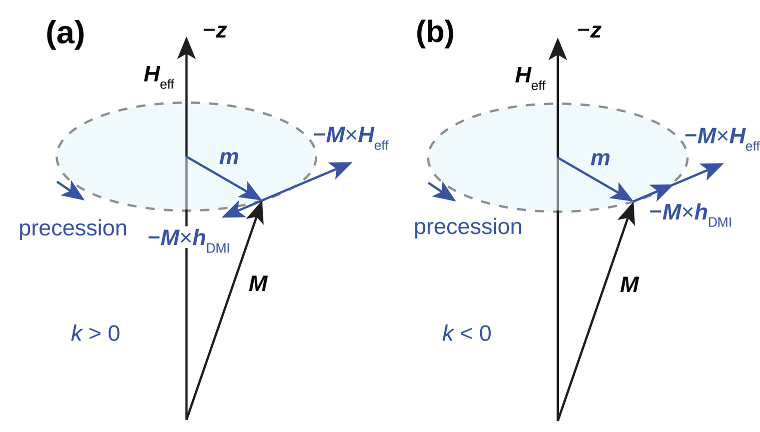
(a) Spin configurations of two different types of magnetic skyrmions. (b) Illustration of origin of interfacial DMI by super-exchange interaction.

DMI may arise at the interface between a ferromagnet and a metal with a very strong spin-orbit coupling (SOC) due to a 3-site super-exchange interaction. It is responsible for the atomic-scale magnetic skyrmions, the topological spin configurations that hold promise for future non-volatile memory and computing [6].

DMI is an antisymmetric exchange interaction with the energy term between two spins: $H_{DMI} = -D_{ij}\cdot(S_i \times S_j)$, which together with Heisenberg exchange interaction, favors canted alignment of neighboring spins.



(a) Brillouin spectra recorded at a fixed incident angle of θ = 45° (k = 17.3 μm⁻¹) under oppositely oriented external magnetic fields. (b) Asymmetric spin-wave dispersion relation of a Pt(4nm) / Co(1.6nm) / Ni(1.6nm) film showing interfacial DMI at the Pt/Co interface. Dots represent experimental data, while solid lines are theoretical predictions.



Schematics of the precession of the magnetization M under the total effective field $H_{eff} + h_{DMI}$ for (a) k>0 and (b) k<0. All the vectors in the xy-plane are labelled blue. This explains why the dispersion relation is asymmetric.

Using BLS, we made the first direct observation of interfacial DMI in ultrathin Pt/Co/Ni and Pt/CoFeB films. Our results show the asymmetry of the SW dispersion relation and lifetime due to DMI depending on propagation direction, which agree well with our theoretical predictions [7, 8].

Acknowledgement

The samples for the experiments were provided by Prof Yang Hyunsoo of the ECE Department, NUS.

References

[1] Soshin Chikazumi, Physics of ferromagnetism (Oxford University Press, New York, 1997).
[2] M Krawczyk and D Grundler, J. Phys.: Condens. Matter 26, 123202 (2014).
[3] Z. K. Wang, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, S. Jain, and A. O. Adeyeye, Appl. Phys. Lett. 94, 083112 (2009).
[4] K. Di, H. S. Lim, V. L. Zhang, M. H. Kuok, S. C. Ng, M. G. Cottam, and H. T. Nguyen, Phys. Rev. Lett. 111, 149701 (2013); K. Di, V. L. Zhang, M. H. Kuok, H. S. Lim, S. C. Ng, K. Narayanapillai, and H. Yang, Phys. Rev. B 90, 060405(R) (2014).
[5] K. Di, H. S. Lim, V. L. Zhang, S. C. Ng, and M. H. Kuok, Appl. Phys. Lett. 103, 132401 (2013).
[6] A. Fert, V. Cros, and J. Sampaio, Nat. Nanotech. 8, 152 (2013).
[7] K. Di, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, J. Yu, J. Yoon, X. Qiu, and H. Yang, Phys. Rev. Lett. 114, 047201 (2015).
[8] K. Di, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, X. Qiu, and H. Yang, Appl. Phys. Lett. 106, 052403 (2015).

Publication Highlights

PHYSICAL REVIEW B **90**, 060405(R) (2014)

Band structure of magnonic crystals with defects: Brillouin spectroscopy and micromagnetic simulations

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(Received 13 June 2014; revised manuscript received 7 August 2014; published 20 August 2014)

Using Brillouin spectroscopy, an observation has been made of the band structures of nanostructured defect magnonic crystals. The samples are otherwise one-dimensional periodic arrays of equal-width $Ni_{80}Fe_{20}$ and cobalt nanostripes, where the defects are stripes of a different width. A dispersionless defect branch emerges within the band gap with a frequency tunable by varying the defect stripe width, while the other branches observed are similar to those of a defect-free crystal. Micromagnetic and finite-element simulations performed unveil additional tiny band gaps and the frequency-dependent localization of the defect mode in the vicinity of the defects.

DOI: 10.1103/PhysRevB.90.060405 PACS number(s): 75.30.Ds, 75.40.Gb, 78.35.+c, 78.67.Pt

PRL **114**, 047201 (2015) PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2015

Direct Observation of the Dzyaloshinskii-Moriya Interaction in a Pt/Co/Ni Film

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(Received 18 September 2014; published 28 January 2015)

The interfacial Dzyaloshinskii-Moriya interaction in an in-plane anisotropic Pt(4 nm)/Co(1.6 nm)/Ni(1.6 nm) film has been directly observed by Brillouin spectroscopy. It is manifested as the asymmetry of the measured magnon dispersion relation, from which the Dzyaloshinskii-Moriya interaction constant has been evaluated. Linewidth measurements reveal that the lifetime of the magnons is asymmetric with respect to their counter-propagating directions. The lifetime asymmetry is dependent on the magnon frequency, being more pronounced, the higher the frequency. Analytical calculations of the magnon dispersion relation and linewidth agree well with experiments.

DOI: 10.1103/PhysRevLett.114.047201 PACS numbers: 75.30.Ds, 75.70.Ak, 75.70.Tj, 78.35.+c

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Enhancement of spin-wave nonreciprocity in magnonic crystals via synthetic antiferromagnetic coupling

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Spin-wave nonreciprocity arising from dipole-dipole interaction is insignificant for magnon wavelengths in the sub-100 nm range. Our micromagnetic simulations reveal that for the nanoscale magnonic crystals studied, such nonreciprocity can be greatly enhanced via synthetic antiferromagnetic coupling. The nonreciprocity is manifested as highly asymmetric magnon dispersion curves of the magnonic crystals. Furthermore, based on the study of the dependence of the nonreciprocity on an applied magnetic field, the antiparallel alignment of the magnetizations is shown to be responsible for the enhancement. Our findings would be useful for magnonic and spintronics applications.

APPLIED PHYSICS LETTERS **106**, 052403 (2015)

CrossMark

Asymmetric spin-wave dispersion due to Dzyaloshinskii-Moriya interaction in an ultrathin Pt/CoFeB film

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Employing Brillouin spectroscopy, strong interfacial Dzyaloshinskii-Moriya interactions have been observed in an ultrathin Pt/CoFeB film. Our micromagnetic simulations show that spin-wave nonreciprocity due to asymmetric surface pinning is insignificant for the 0.8 nm-thick CoFeB film studied. The observed high asymmetry of the monotonic spin wave dispersion relation is thus ascribed to strong Dzyaloshinskii-Moriya interactions present at the Pt/CoFeB interface. Our findings further enhance the significance of CoFeB as an important material for magnonic and spintronic applications.

[http://dx.doi.org/10.1063/1.4907173]