

Efficient spin-wave excitation by surface acoustic waves in ultralow-damping yttrium iron garnet–zinc oxide heterostructures

Yannik Kunz^{1,*}, Julian Schöler¹, Finlay Ryburn², Kevin Künstle¹, Michael Schneider¹, Katharina Lasinger^{1,2}, Yangzhan Zhang², Philipp Pirro¹, John Gregg², and Mathias Weiler¹

¹*Fachbereich Physik and Landesforschungszentrum OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, 67663 Kaiserslautern, Germany*

²*Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*



(Received 14 March 2025; revised 28 May 2025; accepted 5 June 2025; published 23 July 2025)

We demonstrate the efficient excitation of spin waves in the ultralow magnetic damping material yttrium iron garnet (YIG) by surface acoustic waves (SAWs). To this end, we use interdigital transducers fabricated on a piezoelectric zinc oxide (ZnO) thin film covering the YIG. This enables the excitation of coherent, propagating Rayleigh-type and Sezawa-type SAWs. We find that the ultralow magnetic damping of YIG is retained after the ZnO deposition and we perform a comprehensive investigation of the magnetoelastic interaction due to the different SAW modes as a function of the external magnetic field magnitude and orientation. By measuring the SAW attenuation, our experiments reveal a highly anisotropic and non-reciprocal SAW–spin-wave interaction in agreement with our model calculation, while demonstrating that low-damping magnons can be efficiently excited by SAWs.

DOI: [10.1103/97kd-ysh6](https://doi.org/10.1103/97kd-ysh6)

I. INTRODUCTION

In recent years, the control and manipulation of magnetization and its dynamics by magnetoacoustic effects has attracted significant interest [1]. Research topics on surface acoustic wave (SAW)-driven magnetoacoustics range from magnetoelastic switching of magnetic states [2], moving of skyrmions [3] and domain walls [4], or the excitation of vortex dynamics [5,6] to investigations of magnon-phonon coupling strength [7]. Leveraging hybrid mechanisms such as magnetoelastic [8], magnetorotational [9,10], spin-rotational [11], or out-of-plane (OOP) phononic angular momentum [12] coupling paves the way for exploring novel phenomena, both fundamentally and for applications. Recent studies have extended the investigation of magnetoacoustic interactions to synthetic antiferromagnets [13,14] and single-phase antiferromagnets [15]. The excitation of magnetization dynamics in the form of spin waves (SWs) by acoustic waves, also referred to as phonon-magnon interaction, is intensively studied. On one hand, the magnetoelastic interaction of SAWs with

SWs in complex multilayered systems has been shown to be an effective tool for manipulation of the SAW transmission, giving rise to giant nonreciprocity [13,14,16–19]. On the other hand, the SW excitation by SAWs can exceed the nonlinear criticality [20] of spin-wave stability by parametric amplification [21]. Thus, the excitation of magnons via magnetoacoustic interactions is a promising approach to overcome the challenge of launching spin waves efficiently in magnonic devices, which aim to exploit magnons for information processing [22] or computing [23–25]. The intrinsic nonlinearity of SWs renders them ideal candidates for novel computing schemes such as neuromorphic computing [26], reservoir computing [27], and even quantum computing [28–30]. Intrinsically, magnonic applications rely on the coherent excitation of SWs [31], as is achievable by magnon-phonon interactions [32,33].

Commonly used magnetostrictive metallic magnets, such as Ni [8], Fe [34], or permalloy [35] typically exhibit comparatively high magnetic damping [36–38]. While these materials are well-suited for manipulation of magnetic states [2] or modulation of the SAW transmission [10], their high Gilbert-damping coefficients result in short magnon lifetimes. This renders them unsuitable for magnonic applications, in which long-lived spin waves contribute to the energy efficiency of the devices. The typical material of choice in magnonics is yttrium iron garnet (YIG) [39,40], as it has record magnon lifetimes. The weak spin-orbit interaction of YIG yields

*Contact author: ykunz@rptu.de

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

magnetoelastic coefficients that are 1 order of magnitude smaller than those of typical ferromagnetic metals, rendering YIG unsuitable for devices exploiting the manipulation of the SAW transmission by magnetostriction. However, as the magnetoelastic effective magnetic field scales inversely with the saturation magnetization, with $M_{S,YIG} \approx 140$ kA/m [40], efficient SW excitation via SAWs can still be achieved as we demonstrate in the following. In previous realizations of magnetoacoustic devices based on YIG grown on piezoelectric materials via sputtering deposition or pulsed laser deposition (PLD) [41], the magnetic damping was vastly increased due to the lattice mismatch between the piezoelectric material and the YIG. Although it is possible to deposit YIG with ultralow magnetic damping by sputtering [42,43] or PLD [44], comparable to that of YIG grown by liquid phase epitaxy (LPE), the gadolinium gallium garnet (GGG) substrate remains indispensable.

To study magnetoacoustic interactions in low-damping YIG, here we use heterostructures consisting of a sputter-deposited piezoelectric zinc oxide (ZnO) layer fabricated on top of a YIG film grown on a GGG substrate by LPE. Similar heterostructures have been exploited in bulk acoustic resonators [45], and for megahertz-frequency SAW devices [46–48]. In contrast to those studies, here we demonstrate the coherent excitation of gigahertz-frequency magnons by SAW phonons and the associated resonant SAW attenuation in YIG in a systematic study of the magnon-phonon interaction as a function of SAW type and external magnetic field orientation. We further theoretically model the phonon-magnon interaction and provide experimental evidence that the resonant spin-wave excitation occurs while preserving the ultralow-damping YIG properties.

II. MAGNON EXCITATION BY SURFACE ACOUSTIC WAVES IN YIG/ZnO

On our device, we use sets of interdigital transducers (IDTs) patterned on the piezoelectric ZnO to launch propagating SAWs. The induced periodic elastic deformation extends through the ZnO layer into the YIG layer, where the elastic deformation interacts with the spin system. The sample fabrication and properties of the resulting gigahertz-range SAWs in a comparable layer stack are reported in detail in Ref. [49]. The investigated device consists of a 103 nm thin YIG layer grown in the [111] direction on a 500 μm GGG substrate via LPE. An 890 nm ZnO layer is deposited via rf-magnetron sputter deposition, while sets of Ti(5 nm)/Au(70 nm) IDTs are structured by electron beam lithography and electron beam evaporation. The sending and the receiving IDTs are located 500 μm apart, with the SAW propagating parallel to the $[\bar{1}10]$ direction. A schematic of the sample is shown in Fig. 1(a),

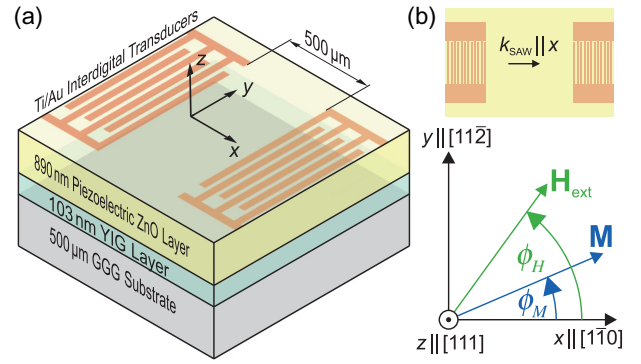


FIG. 1. Investigated device and the coordinate system. As shown in (a), the sample consists of a GGG(500 μm)/YIG(103 nm)/ZnO(890 nm) stack with Ti/Au interdigital transducers of 2.8 μm periodicity. The coordinate system used is illustrated in (b). The x axis is chosen to be parallel to the $[\bar{1}10]$ direction of the YIG and the SAW propagation direction. The z axis indicates the out-of-plane direction parallel to the $[111]$ crystal orientation of the YIG. The direction of the in-plane-oriented external magnetic field $\mathbf{H}_{\text{ext}}$ is parametrized by $\phi_H = \angle(\mathbf{H}_{\text{ext}}, \mathbf{k}_{\text{SAW}})$ and the direction of the magnetization $\mathbf{M}$ relative to the SAW propagation direction, defined by $\mathbf{k}_{\text{SAW}}$, is parametrized by $\phi_M = \angle(\mathbf{M}, \mathbf{k}_{\text{SAW}})$.

and details of the preparation are provided in Supplemental Material [50]. The magnetic parameters of the YIG after the ZnO deposition are determined by in-plane angle-resolved and out-of-plane ferromagnetic resonance (FMR) spectroscopy. The results are summarized in Appendix B. Notably, the extracted Gilbert damping $\alpha = 5.2 \times 10^{-4}$ is comparable to that found for YIG films of similar thickness without ZnO [51], indicating the preservation of the ultralow magnetic damping property of the YIG after ZnO deposition.

We define our coordinate system such that the x axis lies in the plane, parallel to the propagation direction of the SAW, while the z axis is oriented out of the plane along the $[111]$ direction. The external field and magnetization directions are parametrized by their angle relative to the SAW propagation, defined by $\mathbf{k}_{\text{SAW}}$, as illustrated in Fig. 1(b).

To study the SAW-SW interaction we connect the opposing set of IDTs to a vector network analyzer (VNA). All measurements were conducted with an applied microwave power of +14 dBm. By measuring the S_{21} transmission parameter and using time gating [24,52], we extract the transmitted SAW amplitude. Hereby, the magnitude of the S_{21} parameter is proportional to the transmitted SAW power as $P_{\text{SAW}} \propto S_{21}$. The sample is placed in a rotatable electromagnet to change the externally applied magnetic field magnitude $\mu_0 H_{\text{ext}}$ and orientation ϕ_H relative to the SAW propagation direction.

We first apply the external magnetic field at the fixed orientation of $\phi_H = 40^\circ$ and investigate the transmission of the Rayleigh-type SAW at a frequency of around 2.45 GHz

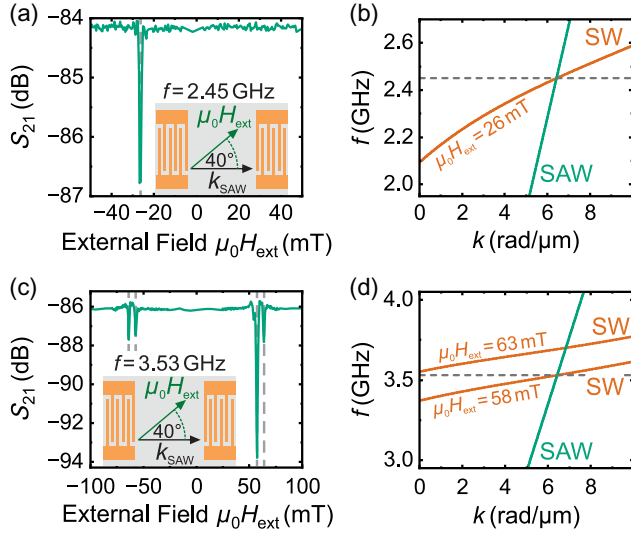


FIG. 2. Magnetic field-dependent SAW absorption for (a) the Rayleigh-type mode at 2.45 GHz and (c) the Sezawa-type mode at 3.53 GHz at a fixed external magnetic field orientation ϕ_H of 40° . The corresponding SW and SAW dispersion relations at the resonance magnetic field are shown in (b),(d).

and transmission of the Sezawa-type SAW at 3.53 GHz as a function of field strength. The transmission parameter S_{21} is shown in Figs. 2(a) and 2(c). As can be seen, for the Rayleigh-type mode at 2.45 GHz in Fig. 2(a), we observe a resonant absorption of the SAW at an external field $\|\mu_0 H_{\text{ext}}\|$ of 26 mT. While the reduction of the S_{21} parameter when the spin wave resonance condition is fulfilled is attributed to coherent conversion of SAWs to SWs [33], the generated SWs dissipate by incoherent scattering [53]. This field corresponds to the intersection of the SW dispersion with the SAW dispersion shown in Fig. 2(b) at the wave vector of $6.43 \text{ rad}/\mu\text{m}$, indicating the resonant interaction of the phonons with magnons. Thus, during the interaction, the energy and momentum conservation is fulfilled:

$$\hbar f_{\text{phonon}} = \hbar f_{\text{magnon}}, \quad (1)$$

$$\hbar k_{\text{phonon}} = \hbar k_{\text{magnon}}, \quad (2)$$

where $k = \|\mathbf{k}\|$ denotes the wave vector and f the frequency. Notably, the interaction is highly nonreciprocal at this magnetic field orientation, showing a relative absorption of approximately -2.8 dB at the negative resonance magnetic field of -26 mT , while seemingly no absorption is observed at positive magnetic fields. This is attributed to the helicity mismatch effect [10,54], which results in different interaction efficiencies depending on the helicity of the surface acoustic wave (SAW) and the precession orientation of the spin waves (SWs). This nonreciprocity is discussed in the context of our angle-resolved measurements later.

In the case of the Sezawa mode at $f = 3.53 \text{ GHz}$, shown in Fig. 2(c), we find multiple absorption lines at the fields $\|\mu_0 H_{\text{ext}}\|$ of 58 and 63 mT. Here the resonance at lower field is again found at the intersection of the SAW and SW dispersion relations. Additionally, the higher-field resonance occurs around the field of the $k = 0$ mode, i.e., the FMR. The FMR excitation is caused by a direction excitation of the spin system by the alternating current in the microstructures, as we verify and discuss in Appendix C. Notably, for the Sezawa mode, the absorption is most prominent at positive values of the externally applied magnetic field, opposite the corresponding observations for the Rayleigh-type mode in Fig. 2(a). This is attributed to the differing contributions of individual strain components of the Rayleigh-type and Sezawa-type modes, in agreement with their reversed helicity [55]. The role of SAW helicity and SW coupling was demonstrated, for instance, by Will-Cole *et al.* [56] in an engineered piezoelectric/magnetic layered system.

III. MAGNETOACOUSTIC INTERACTION SYMMETRY OF RAYLEIGH- AND SEZAWA-TYPE MODES

To map the magnetoacoustic interaction symmetry of the two SAW modes, we perform field- and angle-dependent measurements. To focus on the magnetic field dependence, we consider the relative SAW transmission:

$$\Delta S_{21}(\mu_0 H_{\text{ext}}) = S_{21}(\mu_0 H_{\text{ext}}) - \bar{S}_{21}(\|\mu_0 H_{\text{ext}}\| > 40 \text{ mT}), \quad (3)$$

where $\bar{S}_{21}$ denotes the averaged transmission parameter at fields $\|\mu_0 H_{\text{ext}}\| > 40 \text{ mT}$. The resulting relative SAW transmission is shown in Fig. 3(a). The SAW-SW interaction is highly anisotropic and nonreciprocal. The anisotropy is due to the anisotropic dipolar-exchange SW dispersion that dominates the angular dependence of the resonant magnetic field, while the magnetic anisotropy $\mu_0 H_{\text{ani}}$ is on the order of only about $-2\mu_0 K_u/M_S \approx 0.73 \text{ mT}$, as shown in Appendix B. Lewis and Patterson [46] reported a nonreciprocal SAW attenuation at a frequency of 200 MHz and a magnetic field orientation ϕ_H of 90° . In their study the origin of the nonreciprocity could not be clearly assigned, and the nonreciprocity occurred under an angle where the SAW-SW interaction is reciprocal in our data. In Fig. 3(a), the Rayleigh mode has a nonvanishing coupling efficiency at $\phi_H = 0^\circ$ and $\phi_H = 90^\circ$, corresponding to the backward-volume and the Damon-Eshbach spin-wave geometry, respectively. This warrants a closer investigation of the symmetry of the magnetoacoustic interaction, as no magnetoacoustic coupling is expected for these orientations under the assumption of a pure compressional SAW mode [57].

To model the measurement data, we follow the approach developed by Dreher *et al.* [58] and Küß *et al.* [10], using

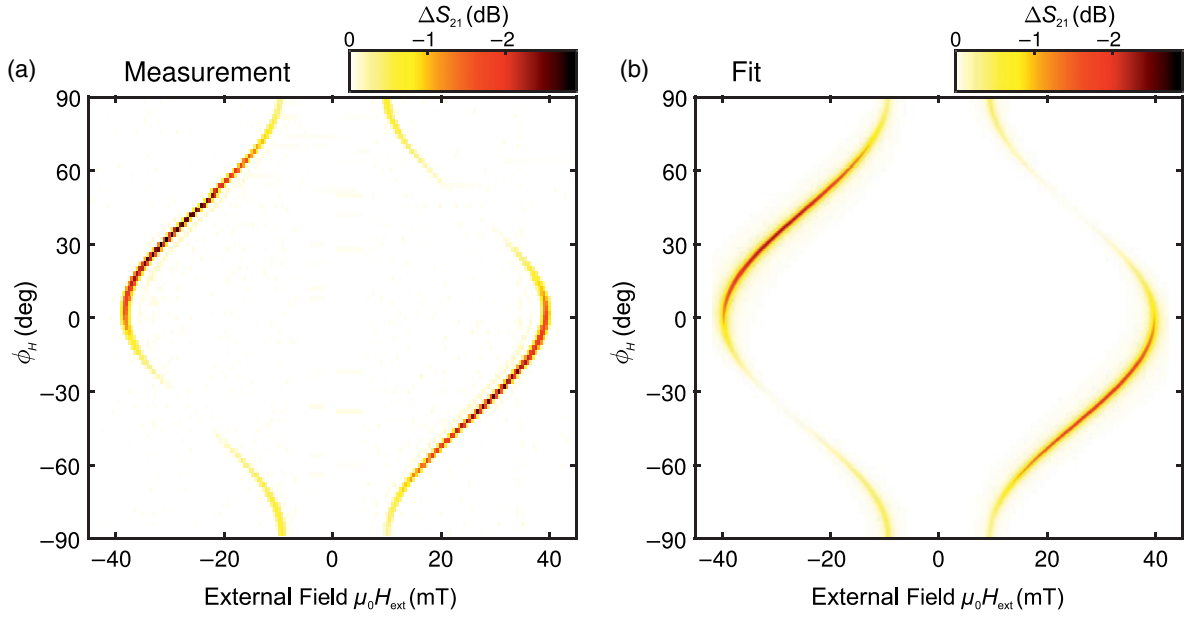


FIG. 3. Coupling symmetry of the Rayleigh-type SAW mode measured at 2.45 GHz. (a) Measurement and (b) theoretical modeling. Remarkably, the interaction is highly nonreciprocal. The magnetic parameters used are determined by a least-squares optimization using the position of the resonance, while the strain parameters of the SAW are extracted from an optimization of the full dataset. All parameters used are summarized in Table I.

the effective magnetic driving field approach, detailed in Appendix A. The total absorbed power P_{abs} is derived as

$$P_{\text{abs}} = -\mu_0 \pi f \text{Im} \left(\int_V \mathbf{h}_{\text{MEC}}^* \chi \mathbf{h}_{\text{MEC}} dV \right), \quad (4)$$

where χ is the dynamical Polder susceptibility tensor, f the frequency, $\mathbf{h}_{\text{MEC}}$ the magnetoacoustic excitation field, and V the magnetic volume. For the derivation of $\mathbf{h}_{\text{MEC}}$, see Appendix A. We determine the magnetic parameters by first fitting the angle-dependent resonance magnetic

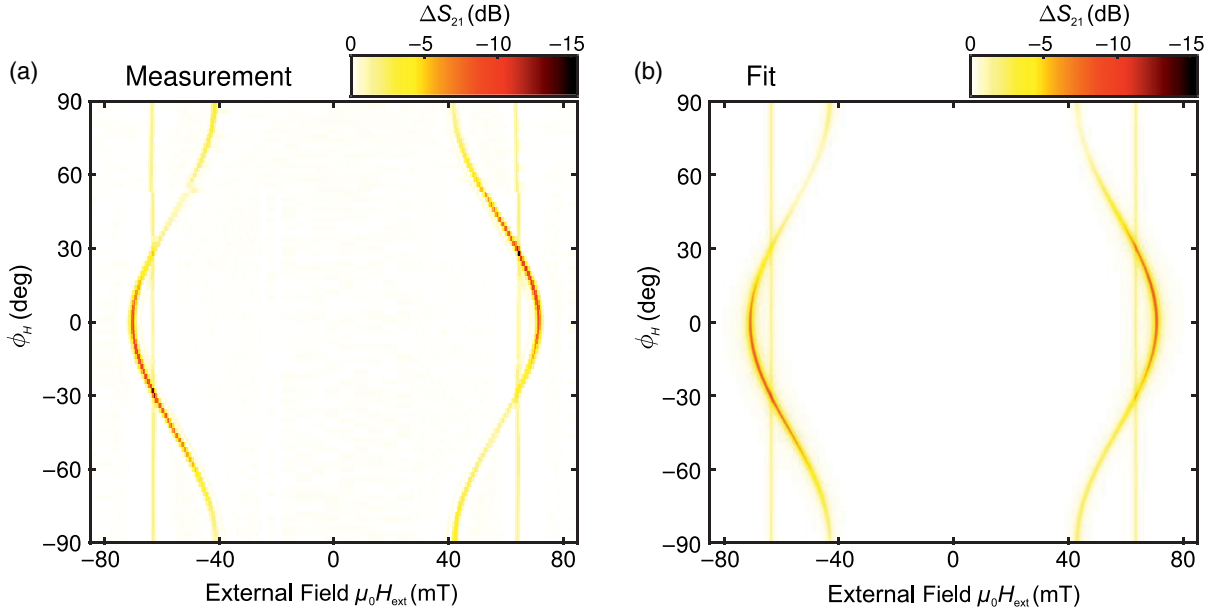


FIG. 4. Coupling symmetry of the Sezawa-type SAW mode measured at 3.53 GHz. (a) Measurement and (b) theoretical modeling. Notably, the interaction symmetry is roughly inverted compared with that of the Rayleigh-type mode shown in Fig. 3 as a consequence of the differing strain components and reversed helicity. The angle-independent absorption line at 53 mT results from a direct excitation of the ferromagnetic resonance.

field positions with the spin-wave dispersion. For this, the thin film approximation of Kalinkos and Slavin [59] for description of the dipolar terms, the exchange interaction terms, and the anisotropy contributions is included. Under the assumption that $\mathbf{M} \parallel \mathbf{H}$, the SW dispersion can be expressed as

$$f = \frac{\gamma}{2\pi} \mu_0 \sqrt{H_{11} H_{22}}, \quad (5)$$

where f denotes the frequency, γ is the gyromagnetic ratio, and H_{11} and H_{22} depend on the external field and the contributions mentioned above (see Appendix A). A summary of the magnetic parameters used is given in Table I.

We treat the relative strain components that define the SAW type as free parameters; they are determined by a least-squares optimization of the experimental data. Hereby, a set of normalized strain parameters is used, and

TABLE I. Magnetic parameters and normalized strain components of both the Rayleigh mode and the Sezawa mode obtained by parameter optimization. The magnetoelastic coupling coefficients b_1 and b_2 are taken from Ref. [60]. For the definition of the strain component amplitude and phase, see Supplemental Material [50].

Quantity	Mode	
	Rayleigh	Sezawa
Frequency f (GHz)	2.45	3.53
Group velocity v_G (m/s)	2458	2641
Wave vector k (rad/ μm)		6.43
YIG film thickness d (nm)		94.2
g factor g		2.11
Saturation magnetization $\mu_0 M_S$ (mT)		0.158
Exchange constant A (pJ/m)		3.41
Uniaxial anisotropy field $\mu_0 H_u$ (mT)		-0.365
Uniaxial isotropic easy axis ϕ_u (deg)		-43.3
OOP anisotropy field $\mu_0 H_{\text{OOP}}$ (mT)		-7.0
Effective damping α_{eff}	0.0070	0.0069
Magnetoelastic coupling coefficient b_1 (J/m ³)	3.48×10^{-7}	
Magnetoelastic coupling coefficient b_2 (J/m ³)	3.48×10^{-7}	
Amplitude ε_{xx}	1	0.219
Phase ε_{xx} (rad)	0	0
Amplitude ε_{xy}	0.372	0.306
Phase ε_{xy} (rad)	$-1.086\pi/2$	$-1.218\pi/2$
Amplitude ε_{xz}	0.940	1
Phase ε_{xz} (rad)	$0.944\pi/2$	$-1.177\pi/2$
Amplitude ε_{yz}	0.124	0.166
Phase ε_{yz} (rad)	$1.324\pi/2$	$0.586\pi/2$

the total absorption is multiplied by a scaling parameter. Further, the effective Gilbert-damping parameter (for the definition, see Appendix A, which parametrizes the linewidth, is fitted. The parameters obtained are provided in Table I. As can be seen in Fig. 3(b), the theoretical model with the set of optimized parameters can quantitatively reproduce the experimental dataset.

Next we focus on the investigation of the Sezawa-like mode at $f = 3.53$ GHz and its SAW-SW interaction symmetry. We again measure the dependence of the relative SAW transmission on the magnetic field magnitude and orientation, now choosing for normalization of ΔS_{21} the field range $\|\mu_0 H_{\text{ext}}\| > 80$ mT. The measurement results obtained are shown in Fig. 4(a). As expected, at higher frequency the resonance condition shifts toward larger external magnetic fields. The angle-resolved measurement reveals the full coupling symmetry. As expected, the maximum coupling efficiency is now observed at ϕ_H values that differ from those observed for the Rayleigh mode shown in Fig. 3. The difference in the interaction symmetry arises from the reversed helicity of the SAW, i.e., its polarization, relative to the Rayleigh mode. This reversal occurs due to an additional strain node within the material, as the Sezawa mode represents a higher-order SAW mode compared with the Rayleigh mode. This becomes apparent in Table I by the sign change of the ε_{xz} -phase component. In Fig. 4(a), a near vertical line of contrast is visible at an external magnetic field $\mu_0 H_{\text{ext}}$ of approximately 58 mT. We argue that this additional excitation does not originate from the interaction of the SAW with the spin system, but is caused by excitation of the uniform SW mode (FMR). The FMR field is independent of ϕ_H , in accordance with vanishing in-plane magnetic anisotropy. We attribute the FMR excitation to the alternating current in the microstructured pads, as the momentum conservation between the phonon and the FMR magnon could not be fulfilled. Further, the direct FMR excitation is continuous in frequency and therefore not constrained by the IDT periodicity, which limits the excitation spectra of the IDTs to discrete frequencies. The measurement of the S_{11} reflection parameter confirms this, as shown in Fig. 6 in Appendix C. Further, we observe a large increase of the absorbed SAW power from around 2.8 dB for the Rayleigh mode to around 15 dB for the Sezawa mode. On one hand, this can be attributed to the increase in frequency, resulting in an increased power absorption as $P_{\text{abs}} \propto f$. On the other hand, the transverse components of the Sezawa mode penetrate deeper into the material compared with the Rayleigh mode [55], leading to a higher magnetoelastic driving field generated by the SAW in the YIG, which is buried beneath the ZnO layer in our samples. Thus, the SW excitation is more efficient than for the Rayleigh-type mode.

To model the dataset obtained, we follow the same approach as discussed above for the Rayleigh-type mode. The FMR excitation is computed as the $k = 0$

mode with an out-of-plane excitation field, yielding an angle-independent excitation efficiency. The strain parameters of the SAW and the linewidth are extracted with use of the same approach as described before, provided in Table I. The results are shown in Fig. 4(b). We conclude that the effective field approach can sufficiently and accurately model the experimentally obtained data, for both the Rayleigh-type mode and the Sezawa-type mode.

IV. SUMMARY AND CONCLUSIONS

We presented a comprehensive study of the interaction of SAWs and SWs in a heterostructure of GGG/YIG/ZnO. The angle dependence of the phonon-magnon coupling was extracted by SAW transmission measurements. The measurements could be quantitatively replicated with our phenomenological model calculations based on magnetoacoustic interactions. By fitting our data to this model, we extract the magnetic properties of the ferromagnetic material with high precision, as the interaction symmetry is strongly dependent on these parameters. Further, our data indicate that SWs in the ultralow magnetic damping material YIG can be efficiently excited by magnetoacoustic interactions, as the SAW absorption is increased by 2.8 dB at a frequency of 2.45 GHz for the Rayleigh mode and by up to 15 dB at a frequency of 3.53 GHz for the Sezawa mode. The total absorbed SAW power is heavily dependent on the thickness of the material stack due to the characteristic decay of the SAW amplitude into the bulk. Thus, engineering the layer stack can further increase the efficiency of magnon pumping by SAWs through optimization of the SAW-mode and SW-mode overlap. Precise control requires solving the equations of motion for the acoustic system, as described in Refs. [49,61]. The penetration depth decreases with increasing wave vector, leading to a vanishing mode overlap between the SAW and SW modes and, consequently, the coupling vanishes. Decreasing the ZnO thickness enables the SAW to penetrate the YIG at higher wave vectors. The same argument applies to the Sezawa mode; however, thinning of the ZnO layer causes the lower cutoff frequency and wave vector to increase [62]. Consequently, the Sezawa mode exists only for shorter wavelengths providing smaller penetration depths, resulting in reduced mode overlap between the SAW and the SW. Decreasing the thickness of the ZnO shifts the lower cutoff frequency of the Sezawa modes upward and thereby increases the range of nonleaky SAW modes [62]. The emergence of highly nonreciprocal coupling is characteristic of the inherent chirality in the system, by means of the intrinsic helicity of the SAWs and SWs.

ACKNOWLEDGMENTS

This work was supported by the European Research Council under the European Union's Horizon Europe research and innovation program (Consolidator Grant

MAWiCS, Grant Agreement No. 101044526). The work of F.R. was supported by a UK Engineering and Physical Sciences Research Council Industrial Cooperative Award in Science and Technology under Grant No. 2286081.

DATA AVAILABILITY

The data that support the findings of this article are openly available [63].

APPENDIX A: MODELING OF THE MAGNETOELASTIC COUPLING

We model the magnetic field and angle-dependent coupling of the SAW with SWs in the YIG by following the effective field approach introduced by Dreher *et al.* [58] and Küß *et al.* [10]. First, the equilibrium magnetization direction is computed by our minimizing the free energy density G . For this, we consider the Zeeman energy, the in-plane uniaxial anisotropy, and the out-of-plane anisotropy:

$$G = -\mu_0 \mathbf{H} \cdot \mathbf{M} + K_u(m_x m_y + m_x m_z + m_y m_z) + K_s(\tilde{n} \cdot \mathbf{M})^2, \quad (\text{A1})$$

where K_u denotes the uniaxial magnetic anisotropy constant, $\tilde{n}$ is the demagnetizing tensor, and K_s is the out-of-plane anisotropy constant. The dynamical driving field $\mu_0 \mathbf{h}_{\text{MEC}}$ generated by the SAW is derived from the magnetoelastic energy density G^d :

$$G^d = \frac{b_1}{M_S^2}(\varepsilon_{xx} M_x^2 + \varepsilon_{yy} M_y^2 + \varepsilon_{zz} M_z^2) + 2 \frac{b_2}{M_S^2}(\varepsilon_{xy} M_x M_y + \varepsilon_{xz} M_x M_z + \varepsilon_{yz} M_y M_z). \quad (\text{A2})$$

The driving field $\mu_0 \mathbf{h}_{\text{MEC}} = (\mu_0 h_1, \mu_0 h_2)^T$ is of the form

$$\mu_0 h_1 = -2 \frac{b_2}{M_S} [\cos \phi_0 \varepsilon_{xz} + \sin \phi_0 \varepsilon_{yz}] \quad (\text{A3})$$

$$\mu_0 h_2 = -2 \frac{b_2}{M_S} \cos(2\phi_0) \varepsilon_{xy} + 2 \frac{b_1}{M_S} \sin \phi_0 \cos \phi_0 \varepsilon_{xx}, \quad (\text{A4})$$

where the “1” direction points parallel to the magnetization and the “2” direction is perpendicular in the OOP direction. The response of the spin-wave system can then be computed by means of the Polder susceptibility χ :

$$\mathbf{M} = \chi \mathbf{h}_{\text{MEC}}, \quad (\text{A5})$$

$$\chi_{11}^I = H \cos(\phi_0 - \phi_H) + \frac{2A}{\mu_0 M_S} k^2 + M_S G_0 - \frac{2K_S}{M_S}$$

$$+ \frac{2K_u}{M_S} \cos^2(\phi_0 - \phi_H) - i \frac{\alpha_{\text{eff}} \omega}{\mu_0 \gamma},$$

$$\chi_{12}^I = -\chi_{21}^I = i \frac{\omega}{\mu_0 \gamma},$$

$$\chi_{22}^I = H \cos(\phi_0 - \phi_H) + \frac{2A}{\mu_0 M_S} k^2 + M_S(1 - G_0) \sin^2(\phi_0) + \frac{2K_u}{M_S} \cos(2(\phi_0 - \phi_H)) - i \frac{\alpha_{\text{eff}} \omega}{\mu_0 \gamma}, \quad (\text{A6})$$

where $\omega = 2\pi f$ is the angular frequency, $\alpha^{\text{eff}} = \frac{\gamma}{2\omega} \mu_0 \Delta H + \alpha^{\text{FMR}}$ is the effective Gilbert damping, A is the exchange constant, M_S is the saturation magnetization, and G_0 describes the dipolar term by $G_0 = (1 - \exp(-\|k\ell\|))/k\ell$. The power absorption due to the excitation of the magnetic system via a dynamical rf field is given by $P_{\text{SW}} = -\frac{\mu_0 \omega}{2} \text{Im}(\int_V \mathbf{h}^* \chi \mathbf{h} dV)$ [64], where the integration is performed over the magnetic volume, under the assumption of a uniform strain and spin-wave-mode profile over the thickness of the magnetic layer. Because of the decay of the SAW, the strength of the generated magnetoelastic driving field is reduced with increasing propagation. Consequently, the integral becomes a differential equation, which is solved by an exponential ansatz [10]. Finally, the relative transmitted SAW power can be computed as

$$\frac{P_{\text{SAW}}}{P_0} = \exp\left[-C \frac{\omega \mu_0 V}{2} \text{Im}(\mathbf{h}_0^* \chi \mathbf{h}_0)\right], \quad (\text{A7})$$

where $\mathbf{h}_0$ refers to the driving field generated by the SAW at the start of propagation and C is a constant that scales the strain amplitude.

Further, from the Polder susceptibility, we introduce the definitions $H_{11} = \text{Re}(\chi_{11})$ and $H_{22} = \text{Re}(\chi_{22})$ to obtain the

spin-wave dispersion as

$$f = \frac{\gamma}{2\pi} \mu_0 \sqrt{H_{11} H_{22}}. \quad (\text{A8})$$

APPENDIX B: MAGNETIC PARAMETERS DETERMINED BY FERROMAGNETIC RESONANCE SPECTROSCOPY

We use well-established VNA-based broadband ferromagnetic resonance spectroscopy to determine the magnetic parameters of the YIG upon ZnO deposition. For this purpose, a blank, cut piece of the sample is used to ensure comparability. We perform FMR measurements in the OOP geometry to extract the saturation magnetization and the gyromagnetic ratio. Angle-resolved FMR spectroscopy is used to determine the magnetic anisotropy. The results are shown in Fig. 5.

We fit the OOP FMR data with the appropriate Kittel equation, given by

$$f_{\text{res}}(\mu_0 H_{\text{ext}}) = \frac{g \mu_B}{2\pi \hbar} (\mu_0 H_{\text{ext}} - \mu_0 M_{\text{eff}}). \quad (\text{B1})$$

From the frequency-dependent line width, we determine the Gilbert damping and the inhomogeneous linewidth by fitting the expression

$$\mu_0 \Delta H_{\text{res}} = \frac{2h\alpha}{g\mu_B} f + \mu_0 \Delta H_{\text{inhomo}} \quad (\text{B2})$$

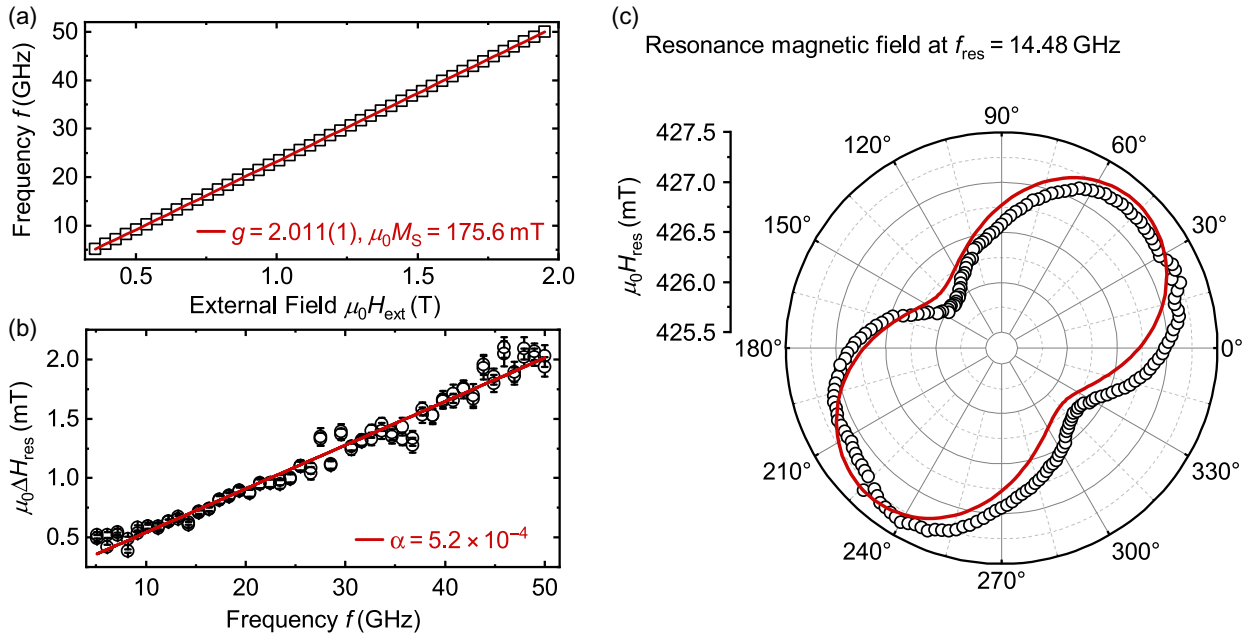


FIG. 5. (a),(b) Example Kittel fit and linewidth result in the OOP geometry. (c) Resonance magnetic field at a fixed frequency f of 14.48 GHz. The orientation of the external magnetic field is defined via the angle ϕ_H relative to the wave vector of the SAW such that $\phi_H = 0 \parallel k_{\text{SAW}}$.

We find a Gilbert-damping parameter α of 5.2×10^{-4} . This indicates that the low magnetic damping property of the YIG is preserved during the ZnO deposition.

In Fig. 5(c) we show the resonance magnetic field as a function of the orientation of the external magnetic field, exemplary at a frequency of 14.48 GHz. As can be seen, the sixfold anisotropy, expected for a cubic crystal structure oriented in the [111] direction, is overlapped by a dominant uniaxial anisotropy. To determine the magnetic anisotropy parameters, we calculate the angle-dependent

ferromagnetic resonance frequency as follows. We apply an adapted approach inspired by Lee *et al.* [65] and start from the free energy density G [66]:

$$G = -\mu_0 \mathbf{H} \cdot \mathbf{M} + \frac{1}{2} \mu_0 (\tilde{\mathbf{n}} \cdot \mathbf{M})^2 + K_1 (m_x^2 m_y^2 + m_y^2 m_z^2 + m_z^2 m_x^2) + K_2 m_x^2 m_y^2 m_z^2 + K_u (m_x m_y + m_x m_z + m_y m_z) + K_S (\tilde{\mathbf{n}} \cdot \mathbf{M})^2. \quad (\text{B3})$$

We use the normalized magnetization $\mathbf{m} = \mathbf{M}/M_S$. K_1 and K_2 denote the first-order and second-order cubic magnetic anisotropy constants, K_u denotes the uniaxial anisotropy constant, and K_S denotes the out-of-plane anisotropy constant. The resonance frequency is derived with use of the relation provided by Suhl [67] and Smit and Beljers [68]: $f = \frac{\gamma}{2\pi M_S \sin \theta} (G_{\theta\theta} G_{\phi\phi} - G_{\theta\phi}^2)^{1/2}$. As we measure in the high-field limit, the magnetic field dragging effect is ignored. We compute the angle-dependent FMR frequency as

$$f(H_0, \phi_H) = \frac{g\mu_B}{h} \times \sqrt{\left(\mu_0 H_0 + \mu_0 M_{\text{eff}} + \frac{2K_u}{M_S} \cos^2(\phi_0 - \phi_u) - \frac{K_1}{M_S} + \frac{K_2}{18M_S} (2 - \cos(6\phi_H)) \right) \left(\mu_0 H_0 + \frac{2K_u}{M_S} \cos(2(\phi_0 - \phi_u)) - \frac{K_2}{3M_S} \cos(6\phi_H) \right)}. \quad (\text{B4})$$

As is common, in Eq. (B4) we replaced the term $\mu_0 M_S - 2K_S/M_S$ with the effective magnetization $\mu_0 M_{\text{eff}}$. The magnetic parameters obtained are summarized in Table II.

Investigation the origin of the dominating uniaxial anisotropy is beyond the scope of this study. However, we suspect it originates from the anisotropic thermal expansion of the YIG, which is expected in Wurzite-type crystals [69]. During the ZnO sputtering process, the substrate is heated, and thus the different thermal expansion coefficients of YIG and ZnO induce a permanent strain on the YIG when it is cooling down, resulting in

an additional uniaxial anisotropy. Such observations were reported before [10].

As is apparent from the angle-resolved FMR measurements shown in Fig. 5, the uniaxial anisotropy vastly dominates over the crystalline anisotropy, while still being in the militesla range. Consequently, for modeling of the magnetoelastic interaction, we consider only the terms associated with the uniaxial anisotropy.

APPENDIX C: DIRECT FMR EXCITATION BY MICROSTRUCTURED PADS

As stated in the main text, we observe in Fig. 4(a) a direct excitation of the ferromagnetic resonance. Since the excitation of the FMR via the SAW can be excluded due to the violation of momentum conservation, we suspect the additional absorption line originates as follows. In commonly used devices, the magnetic film is deposited between the IDTs on a piezoelectric layer, while the microstructured IDTs are located only on the piezoelectric layer [16]. In our device the IDTs are placed on top of the piezoelectric layer, which covers the YIG. The alternating current in the microstructured patterns generates an approximately uniform magnetic field, which directly interacts with the magnetic system in the YIG and excites its FMR. To test this hypothesis, we measured the reflected signal S_{11} as a function of the field and frequency, as shown in Fig. 6.

TABLE II. Magnetic parameters obtained from FMR spectroscopy measurements. The crystalline magnetic anisotropy constants K_1 and K_2 as well as the saturation magnetization $\mu_0 M_S$ are taken from Lee *et al.* [65].

Parameter	Value
g	2.011
$\mu_0 M_{\text{eff}}$ (mT)	183
$\mu_0 M_S$ (mT)	176 [65]
α^{FMR}	5.2×10^{-4}
$\mu_0 \Delta H_{\text{inhomo}}$ (mT)	0.17
K_u (J/m ³)	-51.0
ϕ_u (deg)	-43.3
K_1 (J/m ³)	-542.1 [65]
K_2 (J/m ³)	-137.2 [65]

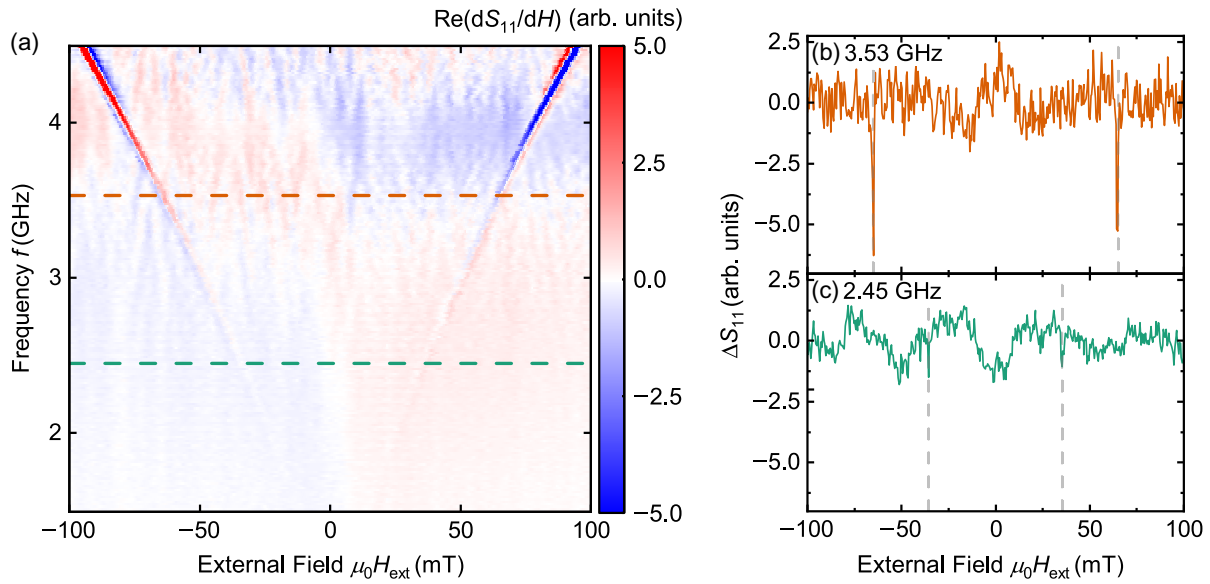


FIG. 6. S_{11} reflection measurement as a function of the external magnetic field $\mu_0 H_{\text{ext}}$ with one of the IDTs connected to the VNA. (a) Reflected S_{11} signal, derived with respect to the external magnetic field, revealing the FMR signature. The green line at 2.45 GHz and the orange line at 3.53 GHz highlight the frequency at which the Rayleigh- and Sezawa-type SAWs are excited, respectively. (b) Background-corrected S_{11} signal at 2.45 GHz as a function of the external magnetic field. (c) Background-corrected signal S_{11} at 3.53 GHz as a function of the external magnetic field. At certain FMR fields the additional absorption due to the excitation of the FMR becomes apparent.

We apply the well-established derivative divide method [70] to extract the magnetic field-dependent signal and remove the frequency-dependent background. As illustrated in Fig. 6(a), the excitation of the ferromagnetic resonance is visible. Notably, it occurs continuously in frequency. Therefore, it is not constrained by IDT periodicity, which would otherwise permit the excitation of only discrete wave vectors and, consequently, frequencies. Nevertheless, the SAW excitation remains visible, as illustrated by the line-cuts shown in Fig. 6(b) at the frequency corresponding to the excitation of the Rayleigh-type mode at 2.45 GHz. A similar observation holds for the frequency of 3.53 GHz, indicating the excitation of the Sezawa-type mode in Fig. 6.

We argue that due to the direct excitation of the FMR, less microwave power applied to the IDT is available for the SAW excitation. This results in an additional field-dependent, but angle-independent, absorption line in the SAW-transmission measurement, as observed in Fig. 4. Further, the FMR line is clearly visible for the Sezawa mode only at 3.53 GHz, and not at 2.45 GHz, because generally the microwave power absorption scales with the frequency, following the relation $P_{\text{abs}} \propto f$ [66].

[1] W.-G. Yang and H. Schmidt, Acoustic control of magnetism toward energy-efficient applications, *Appl. Phys. Rev.* **8**, 021304 (2021).

[2] V. Sampath, N. D'Souza, D. Bhattacharya, G. M. Atkinson, S. Bandyopadhyay, and J. Atulasimha, Acoustic-wave-induced magnetization switching of magnetostrictive nanomagnets from single-domain to nonvolatile vortex states, *Nano Lett.* **16**, 5681 (2016).
 [3] Y. Yang, L. Zhao, D. Yi, T. Xu, Y. Chai, C. Zhang, D. Jiang, Y. Ji, D. Hou, W. Jiang, J. Tang, P. Yu, H. Wu, and T. Nan, Acoustic-driven magnetic skyrmion motion, *Nat. Commun.* **15**, 1018 (2024).
 [4] W. Edrington, U. Singh, M. A. Dominguez, J. R. Alexander, R. Nepal, and S. Adenwalla, Saw assisted domain wall motion in Co/Pt multilayers, *Appl. Phys. Lett.* **112**, 052402 (2018).
 [5] V. Iurchuk, J. Lindner, J. Fassbender, and A. Kákay, Excitation of the gyrotropic mode in a magnetic vortex by time-varying strain, *Phys. Rev. Lett.* **133**, 146701 (2024).
 [6] A. Koujok, A. Riveros, D. R. Rodrigues, G. Finocchio, M. Weiler, A. Hamadeh, and P. Pirro, Resonant excitation of vortex gyrotropic mode via surface acoustic waves, *Appl. Phys. Lett.* **123**, 132403 (2023).
 [7] Y. Hwang, J. Puebla, K. Kondou, C. Gonzalez-Ballester, H. Isshiki, C. S. Muñoz, L. Liao, F. Chen, W. Luo, S. Maekawa, and Y. Otani, Strongly coupled spin waves and surface acoustic waves at room temperature, *Phys. Rev. Lett.* **132**, 056704 (2024).
 [8] M. Weiler, L. Dreher, C. Heeg, H. Huebl, R. Gross, M. S. Brandt, and S. T. B. Goennenwein, Elastically driven ferromagnetic resonance in nickel thin films, *Phys. Rev. Lett.* **106**, 117601 (2011).
 [9] M. Xu, K. Yamamoto, J. Puebla, K. Baumgaertl, B. Rana, K. Miura, H. Takahashi, D. Grundler, S. Maekawa, and

- Y. Otani, Nonreciprocal surface acoustic wave propagation via magneto-rotation coupling, *Sci. Adv.* **6**, eabb1724 (2020).
- [10] M. Küß, M. Heigl, L. Flacke, A. Hörner, M. Weiler, M. Albrecht, and A. Wixforth, Nonreciprocal Dzyaloshinskii–Moriya magnetoacoustic waves, *Phys. Rev. Lett.* **125**, 217203 (2020).
- [11] D. Kobayashi, T. Yoshikawa, M. Matsuo, R. Iguchi, S. Maekawa, E. Saitoh, and Y. Nozaki, Spin current generation using a surface acoustic wave generated via spin-rotation coupling, *Phys. Rev. Lett.* **119**, 077202 (2017).
- [12] L. Liao, F. Chen, J. Puebla, J.-i. Kishine, K. Kondou, W. Luo, D. Zhao, Y. Zhang, Y. Ba, and Y. Otani, Nonreciprocal magnetoacoustic waves with out-of-plane phononic angular momenta, *Sci. Adv.* **10**, eado2504 (2024).
- [13] M. Küß, S. Glamsch, Y. Kunz, A. Hörner, M. Weiler, and M. Albrecht, Giant surface acoustic wave nonreciprocity with low magnetoacoustic insertion loss in CoFeB/Ru/CoFeB synthetic antiferromagnets, *ACS Appl. Electron. Mater.* **5**, 5103 (2023).
- [14] R. Lopes Seeger, L. La Spina, V. Laude, F. Millo, A. Bartaszyte, S. Margueron, A. Solignac, G. de Loubens, L. Thevenard, C. Gourdon, C. Chappert, and T. Devolder, Symmetry of the coupling between surface acoustic waves and spin waves in synthetic antiferromagnets, *Phys. Rev. B* **109**, 104416 (2024).
- [15] Z. Zhang, F. Y. Gao, J. B. Curtis, Z.-J. Liu, Y.-C. Chien, A. von Hoegen, M. T. Wong, T. Kurihara, T. Suemoto, P. Narang, E. Baldini, and K. A. Nelson, Terahertz field-induced nonlinear coupling of two magnon modes in an antiferromagnet, *Nat. Phys.* **20**, 801 (2024).
- [16] M. Küß, S. Glamsch, A. Hörner, and M. Albrecht, Wide-band nonreciprocal transmission of surface acoustic waves in synthetic antiferromagnets, *ACS Appl. Electron. Mater.* **6**, 1790 (2024).
- [17] L. Thevenard, C. Gourdon, J. Y. Prieur, H. J. von Bardeleben, S. Vincent, L. Becerra, L. Largeau, and J.-Y. Duquesne, Surface-acoustic-wave-driven ferromagnetic resonance in (Ga,Mn)(As,P) epilayers, *Phys. Rev. B* **90**, 094401 (2014).
- [18] P. J. Shah, D. A. Bas, I. Lisenkov, A. Matyushov, N. X. Sun, and M. R. Page, Giant nonreciprocity of surface acoustic waves enabled by the magnetoelastic interaction, *Sci. Adv.* **6**, eabc5648 (2020).
- [19] D. A. Bas, R. Verba, P. J. Shah, S. Leontsev, A. Matyushov, M. J. Newburger, N. X. Sun, V. Tyberkevich, A. Slavin, and M. R. Page, Nonreciprocity of phase accumulation and propagation losses of surface acoustic waves in hybrid magnetoelastic heterostructures, *Phys. Rev. Appl.* **18**, 044003 (2022).
- [20] M. Geilen, R. Verba, A. Hamadeh, A. Nicoloiu, D. Narducci, A. Dinescu, M. Ender, M. Mohseni, F. Ciubotaru, M. Weiler, A. Müller, B. Hillebrands, C. Adelmann, and P. Pirro, Parametric excitation and instabilities of spin waves driven by surface acoustic waves, *Adv. Phys. Res.* **14**, 2400086 (2024).
- [21] A. Jander, P. Dhagat, and C. Rivard, Parametric pumping of coherent spin waves by surface acoustic waves, *J. Appl. Phys.* **137**, 073902 (2025).
- [22] A. N. Mahmoud, F. Vanderveken, C. Adelmann, F. Ciubotaru, S. Hamdioui, and S. Cotofana, Multifrequency data parallel spin wave logic gates, *IEEE Trans. Magn.* **57**, 1 (2021).
- [23] A. V. Chumak, A. A. Serga, and B. Hillebrands, Magnon transistor for all-magnon data processing, *Nat. Commun.* **5**, 4700 (2014).
- [24] Q. Wang, P. Pirro, R. Verba, A. Slavin, B. Hillebrands, and A. V. Chumak, Reconfigurable nanoscale spin-wave directional coupler, *Sci. Adv.* **4**, e1701517 (2018).
- [25] M. P. Kostylev, A. A. Serga, T. Schneider, B. Leven, and B. Hillebrands, Spin-wave logical gates, *Appl. Phys. Lett.* **87**, 153501 (2005).
- [26] A. V. Chumak *et al.*, Advances in magnetics roadmap on spin-wave computing, *IEEE Trans. Magn.* **58**, 1 (2022).
- [27] A. P. Papp, W. Porod, and G. Csaba, Nanoscale neural network using non-linear spin-wave interference, *Nat. Commun.* **12**, 6422 (2021).
- [28] H. Y. Yuan, Y. Cao, A. Kamra, R. A. Duine, and P. Yan, Quantum magnonics: When magnon spintronics meets quantum information science, *Phys. Rep.* **965**, 1 (2022).
- [29] S. N. Andrianov and S. A. Moiseev, Magnon qubit and quantum computing on magnon Bose-Einstein condensates, *Phys. Rev. A* **90**, 042303 (2014).
- [30] M. Mohseni, V. I. Vasyuchka, V. S. L'vov, A. A. Serga, and B. Hillebrands, Classical analog of qubit logic based on a magnon Bose–Einstein condensate, *Commun. Phys.* **5**, 196 (2022).
- [31] P. Pirro, V. I. Vasyuchka, A. A. Serga, and B. Hillebrands, Advances in coherent magnonics, *Nat. Rev. Mater.* **6**, 1114 (2021).
- [32] T. Hioki, Y. Hashimoto, and E. Saitoh, Coherent oscillation between phonons and magnons, *Commun. Phys.* **5**, 115 (2022).
- [33] Y. Kunz, M. Küß, M. Schneider, M. Geilen, P. Pirro, M. Albrecht, and M. Weiler, Coherent surface acoustic wave–spin wave interactions detected by micro-focused Brillouin light scattering spectroscopy, *Appl. Phys. Lett.* **124**, 152403 (2024).
- [34] J.-Y. Duquesne, P. Rovillain, C. Hepburn, M. Eddrief, P. Atkinson, A. Anane, R. Ranchal, and M. Marangolo, Surface-acoustic-wave induced ferromagnetic resonance in Fe thin films and magnetic field sensing, *Phys. Rev. Appl.* **12**, 024042 (2019).
- [35] T. R. Long, Magnetoelastic sensitivity and composition of permalloy films, *J. Appl. Phys.* **37**, 1470 (1966).
- [36] K. Kobayashi, N. Inaba, N. Fujita, Y. Sudo, T. Tanaka, M. Ohtake, M. Futamoto, and F. Kirino, Damping constants for permalloy single-crystal thin films, *IEEE Trans. Magn.* **45**, 2541 (2009).
- [37] J. Walowski, M. D. Kaufmann, B. Lenk, C. Hamann, J. McCord, and M. Münzenberg, Intrinsic and non-local Gilbert damping in polycrystalline nickel studied by ti:sapphire laser fs spectroscopy, *J. Phys. D Appl. Phys.* **41**, 164016 (2008).
- [38] K. Gilmore, M. D. Stiles, J. Seib, D. Steiauf, and M. Fähnle, Anisotropic damping of the magnetization dynamics in Ni, Co, and Fe, *Phys. Rev. B* **81**, 174414 (2010).

- [39] S. Geller and M. A. Gilleo, Structure and ferrimagnetism of yttrium and rare-earth-iron garnets, *Acta Crystallogr.* **10**, 239 (1957).
- [40] V. Cherepanov, I. Kolokolov, and V. L'vov, The saga of YIG: Spectra, thermodynamics, interaction and relaxation of magnons in a complex magnet, *Phys. Rep.* **229**, 81 (1993).
- [41] T. Wong, J. Park, K. Hayashi, M. J. Gross, R. Kim, X. Wang, S. E. Lofland, N. D. Orloff, D. B. Gopman, S. Lee, P. A. Crowell, C. A. Ross, and I. Takeuchi, Acoustically driven ferromagnetic resonance in YIG thin films, *Appl. Phys. Lett.* **125**, 052402 (2024).
- [42] R. Torráo, O. Alves, B. Archanjo, L. Sampaio, and F. Garcia, Reproducible low Gilbert damping yttrium iron garnet by magnetron sputtering, *J. Alloys Compd.* **923**, 166300 (2022).
- [43] J. Ding, T. Liu, H. Chang, and M. Wu, Sputtering growth of low-damping yttrium-iron-garnet thin films, *IEEE Magn. Lett.* **11**, 1 (2020).
- [44] M. C. Onbasli, A. Kehlberger, D. H. Kim, G. Jakob, M. Kläui, A. V. Chumak, B. Hillebrands, and C. A. Ross, Pulsed laser deposition of epitaxial yttrium iron garnet films with low Gilbert damping and bulk-like magnetization, *APL Mater.* **2**, 106102 (2014).
- [45] S. G. Alekseev, S. E. Dizhur, N. I. Polzikova, V. A. Luzanov, A. O. Raevskiy, A. P. Orlov, V. A. Kotov, and S. A. Nikitov, Magnons parametric pumping in bulk acoustic waves resonator, *Appl. Phys. Lett.* **117**, 072408 (2020).
- [46] M. F. Lewis and E. Patterson, Acoustic-surface-wave isolator, *Appl. Phys. Lett.* **20**, 276 (1972).
- [47] R. Inaba and N. Mikoshiba, Parametric amplification of surface acoustic wave of ZnO-Ga-doped yttrium iron garnet, *Appl. Phys. Lett.* **41**, 25 (1982).
- [48] F. W. Voltmer, R. M. White, and C. W. Turner, Magnetostrictive generation of surface elastic waves, *Appl. Phys. Lett.* **15**, 153 (1969).
- [49] F. Ryburn, K. Künstle, Y. Zhang, Y. Kunz, T. Reimann, M. Lindner, C. Dubs, J. F. Gregg, and M. Weiler, Generation of gigahertz-frequency surface acoustic waves in $\text{Y}_3\text{Fe}_5\text{O}_{12}/\text{ZnO}$ heterostructures, *Phys. Rev. Appl.* **23**, 034062 (2025).
- [50] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/97kd-ysh6> for details on the definition of the surface acoustic wave composition regarding the strain components and the fitting procedure used for the magnetoelastic coupling symmetry as a function of the externally applied magnetic field magnitude and orientation.
- [51] C. Dubs, O. Surzhenko, R. Linke, A. Danilewsky, U. Brückner, and J. Dellith, Sub-micrometer yttrium iron garnet LPE films with low ferromagnetic resonance losses, *J. Phys. D Appl. Phys.* **50**, 204005 (2017).
- [52] Z. Chen and D. Lewis, in *2024 18th European Conference on Antennas and Propagation (EuCAP)* (IEEE, Glasgow, UK, 2024), p. 1.
- [53] T. An, V. I. Vasyuchka, K. Uchida, A. V. Chumak, K. Yamaguchi, K. Harii, J. Ohe, M. B. Jungfleisch, Y. Kajiwara, H. Adachi, B. Hillebrands, S. Maekawa, and E. Saitoh, Unidirectional spin-wave heat conveyer, *Nat. Mater.* **12**, 549 (2013).
- [54] K. Yamamoto, M. Xu, J. Puebla, Y. Otani, and S. Maekawa, Interaction between surface acoustic waves and spin waves in a ferromagnetic thin film, *J. Magn. Magn. Mater.* **545**, 168672 (2022).
- [55] J.D.N. Cheeke, *Fundamentals and Applications of Ultrasonic Waves* (CRC Press, Boca Raton, FL, 2002), 1st ed.
- [56] A. Will-Cole, X. Du, B. Luo, V. Lauter, A. Grutter, L. Hackett, M. Miller, Y. Deng, B. Smith, O. Pitcl, N. X. Sun, R. H. Olsson, and M. Eichenfield, Chiral microwave non-reciprocity demonstrated via Rayleigh and Sezawa modes supported in an $\text{Al}_{0.58}\text{Sc}_{0.42}\text{N}/4\text{H-SiC}$ platform, *Phys. Rev. Appl.* **23**, 034058 (2025).
- [57] M. Küß, M. Heigl, L. Flacke, A. Hefele, A. Hörner, M. Weiler, M. Albrecht, and A. Wixforth, Symmetry of the magnetoelastic interaction of Rayleigh and shear horizontal magnetoacoustic waves in nickel thin films on LiTaO_3 , *Phys. Rev. Appl.* **15**, 034046 (2021).
- [58] L. Dreher, M. Weiler, M. Pernpeintner, H. Huebl, R. Gross, M. Brandt, and S. Goennenwein, Surface acoustic wave-driven ferromagnetic resonance in nickel thin films: Theory and experiment, *Phys. Rev. B Condens. Matter* **86**, 5 (2012).
- [59] B. A. Kalinikos and A. N. Slavin, Theory of dipole-exchange spin wave spectrum for ferromagnetic films with mixed exchange boundary conditions, *J. Phys. C: Solid State Phys.* **19**, 7013 (1986).
- [60] R. Comstock, Magnetoelastic coupling constants of the ferrites and garnets, *Proc. IEEE* **53**, 1508 (1965).
- [61] G. W. Farnell and E. Adler, *Physical Acoustics* (Academic Press, New York City, NY, 1972), Vol. 9, p. 35.
- [62] D. P. Morgan, *Surface-Wave Devices for Signal Processing* (Elsevier, Amsterdam, Netherlands, 1985), Vol. 19.
- [63] <https://doi.org/10.5281/zenodo.15019898>.
- [64] T. Kobayashi, R. C. Barker, J. L. Bleustein, and A. Yelon, Ferromagnetoelastic resonance in thin films. I. Formal treatment, *Phys. Rev. B* **7**, 3273 (1973).
- [65] S. Lee, S. Grudichak, J. Sklenar, C. C. Tsai, M. Jang, Q. Yang, H. Zhang, and J. B. Ketterson, Ferromagnetic resonance of a YIG film in the low frequency regime, *J. Appl. Phys.* **120**, 033905 (2016).
- [66] S. Rezende, *Fundamentals of Magnonics* (Springer, Cham, Switzerland, 2020).
- [67] H. Suhl, Ferromagnetic resonance in nickel ferrite between one and two kilomegacycles, *Phys. Rev.* **97**, 555 (1955).
- [68] J. Smit and G. Beljers, Ferromagnetic resonance absorption in $\text{BaFe}_{12}\text{O}_{19}$, a highly anisotropic crystal, *Philips Res. Rep.* **10**, 113 (1955).
- [69] H. Iwanaga, A. Kunishige, and S. Takeuchi, Anisotropic thermal expansion in wurtzite-type crystals, *J. Mater. Sci.* **35**, 2451 (2000).
- [70] H. Maier-Flaig, S. T. B. Goennenwein, R. Ohshima, M. Shiraishi, R. Gross, H. Huebl, and M. Weiler, Note: Derivative divide, a method for the analysis of broadband ferromagnetic resonance in the frequency domain, *Rev. Sci. Instrum.* **89**, 076101 (2018).