

Resonating with the Intrinsic Coupling of Magnons and Phonons in Ferro- and Antiferromagnets

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Under resonant conditions, magnons and phonons, ubiquitous excitations in ferro- and antiferromagnets, couple via magnetoelastic interactions. This intrinsic link enables versatile generation, control, and detection of both excitations. This article offers a pedagogical overview of our team's main results and related studies in Japan and abroad, including acoustic spin current generation, nonreciprocal effects, magnon excitation in van der Waals antiferromagnets, advances in magnetoelastic crystals, and strong magnon-phonon coupling.

1. Introduction

Undergraduate physics textbooks lay the groundwork for our understanding of magnetism and, subsequently, magnetoelasticity. From classical electromagnetism, any moving charge generates a magnetic field. On the atomic scale, electrons orbiting the nucleus form current loops that produce orbital magnetism. Electrons also possess intrinsic angular momentum, the spin, a quantum property that provide them with a magnetic moment. In solids, crystal electric fields often fix the electronic orbitals, quenching their direct magnetic contribution. However, spin-orbit coupling links spin and orbital motion, allowing orbitals to influence magnetic behaviour. Because spin couples only weakly to the lattice, this spin-orbit interaction provides the bridge between spin and crystal fields. The resulting spin-orbital-lattice connection establishes the magnetoelastic coupling, where spin orientation and magnetization become intertwined with lattice strain.

For better or worse, magnetoelastic coupling is ubiquitous in magnetic materials, including ferro- and antiferromagnets. In this article, I highlight how our team and others in Japan and abroad are harnessing this coupling, exploiting the interplay between magnetization and strain to uncover new physical effects and applications.

Research on magnetoelastic coupling is as broad as the concept itself. Here, we focus on resonant conditions, where coherent acoustic (phonon) and spin (magnon) wave excitations are defined by specific frequencies or energies. Notably, many important advances also occur under non-resonant conditions. While a comprehensive review is beyond scope, we highlight selected studies on strain-assisted magnetization torque and switching [1, 2], domain wall motion [3–5], magnetic phase transitions [6], and strain-modulated Berry phases [7], among others.

The remainder of this article is organized as follows. I first describe the main components of the devices used in our research, followed by individual sections on acoustic spin current generation, nonreciprocal effects, acoustic magnon excitation in van der Waals antiferromagnets, advances in magnetoelastic crystals, and strong magnon-phonon coupling. Each section is designed to facilitate readers to explore

topics of particular interest independently.

2. Surface acoustic wave devices for magnon-phonon coupling studies

The research presented in this article on magnon-phonon resonant coupling is fundamentally based on surface acoustic wave (SAW) devices. SAW technology, developed in the 1960s, has evolved from radar and communication applications to miniaturized components in modern mobile phones [8]. A typical SAW device consists of metallic finger-like combs, called interdigital transducers (IDTs), patterned by lithography on a piezoelectric substrate. Figure 1(a) shows a schematic of the SAW device used in our work. We fabricated a pair of IDT ports at the ends of a LiNbO_3 substrate, with the magnetic layer of interest placed between them, forming a platform for transmission and absorption experiments. In a typical measurement, a radio-frequency (rf) voltage is applied to one IDT, which, via the inverse piezoelectric effect, generates propagating surface vibrations. These waves travel across the magnetic layer to the second IDT, where they are converted back into a rf voltage through the piezoelectric effect. Comparing the input and output signals reveals the energy absorbed or transmitted by the system.

In a seminal 1958 work, Charles Kittel [9] theoretically described the resonant condition under which ultrasound waves couple to spin waves in magnetic materials. In ferromagnets, the dispersion relations of spin and acoustic waves intersect in the gigahertz (GHz) range, setting the operational frequency requirement for our SAW devices. The SAW frequency is given by $f_{\text{SAW}} = v_s / \lambda_{\text{SAW}}$, where v_s is the sound velocity of the substrate, typically 3000-4000 m/s for common piezoelectrics, and λ_{SAW} is the acoustic wavelength defined by the IDT finger periodicity. Achieving GHz frequencies therefore requires lithographic patterning with feature sizes on the order of a few hundred nanometres. Figure 1(b) presents data from a SAW absorption experiment on a 20 nm Ni (nickel) layer under an applied in-plane magnetic field. At approximately ± 26 mT, we observe resonant absorption of SAWs by the Ni layer. The absorbed acoustic energy drives magnetization precession and excites spin waves, as originally proposed by Kittel [9]. In this measurement, the in-plane magnetic field forms an angle of $\theta = 45^\circ$ with the SAW wavevector k . The absorption strength depends strongly on this angle; further details on the angular dependence can be found in Ref. [10].

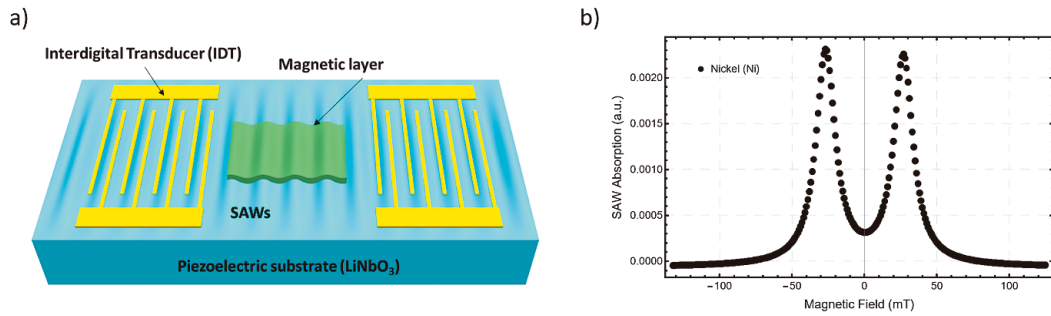


Figure 1. (a) Schematic of a SAW device used in our research, comprising a pair of interdigital transducers (IDTs) and a magnetic layer deposited on a piezoelectric substrate. (b) SAW absorption data for a 20 nm Ni layer under an applied in-plane magnetic field.

3. Acoustic spin current generation

Spin pumping is the transfer of angular momentum from the oscillatory magnetization dynamics of a ferromagnetic layer, driven by ferromagnetic resonance, into an adjacent nonmagnetic layer [11]. This process generates a spin current in the nonmagnetic layer. Similarly, magnetization precession induced by SAW absorption can also produce spin current.

In 2018, we reported spin current generation via acoustic spin pumping [12]. Figure 2(a) shows a schematic of one of our heterostructures: resonant SAW absorption drives magnetization precession in a Ni layer, transferring angular momentum to generate a spin current j_s in an adjacent Cu layer. The spin current is detected via spin-to-charge conversion at interfaces with Rashba spin-orbit coupling (SOC), producing an output voltage dependent on spin polarization [13]. We studied two heterostructures, Ni/Cu/Bi₂O₃ and Ni/Ag/Bi₂O₃, whose interfaces exhibit opposite spin-to-charge conversion signs [14, 15]. Figure 2(b) shows the output voltage for Ni/Cu/Bi₂O₃ (red) and Ni/Ag/Bi₂O₃ (blue), reflecting acoustic spin current generation and Rashba-type conversion. A prior study in Germany demonstrated a similar effect via the spin Hall effect (SHE) [16]. In a 2020 follow-up [17], we showed enhanced acoustic spin current generation using acoustic cavities, which confine SAWs and strengthen their interaction with the magnetic layer.

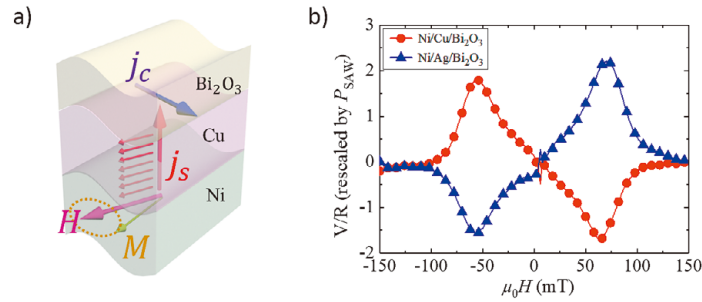


Figure 2. (a) Schematic of acoustic spin pumping in the Ni/Cu/Bi₂O₃ heterostructure. (b) Output voltage for Ni/Cu/Bi₂O₃ (red) and Ni/Ag/Bi₂O₃ (blue), reflecting acoustic spin current generation and Rashba-type spin-to-charge conversion. Schematic in (a) is reproduced with permission from [12].

Other variants of acoustic spin current generation have been reported by research teams in Japan. In 2012, Uchida et al. [18] demonstrated acoustic generation of spin currents in a Pt/Y₃Fe₅O₁₂ (YIG) hybrid structure on a piezoelectric actuator, where sound waves modulate magnon distribution in YIG. In 2017, Kobayashi et al. [19] reported spin current generation via lattice rotation in a Cu layer driven by SAWs, a mechanism called spin rotation coupling. While this mechanism does not require a magnetic layer, the study used a Ni-Fe film, and no other studies have confirmed spin rotation-induced currents without a magnetic layer, warranting further analysis of [19]. In 2021, Kawada et al. [20] observed spin currents driven by SAWs in metallic nonmagnetic layers with strong SOC. The spin current direction appears to follow the expected spin Hall coefficients, and the effect was termed the acoustic spin Hall effect, though its underlying mechanism remains to be fully understood.

4. Magnon–phonon nonreciprocal effects

Nonreciprocity refers to a direction-dependent response, in contrast to reciprocal systems, which behave symmetrically forward and backward. In technology, diodes and isolators are prime examples of nonreciprocal components. In the context of wave phenomena, the coupling between SAWs (phonons) and spin waves (magnons) offers intriguing possibilities, as both possess well-defined energies and wavevectors.

It is useful to elaborate on the characteristics of the SAWs we typically work with. These are Rayleigh waves, a type of seismic wave, with principal strain components being longitudinal (ε_{xx}) and transverse/shear (ε_{xz}). In seismology, the longitudinal wave is called the primary wave (arriving first) and the shear wave the secondary wave. Unlike earthquake Rayleigh waves, which are slow (0.01–few Hz), the SAWs in our experiments operate in the GHz range to match the spin wave dispersion described by Kittel [9].

The longitudinal and shear strains play a crucial role in magnon-phonon coupling. Dreher et al. [21] showed that SAW absorption in a ferromagnetic layer can become nonreciprocal when the shear strain ε_{xz} is significant. Figure 3 shows data from [21], where α is the angle between an in-plane magnetic field and the SAW propagation direction. The data reveal two key points: (i) maximum absorption shows a fourfold symmetry, peaking at $\alpha = \pm 45^\circ$ for both field polarities, and (ii) when ε_{xx} dominates and ε_{xz} is negligible, absorption is symmetric (reciprocal, Fig. 3a), whereas significant ε_{xz} induces asymmetric, nonreciprocal absorption (Fig. 3b).

The shear strain ε_{xz} depends on the layer thickness along the z-axis; thicker magnetic layers enhance this strain component. This observation has been experimentally confirmed by research teams in Japan [22, 23].

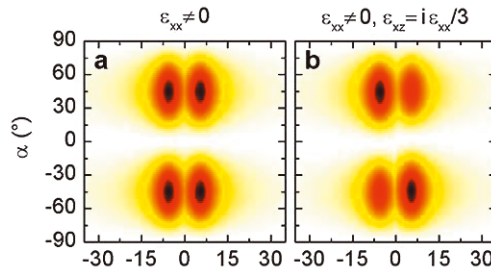


Figure 3. SAW resonant absorption in a Ni layer, with α representing the angle between an in-plane magnetic field and the SAW propagation direction. (a) Absorption when longitudinal strain ε_{xx} dominates and shear strain ε_{xz} is negligible. (b) Absorption when shear strain ε_{xz} is significant, leading to nonreciprocal behaviour. Data in this figure is reproduced with permission from [21].

In 2020, our team reported large nonreciprocal SAW absorption in an ultra-thin 1.6 nm CoFeB layer [24]. At this thickness, with a SAW wavelength of $\lambda_{\text{SAW}} \approx 600$ nm, the shear strain ε_{xz} is expected to vanish. Figure 4(a) shows the device schematic, similar to that described in Sec. 2, with CoFeB grown on Ta and capped with MgO. Figure 4(b) shows SAW power absorption at an in-plane magnetic field angle of 10° , revealing a pronounced difference when reversing the SAW wavevector (P_{-k} , blue; P_{+k} , red).

The vanishing ε_{xz} required a new explanation. A 1976 study by Maekawa and Tachiki [25] described SAW attenuation in ferro- and antiferromagnets due to lattice rotation coupling with magnetic anisotropy.

Lattice rotation direction depends on the SAW wavevector, enabling nonreciprocal absorption. Applying this theory to our data, we observed nonreciprocal acoustic attenuation with up to 100% rectification under optimized conditions, suggesting an acoustic analogue of an electronic diode [24].

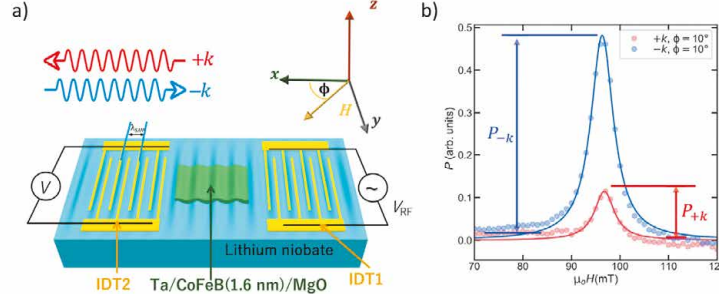


Figure 4. (a) Schematic of the SAW device used in the study of Ref. [24]. (b) Nonreciprocal SAW absorption in a 1.6 nm CoFeB layer under an in-plane magnetic field at 10° . This figure is reproduced with permission from [24].

Beyond its scientific significance, the technological relevance of nonreciprocal effects has spurred studies worldwide. Notable examples include SAW nonreciprocal absorption in synthetic antiferromagnets [26–29], ferromagnet/semiconductor hybrids [30], ferromagnetic bilayers with dipolar coupling [31], and noncollinear layer magnetizations [32]. More recently, we also reported SAW nonreciprocal absorption in the ferrimagnet $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG) [33], and one more study including effects involving out-of-plane phononic angular momentum [34].

5. Acoustic magnon excitation in van der Waals antiferromagnets

Antiferromagnets are magnetically ordered materials, but unlike ferromagnets, where all moments align uniformly, antiferromagnetic moments alternate between atomic sites. This makes antiferromagnets more robust against external fields and free of stray fields, offering opportunities for dense spintronic devices [35, 36]. However, these same properties complicate magnetization control and readout, slowing the understanding and application of antiferromagnets.

Magnetoelastic coupling, ubiquitous in both ferro- and antiferromagnets, provides a potential route for phonon-mediated control or readout of magnetization. In SAW devices similar to Figure 1(a), current technology limits SAW operation to ~ 1 –20 GHz, whereas spin wave dispersions in most antiferromagnets lie at > 50 GHz to THz. Alternatives exist: synthetic antiferromagnets, formed by alternating ferromagnetic layers coupled via thin nonmagnetic spacers, exhibit low-GHz spin wave resonances [26–29]. Similarly, van der Waals antiferromagnets, with weak interlayer coupling, reduce spin wave frequencies to the low-GHz range.

In 2023, we reported the first experimental evidence of SAW resonant absorption via magnon-phonon coupling in the van der Waals antiferromagnet CrCl_3 [37]. Figure 5(a) shows a microscope image of a SAW device with a stamped CrCl_3 layer between the IDTs, and Figure 5(b) provides a schematic. In CrCl_3 , each atomic layer is ferromagnetic, but layers stack antiferromagnetically via van der Waals coupling (Figure 5c), forming two spin sublattices. These sublattices oscillate either in-phase (acoustic

spin wave mode) or out-of-phase (optic mode).

Figure 5(d) shows SAW absorption in CrCl_3 at $T = 6$ K (blue curve). Two symmetric absorption features appear: one around ± 30 mT (acoustic mode) and one around ± 150 mT (optic mode), consistent with the SAW frequency $f_{\text{SAW}} = 1.1$ GHz. As temperature increases toward the Néel temperature $T_N \approx 14$ K, both absorption features diminish and vanish, reflecting the magnetic transition.

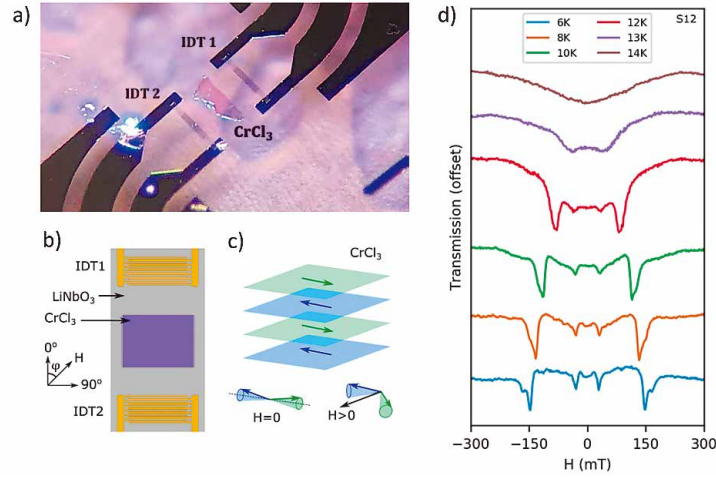


Figure 5. (a) Microscope image of a SAW device with a stamped CrCl_3 layer between the IDTs. (b) Schematic of the SAW device. (c) Orientation of spin sublattices in CrCl_3 . (d) SAW resonant absorption in CrCl_3 under an in-plane magnetic field at temperatures from 6 K (blue) to 14 K (brown). Schematics in (b), (c) and data in (d) are reproduced with permission from [37].

6. Magnetoelastic crystals

An exquisite book by Leon Brillouin on the mathematical physics of wave propagation, with particular emphasis on periodic structures [38], laid the groundwork for today's broad research on photonic crystals [39–41], phononic crystals [42, 43], and more recently magnonic crystals [44, 45]. In our research, the typical SAW wavelength (λ_{SAW}) ranges from a few hundred nanometers to 1–2 μm , allowing the design and fabrication of artificial magnetic lattices within this scale to explore magnon-phonon coupling in what we term magnetoelastic crystals. Figure 6(a) shows the schematic of a Ni/Ti magnetoelastic crystal fabricated on a LiNbO_3 piezoelectric substrate. Using this structure, we probed nonreciprocal SAW absorption determined by the symmetry of the structure as seen by the SAW wavevector k_{SAW} . When k_{SAW} interacts with the magnetoelastic crystal in an orientation lacking mirror symmetry, nonreciprocity appears [Fig. 6(b)], and it reverses when the crystal orientation is reversed [Fig. 6(c)]. In contrast, when the orientation preserves mirror symmetry, nonreciprocity vanishes [Fig. 6(d)], demonstrating the crystal's influence on magnon-phonon coupling [46]. The long phonon propagation lengths, broken time-reversal symmetry of magnons, and external magnetic field tunability together present exciting opportunities for future magnetoelastic crystal-based technologies [47].

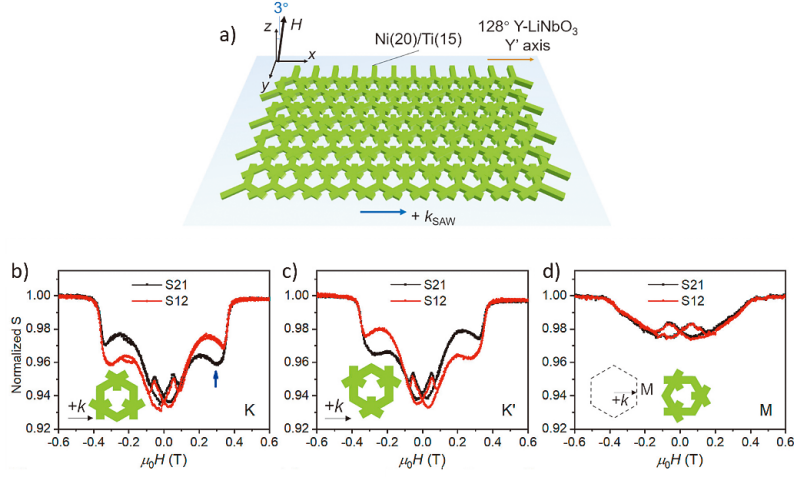


Figure 6. (a) Schematic of the magnetoelastic crystal structure composed of Ni/Ti deposited on a LiNbO₃ piezoelectric substrate. (b) Nonreciprocal SAW absorption observed when the SAW propagation direction (k_{SAW}) encounters the magnetoelastic crystal in an orientation lacking mirror symmetry. (c) The nonreciprocal response reverses when the orientation of the magnetoelastic crystal is reversed. (d) When k_{SAW} propagates along an orientation preserving mirror symmetry, the nonreciprocity vanishes, demonstrating the symmetry dependence of magnon-phonon coupling in the magnetoelastic crystal. This figure is reproduced with permission from [46].

7. Strong magnon-phonon coupling

As described above, surface acoustic wave (SAW) absorption in magnetic layers and the excitation of spin waves occur at the intersection of their respective dispersions, enabling efficient energy transfer. During this process, both phonons (acoustic waves) and magnons (spin waves) contribute to energy losses. When the coupling strength g exceeds the combined loss rates of magnons (k_m) and phonons (k_p), energy exchange between the two persists, defining the strong coupling regime. A hallmark of this regime is the anticrossing of the coupled mode dispersions, a phenomenon widely explored in light-matter interaction [48].

In 2024, we reported the first experimental observation of strong coupling between SAWs and spin waves at room temperature [49]. To minimize phonon losses (k_p), we incorporated a pair of SAW resonators forming an acoustic cavity in addition to the interdigital transducers (IDTs). The magnon losses, on the other hand, are determined by the Gilbert magnetic damping, which is notably low in CoFeB thin films grown on Ti underlayers, similar approaches have shown to produce ultra-low Gilbert magnetic damping [50].

Figure 7(a) presents the calculated magnon (ω_m , purple dashed line) and phonon (ω_p , khaki dashed line) dispersions for a device with a central SAW frequency of $f_{SAW} = 6.56$ GHz and an in-plane magnetic field of 35 mT. The green curves illustrate the expected mode anticrossing in the strong coupling regime. Figure 7(b) shows experimental SAW absorption data for a 30 nm CoFeB layer under varying in-plane magnetic fields, revealing two clear anticrossing features, evidence of two phonon modes confined within the acoustic cavity and the realization of the strong coupling regime.

The anticrossing indicate the formation of a hybrid magnetoelastic mode, exhibiting mixed magnonic and phononic characteristics. Notably, although phonons are typically insensitive to magnetic fields, the observed bending of the phonon dispersion near the magnon resonance demonstrates hybridization

and magnetic response. This emergent hybrid mode holds promise for wave-based information and communication technologies.

By removing the acoustic cavity, phonon losses increase, moving the system out of the strong coupling regime. As shown in Figure 7(c), in such a device, two phonon modes appear with linear magnetic field dependence, absorbed only at the magnon resonance condition.

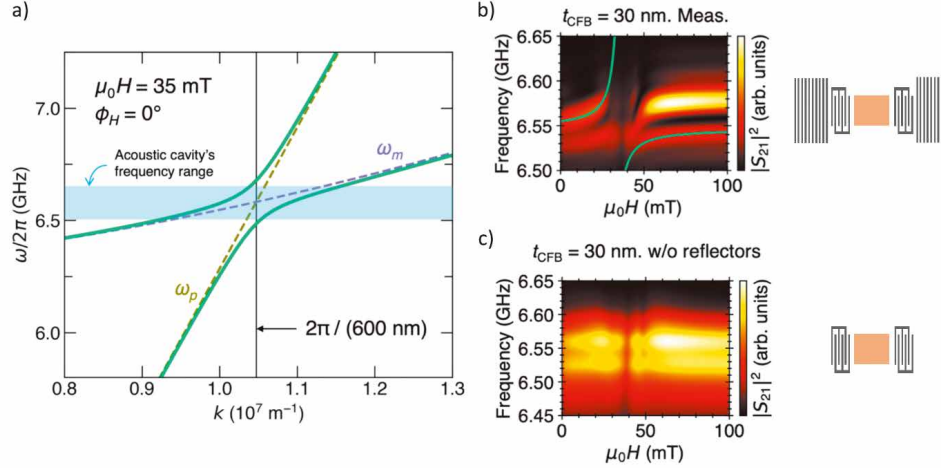


Figure 7. (a) Calculated magnon (ω_m , purple dashed) and phonon (ω_p , khaki dashed) dispersions for a device with a central SAW frequency of $f_{SAW} = 6.56 \text{ GHz}$ and an in-plane magnetic field of 35 mT. The mode anticrossing in the strong coupling regime is shown as green curves. Experimental SAW absorption in a 30 nm CoFeB layer under in-plane magnetic fields is shown (b) with and (c) without acoustic reflectors forming an acoustic cavity. This figure is reproduced with permission from [49].

8. Final remarks

In summary, our research, together with contributions from other teams in Japan and abroad, demonstrates that surface acoustic waves (SAWs) provide a powerful platform for probing and controlling magnetization dynamics through magnon-phonon coupling. Across ferromagnetic and antiferromagnetic systems, and from linear to nonreciprocal and strong coupling regimes, SAW based devices reveal the remarkable versatility of elastic waves in driving and detecting spin phenomena. The ability to engineer materials and device geometries, from layered heterostructures to magnetoelastic crystals, enables precise control over coupling strength, symmetry, and frequency response.

These advances not only deepen our understanding of fundamental magnetoelastic interactions but also open pathways for practical technologies in wave-based computing, signal processing, and spintronic systems. Hybrid magnetoelastic excitations, where phonons' coherence meets magnons' tunability, mark an exciting step toward low-power, reconfigurable information devices. In a recent work, we achieved efficient nonlinear magnon excitation in a SAW resonator supporting hybrid waves [51], pointing the way to acoustic control of nonlinear magnon and quantum magnonic systems [52].

References

- [1] A. Khan, D.E. Nikonov, S. Manipatruni, T. Ghani and I.A. Young, Appl. Phys. Lett. **104**, 262407 (2014).
- [2] S. Bandyopadhyay, J. Atulasimha and A. Barman, Appl. Phys. Rev. **8**, 041323 (2021).
- [3] N. Lei et al., Nat. Comm. **4**, 1378 (2013).
- [4] A. Adhikari and S. Adenwalla, AIP Advances **11**, 015234 (2021).
- [5] M. Fattouhi, F. Garcia-Sanchez, R. Yanes, V. Raposo, E. Martinez and L. Lopez-Diaz, Phys. Rev. Applied **18**, 044023 (2022).
- [6] J. Cenker et al., Nat. Nanotechnol. **17**, 256 (2022).
- [7] H. Chi et al., Nat. Comm. **14**, 3222 (2023).
- [8] D.P. Morgan, Proceedings of the 1998 IEEE International Frequency Control Symposium (1998).
- [9] C. Kittel, Phys. Rev. **110**, 836 (1958).
- [10] J. Puebla, M. Xu, B. Rana, K. Yamamoto, S. Maekawa and Y. Otani, J. Phys. D: Appl. Phys. **53**, 264002 (2020).
- [11] Y. Tserkovnyak, A. Brataas and G.E.W. Bauer, Phys. Rev. B **66**, 224403 (2002).
- [12] M. Xu, J. Puebla, F. Auvray, B. Rana, K. Kondou and Y. Otani, Phys. Rev. B **97**, 180301 (2018).
- [13] J.C. Rojas-Sánchez et al., Nat. Commun. **4**, 2944 (2013).
- [14] J. Puebla, F. Auvray, M. Xu, B. Rana, A. Albouy, H. Tsai, K. Kondou, G. Tatara and Y. Otani, Appl. Phys. Lett. **111**, 092402 (2017).
- [15] F. Auvray, J. Puebla, M. Xu, B. Rana, D. Hashizume and Y. Otani J. Mat. Sci.: Mat. Electr. **29**, 15664 (2018).
- [16] M. Weiler, H. Huebl, F. S. Goerg, F. D. Czeschka, R. Gross and S. T. B. Goennenwein, Phys. Rev. Lett. **108**, 176601 (2012).
- [17] Y. Hwang, J. Puebla, M. Xu, A. Lagarrigue, K. Kondou and Y. Otani, Appl. Phys. Lett. **116**, 252404 (2020).
- [18] K. Uchida, H. Adachi, T. An, H. Nakayama, M. Toda, B. Hillebrands, S. Maekawa and E. Saitoh, J. Appl. Phys. **111**, 053903 (2012).
- [19] D. Kobayashi, T. Yoshikawa, M. Matsuo, R. Iguchi, S. Maekawa, E. Saitoh and Y. Nozaki, Phys. Rev. Lett. **119**, 077202 (2017).
- [20] T. Kawada, M. Kawaguchi, T. Funato, H. Kohno and M. Hayashi, Sci. Adv. **7**, eabd9697 (2021).
- [21] L. Dreher, M. Weiler, M. Pernpeintner, H. Huebl, R. Gross, M. S. Brandt and S. T. B. Goennenwein, Phys. Rev. B **86**, 134415 (2012).
- [22] R. Sasaki, Y. Nii, Y. Iguchi and Y. Onose, Phys. Rev. B **95**, 020407(R) (2017).
- [23] S. Tateno and Y. Nozaki, Phys. Rev. Applied **13**, 034074 (2020).
- [24] M. Xu, K. Yamamoto, J. Puebla, K. Baumgaertl, B. Rana, K. Miura, H. Takahashi, D. Grundler, S. Maekawa and Y. Otani, Sci. Adv. **6**, eabb1724 (2020).
- [25] S. Maekawa and M. Tachiki, AIP Conference Proceedings **29**, 542 (1976).
- [26] R. Verba, V. Tiberkevich and A. Slavin, Phys. Rev. Applied **12**, 054061 (2019).
- [27] H. Matsumoto, T. Kawada, M. Ishibashi, M. Kawaguchi and M. Hayashi, Appl. Phys. Exp. **15**, 063003 (2022).
- [28] M. Küß, M. Hassan, Y. Kunz, A. Hörner, M. Weiler and M. Albrecht, Phys. Rev. B **107**, 214412 (2023).
- [29] M. Küß, M. Hassan, Y. Kunz, A. Hörner, M. Weiler and M. Albrecht, Phys. Rev. B **107**, 024424 (2023).
- [30] A. Hernández-Mínguez, F. Macià, J. M. Hernández, J. Herfort and P. V. Santos, Phys. Rev. Applied **13**, 044018 (2020).
- [31] M. Küß, M. Heigl, L. Flacke, A. Hörner, M. Weiler, A. Wixforth and M. Albrecht, Phys. Rev. Applied **15**, 034060 (2021).
- [32] L. Ushii, A. Slavin and R. Verba, Phys. Rev. Applied **22**, 034046 (2024).
- [33] Y. Ba, J. Puebla, K. Yamamoto, Y. Hwang, L. Liao, S. Maekawa, O. Klein and Y. Otani, Phys. Rev. B

- 111**, 104401 (2025).
- [34] L. Liao, F. Chen, J. Puebla, J. Kishine, K. Kondou, W. Luo, D. Zhao, Y. Zhang, Y. Ba and Y. Otani Sci. Adv. **10**, eado2504 (2024).
- [35] T. Jungwirth, X. Marti, P. Wadley and J. Wunderlich, Nat. Nanotechnol. **11**, 231 (2016).
- [36] V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono and Y. Tserkovnyak, Rev. Mod. Phys. **90**, 015005 (2018).
- [37] T.P. Lyons, J. Puebla, K. Yamamoto, R.S. Deacon, Y. Hwang, K. Ishibashi, S. Maekawa and Y. Otani, Phys. Rev. Lett. **131**, 196701 (2023).
- [38] L. Brillouin, Wave propagation in periodic structures, 2nd edition, Dover publications inc. (1953).
- [39] S. Noda and T. Baba, Roadmap on photonic crystals, 1st edition, Springer New York (2003).
- [40] J. D. Joannopoulos, P.R. Villeneuve and S. Fan, Nature **386**, 143 (1997).
- [41] S. Noda, M. Yoshida, T. Inoue, M. De Zoysa, K. Ishizaki and R. Sakata, Nat. Rev. Elect. Eng. **1**, 802 (2024).
- [42] M-H. Lu, L. Feng and Y-F. Chen, Mat. Today **12**, 12 (2009).
- [43] T. Vasileiadis, J. Varghese, V. Babacic, J. Gomis-Bresco, D. Navarro-Urrios and B. Graczykowski, J. Appl. Phys. **129**, 160901 (2021).
- [44] M. Krawczyk and D. Grundler, J. Phys.: Condens. Matter **26**, 123202 (2014).
- [45] A.V. Chumak, A.A. Serga and B. Hillebrands, J. Phys. D: Appl. Phys. **50**, 244001 (2017).
- [46] L. Liao, J. Puebla, K. Yamamoto, J. Kim, S. Maekawa, Y. Hwang, Y. Ba and Y. Otani, Phys. Rev. Lett. **131**, 176701 (2023).
- [47] L. Liao, J. Liu, J. Puebla, Q. Shao and Y. Otani, npj Spintronics **2**, 47 (2024).
- [48] M. S. Skolnick, T. A. Fisher and D. M. Whittaker, Semicond. Sci. Technol. **13**, 645 (1998).
- [49] Y. Hwang, J. Puebla, K. Kondou, C. Gonzalez-Ballester, H. Isshiki, C. Sánchez Muñoz, L. Liao, F. Chen, W. Luo, S. Maekawa and Y. Otani, Phys. Rev. Lett. **132**, 056704 (2024).
- [50] S. Yoshii, M. Müller, H. Inoue, R. Ohshima, M. Althammer, Y. Ando, H. Huebl and M. Shiraishi, Phys. Rev. B **109**, L020406 (2024).
- [51] Y. Hwang, L. Liao, J. Puebla, M. Brühlmann, C. Gonzalez-Ballester, K. Kondou, N. Ogawa, S. Maekawa and Y. Otani, arXiv:2509.19706 (2025).
- [52] M. Brühlmann, Y. Hwang, J. Puebla and C. Gonzalez-Ballester, arXiv:2509.16199 (2025).

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