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Chiral Magnetoacoustics

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Nonreciprocal microwave devices are key components of communication platforms. Nonreciprocity can arise in chiral systems, where chirality refers to a fixed handedness that is preserved under time reversal. Chiral excitations (quasiparticles) provide opportunities for the realization of miniaturized microwave components with directional properties. In particular, surface acoustic waves that propagate in magnetic media are chiral and can display pronounced nonreciprocal character. Because surface acoustic waves are an established technological platform, hybrid surface acoustic wave/spin wave devices have great application potential. In this mini-review, we introduce the general concept of chiral and nonreciprocal magnetoacoustic waves. We discuss a widely employed phenomenological model based on magnetoelastic coupling and magneto-rotation that quantitatively accounts for many experimental findings and give a brief overview over selected experiments and advances in this emerging research field.

KEYWORDS

magnetoelastic coupling, magneto-rotation, surface acoustic waves, spin waves, chirality, nonreciprocity, Dzyaloshinskii-Moriya interaction, magnetization dynamics

Introduction

Information transport and processing at microwave frequencies are central to modern information processing applications. Gigahertz-frequency free-space radio waves are a cornerstone of our communication platforms. The centimeter-scale wavelength of the corresponding microwave photons, however, makes the miniaturization of signal processing components challenging. Such a miniaturization is crucial for many applications, in particular for mobile devices. A possible route for downscaling is the interconversion of photons to phonons with micrometer-scale wavelength at microwave frequencies and corresponding miniaturization of signal processing components. In this spirit, surface acoustic wave (SAW) devices are widely employed as frequency filters for mobile communication [1–7]. Efficient excitation and detection of SAWs is possible on piezoelectric substrates with metallic grating structures - so-called interdigital transducers (IDTs) - via the piezoelectric effect [8], as schematically shown in Figure 1A. In general, these acoustic devices benefit from a small footprint, mass fabrication capabilities, and high adjustability of the transmission characteristics [1, 5, 7]. Magnons in ferromagnetic materials can provide a similar miniaturiziation as phonons. Complimentary research thus also pursuits the use of magnonic devices for miniaturized logic circuits and field-controllable microwave components, such as phase shifters [9–12].

Such phononic and magnonic devices each have their individual strengths and weaknesses. While phonons can have much longer lifetimes than magnons, they lack the additional symmetry breaking caused by the magnetization degree of freedom. As

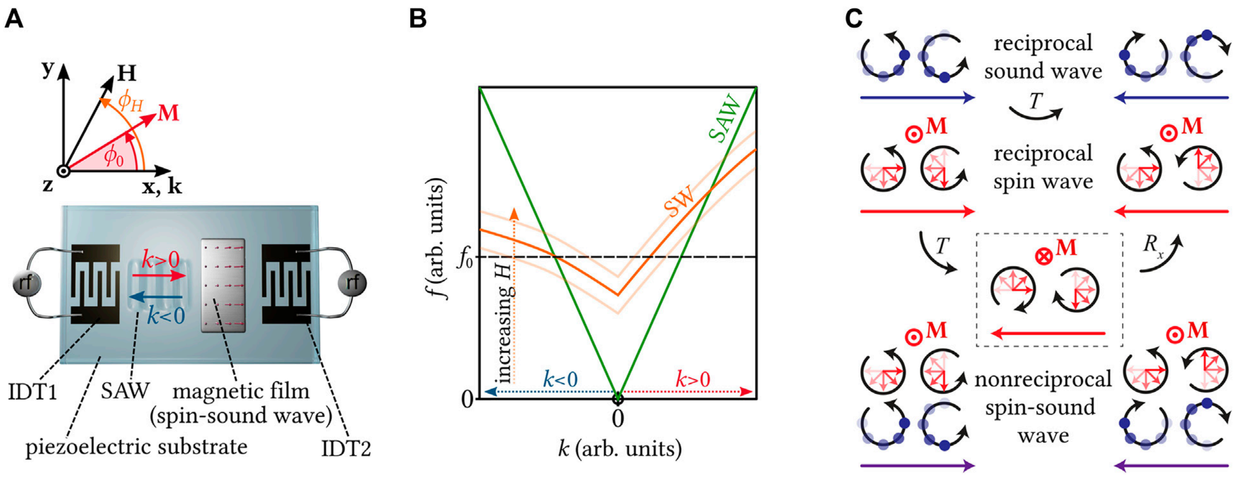

FIGURE 1
(A) Illustration of the investigated piezoelectric-ferromagnetic hybrid device. Nonreciprocal effects are characterized by studying the transmission of counter-propagating SAWs with wave vectors $k > 0$ and $k < 0$. **(B)** The dispersion relation is reciprocal for SAWs but can be nonreciprocal for SWs because of dissimilar interfaces on the opposite sides of the magnetic thin film. If the SAW is excited at a fixed frequency f_0 (dashed line), resonant SAW-SW coupling is only possible for the magnetoacoustic waves propagating to the left side ($k < 0$), and a large nonreciprocal transmission is expected. The SW dispersion is tuned by the magnitude H and angle ϕ_H of the external magnetic field. **(C)** Nonreciprocal spin-sound waves can arise from the interaction of individually reciprocal sound and spin waves. The lattice motion (magnetization precession) at two different lattice sites along the x-axis propagation direction of the sound wave (spin wave) is schematically depicted by the blue dots (red arrows) and the black circles represent the circular motion and its phase shift. The reciprocal counter-propagating waves can be transformed into each other by time reversal T and rotation R_x operations. No symmetry operation exists for the nonreciprocal spin-sound wave.

discussed in detail in Section 3, SAWs are thus generally reciprocal with respect to the acoustic propagation direction, even though they have chiral properties [13]. The helicity of the lattice rotation thereby switches with SAW propagation direction inversion. Spin waves (SWs) are generally achiral [14], unless the symmetry is broken orthogonal to their propagation direction, such as at a surface or interface [15–19]. The helicity of the spin precession is given by the sign of the gyromagnetic ratio and is independent of the SW propagation direction. By combining individually reciprocal SAWs and SWs, chiral and nonreciprocal magnetoacoustic waves can emerge. These magnetoacoustic waves are similar to chiral magnons in their nonreciprocal properties, while still profiting from the long acoustic lifetimes. In such magnetoacoustic devices, if we interchange the location of the sound source and receiver, the transmitted signal will not be the same [20]. In this mini review article we summarize the recent advances in SAW-SW coupling with a focus on nonreciprocal effects. More general reviews about phonon-magnon coupling can be found in references [20–24].

Phenomenology of the magnetoacoustic interaction

Because of spin-orbit interaction, excitations of the lattice atoms from their equilibrium positions that impact the electronic orbitals will cause a concomitant spin excitation. Here, we briefly discuss the resulting magnetoelastic interaction of SAWs and SWs in magnetic thin films based on a phenomenological model that dates back to C. Kittel [25]. To this end, we only consider the Rayleigh-type SAW, which has most often been studied in magnetoacoustic experiments. The retrograde elliptical lattice motion on the substrate surface causes nonzero strain components $\varepsilon_{kl=xx,zz,xz} \neq 0$ in a magnetic thin film deposited on top of a substrate [4, 26, 27], as shown in Figure 1A. Additionally, the Rayleigh-SAW features a lattice rotation $\omega_{xz} \neq 0$. Here, we consider the case where the equilibrium magnetization direction $\mathbf{M}$ is aligned in the plane of the magnetic thin film and encloses the angle ϕ_0 with the x-axis. Because of magnetoelastic coupling to ε_{kl} and magneto-rotation coupling to ω_{xz} [28–30], the free energy of the magnetic thin film is modulated with the frequency $\omega = 2\pi f$ and wave vector $\mathbf{k} = k\hat{\mathbf{x}}$ of the SAW [27, 31]. More general situations, including the out-of-plane orientation of $\mathbf{M}$ and other SAW modes, are discussed in references [27, 32–34].

The resulting magnetization dynamics can be described in terms of effective magnetoacoustic driving fields [27, 29–31]. For magnetic thin films with cubic crystal structure, the driving field reads as

$$\mathbf{h}(x,t) = \begin{pmatrix} h_{\mathrm{oop}} \\ h_{\mathrm{ip}} \end{pmatrix} = \frac{2}{\mu_0} \begin{pmatrix} \left(b_2 \varepsilon_{xz} + \frac{\mu_0}{2} M_{\mathrm{eff}} \omega_{xz}\right) \cos\phi_0 \\ b_1 \varepsilon_{xx} \sin\phi_0 \cos\phi_0 \end{pmatrix} e^{i(kx-\omega t)}, \quad (1)$$

whereby h_{oop} (h_{ip}) is the out-of-plane (in-plane) projection normal to the equilibrium orientation of $\mathbf{M}$, $b_{1,2}$ are the magnetoelastic coupling constants [27, 35], and $M_{\mathrm{eff}} = M_{\mathrm{s}} - H_{\mathrm{k}}$ is the effective magnetization with the saturation magnetization M_s and out-of-plane anisotropy field H_{k}. It is noteworthy that the magneto-rotation coupling does not require spin-orbit interaction, as $M_{\mathrm{eff}} = M_{\mathrm{s}}$ is obtained from the thin film shape anisotropy alone. Magneto-rotation is thus also active in materials with vanishing magnetostriction, such as NiFe [36] or in ultrathin films with vanishing ε_{xz} [29]. Furthermore, spin-rotation coupling [37–39] and gyromagnetic coupling [40] can contribute to the magnetoacoustic driving field $\mathbf{h}$. To obtain the impact of $\mathbf{h}$ on the magnetization dynamics, one needs to solve the Landau–Lifshitz–Gilbert equation to find the solution $\mathbf{M} = \bar{\chi}\mathbf{h}$ with the Polder susceptibility $\bar{\chi}$. The SAW transmission can be experimentally determined with a second receiver IDT and is often modeled by considering the absorbed acoustic power [31]

$$P_{\mathrm{abs}} = \frac{1}{2} wd \int_0^l \mu_0 \omega \mathrm{Im}\left[\mathbf{h}^*(x)\bar{\chi}\mathbf{h}(x)\right] \mathrm{d}x, \tag{2}$$

where w, d, l are width, thickness, and length of the magnetic film and $\mathbf{h}^*(x)$ is the complex conjugate of $\mathbf{h}(x)$. From Eq. 2 it can be seen that in resonance ($\bar{\chi} \neq 0$) the energy P_{abs} of the SAW is transferred to the magnetic system to excite SWs. If P_{abs} is a significant fraction of the initial power P_0 of the SAW, the exponential decay of the amplitude $\mathbf{h}(x)$ in x-direction must be taken into account [30], otherwise $\mathbf{h}(x) = \mathbf{h}$ can be assumed. Moreover, the strain and driving fields are assumed to be approximately constant along the thin film thickness ($kd \lesssim 1$).

If SAW and SW have identical wave vectors $\mathbf{k}$ and frequencies f, resonant magnetoacoustic interaction is possible and hybrid magnetoacoustic waves form [29, 30, 41]. The dispersion of the SAW

$$f = \frac{c_{\mathrm{SAW}}}{2\pi}|k| \tag{3}$$

is defined by the propagation velocity $c_{\mathrm{SAW}} \approx 3500$ m/s [4] and is reciprocal. For magnetic thin films with no in-plane anisotropy ($\phi_0 = \phi_H$) the SW dispersion is [19, 42]

$$f = \frac{\gamma\mu_0}{2\pi}\sqrt{\left(H + Jk^2 + M_s G_0 - H_k\right)\left(H + Jk^2 + M_s(1 - G_0)\sin^2(\phi_0)\right)} - \frac{\gamma D_{\mathrm{eff}}}{\pi M_s} k \sin(\phi_0). \tag{4}$$

with the gyromagnetic ratio γ, orientation ϕ_H, and magnitude H of the external magnetic field $\mathbf{H}$. Furthermore, the dipolar SW term [43] is $G_0 = (1 - \mathrm{e}^{-|k|d})/(|k|d)$ and the magnetic exchange term with the exchange constant A is defined as $J = \frac{2A}{\mu_0 M_s}$. In presence of the Dzyaloshinskii-Moriya interaction (DMI), the SW dispersion becomes nonreciprocal with the thickness-averaged effective DMI constant D_{eff}. The dispersions of a SAW and nonreciprocal SW are schematically depicted in Figure 1B.

In experiments, ϕ_H and H are usually changed to manipulate the SW dispersion. Because the transfer function of an acoustic delayline shows a typical pass-band behavior [2–4], f and k of the SAW are conventionally fixed and correspond to the maxima $k = n\frac{2\pi}{p}$ of the transfer function. Hereby, the IDTs are often operated at higher harmonic resonance frequencies $n = 1, 3, 5, \ldots$ and p is the periodicity of the IDT. Nevertheless, quasi wide-band characterization of nonreciprocal magnetoacoustic waves with IDTs has also been demonstrated [30, 36]. In addition to the IDT-based excitation and detection of magnetoacoustic waves discussed above, the coupling between electrically or thermally excited SAWs with SWs has been characterized by optical measures such as Brillouin light scattering (BLS) [44–47], Faraday rotation [48], magneto-optic Kerr effect (MOKE) [49–51], and x-ray magnetic circular dichroism (XMCD) [52].

Nonreciprocity and chirality

Chirality refers to the situation where an object and its mirror image cannot be superimposed by translation and spatial rotations [14, 53]. Examples are our hands or more general objects that are described by three orthogonal vectors. For chiral excitations, it is additionally required that their chirality remains unchanged under time reversal. Nonreciprocity of propagating waves such as magnons or phonons requires that counter-propagating waves cannot be superimposed by any combination of time reversal, rotation and translation operations. Not all chiral excitations are nonreciprocal. As an example, we consider a sound wave in a solid propagating along x, specifically a circularly polarized wave, viz. a combined shear ε_{xz} and tensile ε_{xx} wave, such as found in the Rayleigh SAW. In Figure 1C (top row) we sketch the lattice displacement of one atom that follows an elliptical motion in the xz plane. Since the strain components ε_{xx} and ε_{xz} are phase-shifted by $\pm 90^\circ$ for $\pm k$, the helicity of the elliptical trajectory of lattice atoms inverts when k is inverted. While a Rayleigh-SAW is chiral because it can be described by three orthogonal vectors which are defined by its helicity, propagation direction, and evanescent contribution along the surface normal [13], it is reciprocal since a time reversal operation T that inverts time $t \to -t$ maps the counter-propagating waves, as indicated in Figure 1C (top row).

In a similar fashion, we consider a spin wave as sketched in Figure 1C (middle row). Here, the helicity of spin-precession

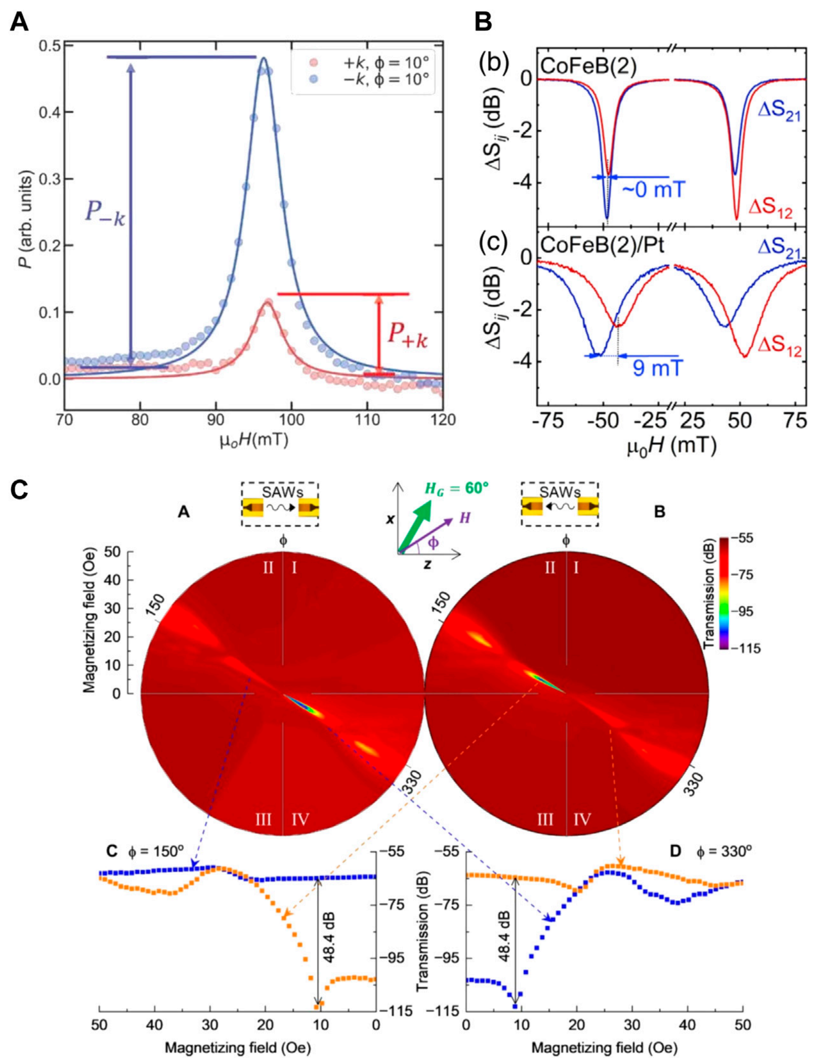

FIGURE 2
Experimental results of nonreciprocal magnetoacoustic surface waves propagating in inverted directions $k > 0$ and $k < 0$ (or $+k$ and $-k$). **(A)** The SAW-SW helicity mismatch effect in Ta(10 nm)/$Co_{20}Fe_{60}B_{20}$(1.6 nm)/MgO(2 nm) is enhanced by magneto-rotation coupling and causes at 6.1 GHz and ϕ_H = 10° a pronounced nonreciprocity of the absorbed power $P_{\pm k}$. **(B)** The resonance fields are solely nonreciprocally shifted for $Co_{40}Fe_{40}B_{20}$(2 nm)/Pt (3 nm), but not for $Co_{40}Fe_{40}B_{20}$(2 nm), since interfacial DMI is mediated by the Pt layer. The background corrected SAW transmission $\Delta S_{21,12}$ for counter-propagating SAWs with $k < 0$ and $k > 0$ was measured at 6.9 GHz and ϕ_H = 64.8°. Adapted from reference [30]. **(C)** The magnetic dipolar fields of the SW cause nonreciprocally shifted resonance fields in the magnetic bilayer FeGaB(20 nm)/Al_2O_3(5 nm)/FeGaB(20 nm) at 1.4 GHz. The upper two panels show the SAW transmission as a function of the external magnetic field magnitude H and orientation ϕ_H for counter-propagating waves. The two diagrams below depict line cuts at ϕ_H = 150, 330° for $k > 0$ (blue) and $k < 0$ (orange). **(A,C)** From [29, 72].

is fixed and does not invert if the propagation direction of the SW is inverted. The counter-propagating SW is obtained by a combination of a time reversal operation T ($t \rightarrow -t$ and $\mathbf{M} \rightarrow -\mathbf{M}$) and a rotation R_x around the direction of propagation x that transforms $(M_x, M_y, M_z) \rightarrow (M_x, -M_y, -M_z)$. Thus, SWs are achiral and reciprocal if the rotation operation R_x is not prohibited by additional symmetry breaking. Examples for such a symmetry breaking are dissimilar interfaces on the opposite sides of a thin film or the interface to vacuum at the sample edge [18, 19, 42, 54] that simultaneously introduces chirality and nonreciprocity.

If we finally consider a combined spin-sound wave, as sketched in Figure 1C (bottom row), there exists no symmetry operation that can map the counter-propagating spin-sound wave. Given an interaction between the magnetic and elastic degrees of freedom, spin-sound waves are thus nonreciprocal. The spin-sound waves are chiral if symmetry along z is broken, as is the case for Rayleigh waves.

Surface acoustic wave-Spin wave helicity mismatch effect

Here, we specifically consider the case where individually reciprocal spin waves and sound waves are coupled to form nonreciprocal magnetoacoustic (spin-sound) waves. In magnetic media, the SAW causes a magnetoacoustic driving field **h,** as defined in Eq. 1. The magnetoacoustic field has a rotational sense which inverts under inversion of SAW propagation direction together with the concomitant inversion of displacement helicity, as depicted in Figure 1C. Because the magnetization precession direction has a fixed right-handed rotational sense, the efficiency of acoustic SW excitation differs for counter-propagating SAWs which gives rise to nonreciprocal SAW absorption. In the following, we call this effect, SAW-SW helicity mismatch effect“.

The SAW-SW helicity mismatch effect was initially observed in yttrium iron garnets [55] and later in nickel [27, 56]. More recently, for a Ta(10 nm)/ $Co_{20}Fe_{60}B_{20}$(1.6 nm)/MgO(2 nm) magnetic thin film Xu et al. observed a large nonreciprocal SAW transmission at 6.1 GHz and $\phi_H = 10°$, as shown in Figure 2A [29]. The absorbed power P_{abs} differs for counter-propagating waves mainly due to the SAW-SW helicity mismatch effect. Because the nonreciprocity is significantly stronger than expected from pure magnetoelastic coupling, other non-magnetoelastic coupling mechanisms, which enlarge the helicity of the magnetoacoustic driving fields must be present. Since magneto-rotation coupling [28–30], spin-rotation coupling [37–39], and gyromagnetic coupling [40] induce additional driving fields with the same symmetry as the shear strain magnetoelastic driving field h_{oop}, it is difficult to separate these individual contributions [29, 36]. Nevertheless, it was demonstrated that good agreement between experiment and simulation is achieved by solely considering magnetoelastic and magneto-rotation coupling for CoFeB magnetic thin films [29, 36]. Besides that, the helicity of the magnetoacoustic driving field and thus the transmission nonreciprocity can be enhanced in magnetic thin films with thick nonmagnetic capping layers [57] or magnetic bilayers [36].

Additionally to the nonreciprocal magnetoacoustic excitation efficiency, magnetic thin film systems with tailored nonreciprocal dispersion of chiral SWs can be used to further increase the overall transmission nonreciprocity, as schematically shown in Figure 1B. Two approaches have so far been discussed in the literature: Interfacial DMI and dipolar fields in magnetic bilayers.

Dzyaloshinskii-Moriya interaction

The DMI at a ferromagnetic–heavy metal interface energetically favors spin structures with a fixed chirality, which is fundamentally responsible for the formation of magnetic skyrmions [58]. Counter-propagating SWs have opposite spatial helicity, as shown in Figure 1C, and are thus non-degenerate in the presence of DMI [15, 19, 42, 59]. The SW dispersion in Eq. 4 causes therefore shifted resonance frequencies for $k > 0$ and $k < 0$ at a fixed external field, as depicted in Figure 1B. Vice versa, shifted resonance fields for a fixed SAW excitation frequency f_0 in magnetoacoustic transmission measurements are expected. This nonreciprocal shift was studied by Küß et al. for two magnetic films $Co_{40}Fe_{40}B_{20}$(2 nm) and $Co_{40}Fe_{40}B_{20}$(2 nm)/Pt (3 nm) at 6.9 GHz and $\phi_H = 64.8°$ [30]. Figure 2B shows the background corrected SAW transmission signal ΔS_{21} and ΔS_{12} for counter-propagating SAWs with $k > 0$ and $k < 0$. Only the sample with the heavy metal Pt capping layer shows nonreciprocally shifted resonance fields of 9 mT because of DMI. Unfortunately, the ferromagnetic–heavy metal interface additionally results in linewidth broadening via the magnetic spin-pumping effect [60]. Thus, the nonreciprocal field shift is not high enough to separate the resonances for counter-propagating SAWs, which limits the overall transmission nonreciprocity. Further information about the potential and behavior of nonreciprocal magnetoacoustic waves with DMI can be found in references [29, 61].

Dipolar fields in magnetic bilayers

It has been known for many years that the dipolar fields of SWs cause a nonreciprocal SW dispersion in magnetic bi- and multilayers because the dynamic dipolar-interaction energy differs for counter-propagating SWs [62–67]. Analytical formulas for the SW dispersion of symmetric magnetic bilayers in antiparallel magnetization configuration can be found in references [67–69]. The potential of nonreciprocal magnetoacoustic waves in synthetic antiferromagnets was initially theoretically discussed by Verba et al. for wide-band nonreciprocal transmission [70] and later for magnetoacoustic circulators [71]. In reference [36], it is experimentally demonstrated that SAWs can magnetoacoustically couple with nonreciprocal optical and acoustic SW modes in magnetic bilayers with parallel alignment of the magnetization. An extremely high nonreciprocity of the SAW transmission magnitude of about 48 dB at a low excitation frequency of 1.4 GHz was observed by Shah et al. for FeGaB(20 nm)/ Al_2O_3(5 nm)/FeGaB(20 nm) [72]. These results are shown in Figure 2C for a bilayer sample with a mutually prepared in-plane anisotropy field H_G at 60° with respect to the x-axis. The huge nonreciprocity of the SW dispersion is attributed on the one hand to the specific alignment of the equilibrium direction of the saturation magnetization, which results from antiferromagnetic coupling of both magnetic layers, the in-plane anisotropy, and external magnetic field at $\phi_H = 150^{\circ}$. On the other hand, large magnetoelastic coupling constants and low SW damping constant enhance the overall SAW-SW coupling and thus the SAW transmission nonreciprocity.

Discussion, conclusion and outlook

For the last years, the potential technological application of nonreciprocal SWs in chiral materials [73, 74], chiral domain walls [75–79], magnetic films with additional symmetry breaking at the interfaces via DMI [15, 17, 59, 80], and magnetic multilayers [16, 67, 81, 82] as nonreciprocal microwave devices has stimulated extensive research activities. In comparison to SWs, coupled SAW-SWs additionally benefit from long propagation lengths [31, 52] and nonreciprocity in these material systems. Thus, magnetoacoustic waves could be a good alternative to SWs for most proposed nonreciprocal applications in magnonics [17, 75, 76, 83]. The magnetoelastic driving field of a horizontal shear-type SAW is in contrast to the Rayleigh-type SAW (Eq. 1) at its maximum for the most interesting geometries for magnonics [33], which are the backward volume ($\phi_0 = 0^{\circ}$) and Damon-Eshbach geometry ($\phi_0 = \pm 90^{\circ}$) [10].

The chirality of SAW-SW can easily be switched because the helicity of the lattice atoms is controlled by the SAW propagation direction and the orientation of the magnetization by the external magnetic field. This potentially allows encoding information in the chiral degree of freedom offered by magnetoacoustic surface waves. Moreover, instead of using unidirectional IDTs [4, 84, 85], the chirality of SAW-SWs makes unidirectional pumping of phonons by magnetization dynamics possible [86].

The pronounced nonreciprocal transmission of magnetoacoustic waves opens an avenue to build new types of miniaturized and energy-efficient microwave components, such as acoustic isolators or circulators [23, 36, 71, 72, 87]. A good magnetoacoustic isolator shows at the same time a low insertion loss IL and a high transmission nonreciprocity ΔS. Since ΔS for the so far realized devices is already very high ($\Delta S \approx 50$ dB, $IL \lesssim -55$ dB [72]) in comparison to state of the art rf-isolators ($\Delta S \approx 20$ dB, $IL \approx 1$ dB), the main challenge in the future lays in reducing IL. A reduction of the insertion loss of the acoustic delay line can be achieved by using impedance-matched unidirectional IDTs [4, 84, 85]. For example, a low IL of about 6 dB at 4 GHz was demonstrated for acoustic delay lines without magnetic thin films [84]. Furthermore, the undesired IL related to the nonresonant magnetoacoustic interaction can become vanishingly small ($\lesssim 0.8$ dB) [29, 36]. Because interfacial DMI is restricted to magnetic thin films and comes with large linewidth broadening due to spin pumping [30], magnetic bi- and multilayers appear to be the more promising and more flexible approach for the realization of magnetoacoustic isolators [36, 54, 70, 71]. Interfacial DMI in magnetic bi- and multilayers can be used to further enhance the SW nonreciprocity [16]. Furthermore, acoustic isolators, which work in zero external magnetic field, can potentially be realized by using magnetic thin films with exchange-bias [88] or/and tailored anisotropies [72, 89]. Switching the magnetization by electrical currents via e.g. Oersted fields, spin-transfer, or spin-orbit torques might be a possible route towards all-electrical reconfigurable acoustic isolators [67, 90].

Moreover, the amplitude and phase of magnetoacoustic waves are characteristically modulated as a function of the external magnetic field. This was used to build low-noise magnetic field sensors [91–93]. For future acoustic magnetic field sensors, it should be additionally possible to determine the sign of the magnetic field if the transmission of the magnetoacoustic wave is nonreciprocal.

Finally, it is possible to characterize SWs in magnetic films [29, 30], bi-, and multilayers [36] via magnetoacoustic transmission measurements. Because the overall transmission depends on the helicities of the driving fields and magnetization precession in the individual layers, the SAW-SW helicity mismatch effect gives insight into the type of the excited SW-mode [36, 70].

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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