CEMS Topical Meeting Online

Magnon-phonon coupling

Aug 19, 2020 (Wed)

Interaction between phonons and magnons has recently attracted a lot of interest in the spintronics field. The interaction can give rise to novel spintronics functionalities such as non-reciprocal transport, enhancement of spin Seebeck effect and spin current generation due to lattice vibration. This topical meeting provides an opportunity to discuss on the such latest topics. We seek a wide range of opinions on the direction and future prospects of novel spintronics based on magnon-phonon interaction.

13:00-13:10 Opening

13:10-13:50
Jorge Puebla
(RIKEN CEMS)

"Spin current generation and non-reciprocity via magnon-phonon"

13:50-14:30
Kei Yamamoto
(JAEA)

"Non-reciprocal pumping of surface acoustic waves by spin wave"

14:30-15:10
Yoichi Nii
(Tohoku-U)

"Nonreciprocal phenomena of phonon in non-centrosymmetric magnets"

15:10-15:30 Break

15:30-16:10
Yukio Nozaki
(Keio-U)

"Quantitative study on spin-vorticity coupling"

16:10-16:50
Mamoru Matsuo
(KITS)

"Spin transport driven by fluid and elastic motions"

16:50-17:30
Takashi Kikkawa
(U-Tokyo)

"Magnon-phonon hybridization in thermal spin transport"

17:30-17:40 Closing

https://cems.riken.jp/topicalmeeting/002_magnon-phonon/

RIKEN CEMS

"Spin current generation and non-reciprocity via magnon-phonon coupling"

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In this talk we present our recent work regarding magnon-phonon coupling. We briefly introduce the mechanism of acoustic spin pumping [1] and demonstrate a spin to charge current conversion via magnon-phonon coupling and inverse Edelstein effect [2]. We further show that in the presence of acoustic reflectors forming an acoustic cavity, we observe an enhancement in acoustic spin pumping of about 3 times in the $Ni/Cu/Bi_2O_3$ heterostructure [3]. We also demonstrate the non-reciprocal absorption of surface acoustic waves when interacting with anisotropic magnets. Under optimized conditions based on theoretical predictions we achieve up to 100% non-reciprocity in a Ta/CoFeB(1.6 nm)/MgO heterostructure [4].

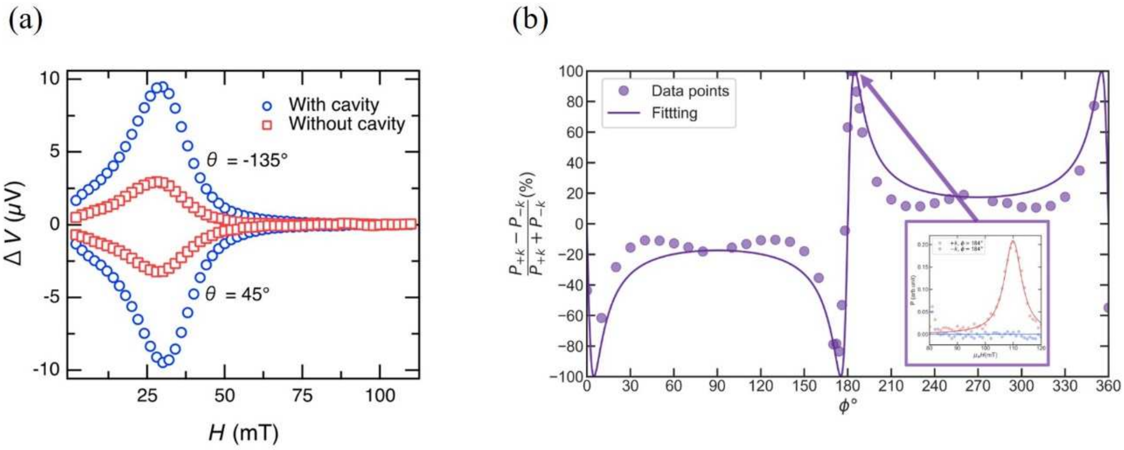

Figure 1: (a) Acoustic spin pumping voltage of a $Ni/Cu/Bi_2O_3$ heterostructure in a surface acoustic wave (SAW) device with (blue open circles) and without (red open squares) acoustic cavity. External in-plane magnetic field is applied at $\theta = 45^0, -135^0$. (b) In-plane magnetic field angle dependence of non-reciprocity ration of SAW absorption in a Ta/CoFeB(1.6 nm)/MgO heterostructure.

[1] J. Puebla, M. Xu, B. Rana, K. Yamamoto, S. Maekawa, Y. Otani, Journal of Physics D: Applied Physics 53 (26), 264002 (2020)
[2] M. Xu, J. Puebla, F. Auvray, B. Rana, K. Kondou, Y. Otani, Physical Review B 97 (18), 180301® (2018)
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[4] M. Xu, K. Yamamoto, J. Puebla, K. Baumgaertl, B. Rana, K. Miura, H. Takahashi, D. Grundler, S. Maekawa, Y. Otani, Science Advances, in press (2020)

Non-reciprocal pumping of surface acoustic waves by spin wave resonance

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Surface acoustic waves (SAWs) are accompanied by rotations of individual atoms near the surface. There is a locking between the axis of rotation and the direction of propagation, which implies that left- and right-moving SAWs have opposite senses of the surface atom rotation. The coupling between the rotation and magnetisation dynamics is expected to depend on whether the axis of rotation is parallel or anti-parallel to the equilibrium magnetisaion. Recent experiments on SAW transmission across magnetic scatterers [1,2] demonstrated that this coupling asymmetry manifests itself as a strong non-reciprocal transmission of SAWs.

In this talk, we theoretically study the SAW non-reciprocity induced by its coupling to magnetisation dynamics. Starting from the coupled equations of motion for acoustic and spin waves, we show that the interaction is characterised by two effective coupling constants, which depend on the angle between the equilibrium magnetisation and the SAW wave vector. We analytically show that the two cancel each other at certain angles, leading to vanishing of the net interaction between magnons and phonons. The formalism is first applied to the aforementioned transmission experiments, then used to predict the inverse effect in which non-reciprocal generation of SAWs is achieved by externally driving spin waves.

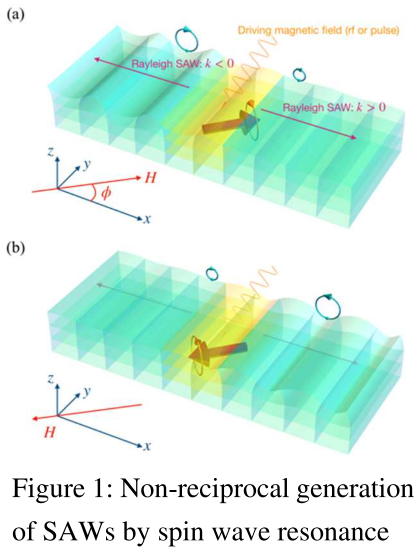

Figure 1: Non-reciprocal generation of SAWs by spin wave resonance

[1] R. Sasaki, Y. Nii, Y. Iguchi and Y. Onose, Phys. Rev. B **9**5, 020407 (2017).

[2] M. Xu, K. Yamamoto, J. Puebla, K. Baumgaertl, B. Rana, K. Miura, H. Takahashi, D. Grundler, S. Maekawa and Y. Otani, Science Advances, in press (2020).

Nonreciprocal phenomena of phonon in noncentrosymmetric magnets

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Relativistic spin-orbit coupling (SOC) plays essential roles in condensed matter physics for emergence of exotic quantum states. Entangled spin-orbital state often induces topological spin textures in either real or momentum spaces, and results in emergent electromagnetic responses. Here, we consider its phononic analogue in noncentrosymmetric magnets. Regarding “phonon angular momentum” [1] as the pseudo-spin degree of freedom of phonon, we unveil novel phenomena emerging from phononic-SOC.

First, we show phononic version of Rashba-like splitting in a chiral medium MnSi. By combining inelastic X-ray scattering and first-principle calculations, we unveiled hedgehog type acoustic phonon band splitting originating from the crystal chirality. Secondly, we show nonreciprocal phonon transport in multiferroics [2,3]. By investigating surface acoustic wave (SAW) propagation in a Ni/$LiNbO_3$ hybrid multiferroic device, we revealed velocity and decay rate becomes inequivalent for counter-propagating SAWs. In a prototypical multiferroic $TbMnO_3$, on the other hand, nonreciprocal phonon transport has been observed as thermal rectification effect [3]. To the best of our knowledge, this is the first observation of thermal diode effect using a single bulk material. Finally, we demonstrate phonon induced magnetization control in Ni/$LiNbO_3$ device [4]. We show that phonon angular momentum inherent in SAW can selectively switch magnetization direction. All these results may offer potential applications in phononics and spintronics field based on the concept of phononic-SOC.

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[4] R. Sasaki, Y. Nii, and Y. Onose, arXiv:2007.03192

Quantitative study on spin-vorticity coupling

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Since a novel type of spin current (SC) generation via spin-vorticity coupling (SVC) in a surface acoustic wave (SAW) was theoretically predicted by Matsuo et al. [1], experimental studies on the SVC had been reported by several groups. In our research group, we succeeded to demonstrate a spinwave resonance (SWR) excitation via alternating SC generated in a NiFe/Cu bilayer when the Rayleigh-type SAW was applied [2]. To improve the understanding in the microscopic mechanism of the angular momentum conversion between microscopic electron spin and macroscopic angular momentum in the SAW, it is significant to obtain the magnitude and spatial distribution of the SAW in the bilayer system.

In this presentation, we will show you our recent experimental studies on (i) highly nonreciprocal SWR excited using magnetoelastic coupling in Ni/Si bilayer [3], (ii) reciprocal SWR excited using gyromagnetic coupling in NiFe single layer [4], and (iii) electrical measurement of alternating SC in NiFe/Cu bilayer [5]. We found that the nonreciprocity of the SWR owing to a shear strain component was strongly enhanced by embedding the Ni far from the surface. From the variation of the nonreciprocity on the thickness of Si covered on the Ni, we can estimate the depth profile of the relative amplitude of the shear strain component with respect to the longitudinal strain component that gives the spatial distribution of the SAW. Moreover, a picometer order SAW amplitude at the surface of the NiFe film was experimentally evaluated from the amplitude of SWR excited via gyromagnetic effect whose amplitude was simply given by the vorticity of SAW. Finally, from the comparison between the amplitude of the alternating SC in NiFe/Cu bilayer and the SAW amplitude evaluated, we found that the conversion efficiency of the angular momentum from the SAW to the electron spin was much larger than in the spin current generation using a vorticity of liquid metal [6].

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Spin transport driven by fluid and elastic motions

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Spin current is a key concept in spintronics. Spin-current generation has been achieved by using angular momentum conversion among magnetization, photons, the orbital motion of electrons, and spin angular momentum. Recently, the interconversion between the mechanical angular momentum of vortical objects and spin has attracted much attention [1,2,3,4]. In this talk, I will present our recent results on spin transport driven by fluid and elastic motions as follows.

In a pipe flow of liquid metal, fluid vorticity couples to electron spins, resulting in a spin current generation [3]. This effect was demonstrated in a turbulent flow regime [2]. Very recently, the fluid-driven spin current is observed in pipe flows at a wide range of Reynolds number [5,6], as the theoretical predictions [3].

Similar spin-vorticity effects are also predicted using the surface acoustic wave injected into small spin-orbit materials such as Cu [1]. Conventionally, a small spin-orbit material is not considered as suitable for a spin-current source because the spin Hall effect relies on the large spin-orbit coupling. We demonstrated the spin-vorticity coupling allows us to utilize the small spin-orbit materials as a good spin current source [4]. Besides, the spin-vorticity coupling that appeared in elastic motion is found to be used for the spinwave excitation in a NiFe thin film [7].

Finally, I also present our recent theoretical work on a magnon current generation [8]. We theoretically show that a torsional oscillation of a ferromagnetic insulator can yield the Dzyaloshinskii-Moriya interaction, and lead to the detectably-large magnon current.

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Magnon-phonon hybridization in thermal spin transport

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Magnetoelastic coupling, the interaction between spin waves (magnons) and lattice waves (phonons), was first investigated more than half a century ago [1] and has renewed attention in spintronics. By this coupling, magnons and phonons, in the vicinity of the crossings of their dispersion relations, are hybridized into quasiparticles called magnon polarons that share mixed magnonic and phononic characters [2]. Magnon polarons can convey spin information with velocities close to those of phonons, much faster than the magnon velocities in the dipolar magnon regime [3]. Besides, thanks to the long-lived phononic constituent, magnon polarons may have longer lifetimes than pure magnons and may enhance spin-current related phenomena. Here we report the magnon-polaron-induced enhancement of the spin Seebeck effect (SSE), i.e., thermal spin-current generation, and the spin Peltier effect (SPE: the reciprocal of SSE) in magnetic garnets ($Y_3Fe_5O_{12}$ and $Lu_2BiFe_4GaO_{12}$) [4-7]. The anomalies appear when the magnon and phonon dispersion curves touch, which maximizes the phase space of magnon-polaron formation. The experimental results are well reproduced by a Boltzmann equation, in which the magnon-phonon hybridization is taken into account. The sharp structures can thereby be attributed to the spin current carried by magnon polarons exhibiting longer lifetimes than pure magnons, which leads to the increased spin-current (heat-current) generation in the SSE (SPE).

The work was done in collaboration with R. Yahiro, R. Ramos, K. Oyanagi, T. Hioki, Y. Hashimoto, Z. Qiu, K. Uchida, E. Saitoh, G. E. W. Bauer, K. Shen, B. Flebus, and R. A. Duine.

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