Wide-Band Nonreciprocity of Surface Acoustic Waves Induced by Magnetoelastic Coupling with a Synthetic Antiferromagnet

Roman Verba, Vasil Tiberkevich, and Andrei Slavin
Phys. Rev. Applied 12, 054061 — Published 26 November 2019
DOI: 10.1103/PhysRevApplied.12.054061
Wide-band nonreciprocity of surface acoustic waves induced by magnetoelastic coupling with a synthetic antiferromagnet

Roman Verba,1,∗ Vasil Tiberkevich,2 and Andrei Slavin2

1Institute of Magnetism, Kyiv 03142, Ukraine
2Department of Physics, Oakland University, Rochester, MI 48309, USA
(Dated: October 1, 2019)

Nonreciprocal propagation of acoustic waves is often achieved by magnetoelastic coupling with spin waves (SW), and is limited to a narrow magnetoelastic gap (∼10 – 100 MHz) near the crossing point of the acoustic and SW dispersions. We propose a different method to achieve a giant frequency band of the surface acoustic wave (SAW) nonreciprocity in an artificial structure, where a nonmagnetic acoustic crystal is magnetoelastically coupled to a synthetic antiferromagnet – a pair of thin ferromagnetic layers whose static magnetizations are held opposite by RKKY interaction. Strongly nonreciprocal, and, approximately, linear dispersion of SW in this system makes it possible to match dispersions of SAW and SW in a wide frequency band for one direction of the wave propagation. Example calculations performed for the LiNbO3/Co/Ru/Co structure confirm the giant nonreciprocity of the SAW propagation in a frequency band exceeding 6 GHz.

I. INTRODUCTION

Wave nonreciprocity – the dependence of the wave propagation characteristics (dispersion and/or damping rate) on the reversal of the propagation direction – is a fascinating fundamental phenomenon, being, also, of a great practical interest for the development of isolators and circulators. The existence of the wave nonreciprocity requires a simultaneous breaking of the time- and space-reversal symmetries [1–3], which is difficult to realize in both natural and artificial materials. In particular, the symmetry of fundamental laws of mechanics prohibits the nonreciprocity of pure acoustic waves (AW) in unmoving media. Nonreciprocal propagation of AWs can be realized in the presence of moving or rotating media [4, 5], or utilizing time-reversal-breaking nonlinear effects [6–8], which all have severe limitations for practical applications. Wave propagation in diffractive media could also appear as unidirectional [9], but, in fact, is neither nonreciprocal, nor is it useful for applications [10].

Alternatively, nonreciprocal propagation of AWs can be induced by interaction with other subsystems of a medium [11]. Usually, one considers magnetoelastic interaction with a magnetic subsystem of a ferromagnetic crystal as a source of acoustic nonreciprocity [12–14]. Indeed, the time-reversal symmetry of the magnetic moment motion is inherently broken – its natural precession is always right-handed. The lack of inversion symmetry in magnetic crystals [15, 16] or in artificial structures [17–19] allows one to realize the nonreciprocity of spin excitations – spin waves (SW) – in many different cases.

Schematic illustration of the nonreciprocal propagation of AWs, induced by magnetoelastic coupling with SWs, is given by Fig. 1. In the simplest and most well-studied case (Fig. 1(a)), the acoustic and spin waves themselves (i.e., without magnetoelastic coupling) are

![Figure 1](image-url)

FIG. 1. Illustration of methods of inducing nonreciprocity of acoustic wave (AW) by magnetoelastic coupling with spin wave (SW): left column – spectra of AW and SW, inset in (a) shows the opening of the magnetoelastic gap of the size \( \Delta f \); right column – AW transmission rates in opposite directions (schematically). Here frames (a) and (b) show the narrow-band nonreciprocity with coinciding and frequency-separated hybridization bands, respectively, and the frame (c) illustrates the method of creation of wide-band nonreciprocity proposed in current work.

reciprocal, and both the wave dispersion and propagation losses are the same for opposite propagation directions. In the vicinity of the crossing points of the AW and SW dispersion characteristics, magnetoelastic interaction leads to the coupling between these waves, and to the opening of the magnetoelastic gaps (effect of wave hybridization or “avoided crossing”). The main experimental manifestation of this coupling is the increased damp-
ing (decreased transmission rate) of AW near the gaps, which is caused by the magnetic losses, that are, usually, much larger than the acoustic ones. Since the size of the magnetoelastic gap depends on the vector structure of the interacting wave, the gaps for opposite wave vectors ±k may be different. Consequently, the AW propagation losses at a given frequency become also different for opposite propagation directions, being, however, large in both directions (so that the relative difference in losses, typically, is rather small) [14]. This simple scheme was previously studied in ferromagnetic single crystals [12, 13] and artificial structures [14].

An alternative method of inducing the AW nonreciprocity was proposed in [20]. In this case the SWs have inherently nonreciprocal spectrum (e.g., due to Dzyaloshinskii-Moriya interaction), which results in the frequency separation of magnetoelastic gaps for opposite propagation direction (Fig. 1(b)). Thus, the high-damping (low transmission) bands are also separated in frequency, which allows one to substantially decrease the insertion losses of a nonreciprocal device in one of the opposite propagation directions.

It should be noted that in both the above describes schemes the nonreciprocal propagation of AW is limited to a frequency range of the order of the magnetoelastic hybridization gap Δf near the crossing points of the dispersion characteristics, which, typically, does not exceed 10-100 MHz [20]. It creates certain limitations for practical applications, such as limited operation band and the necessity to fabricate different structures for different frequency ranges (or their fine tuning by an external magnetic field). In addition, if the magnetoelastic gaps are smaller than the SW linewidth and/or the frequency band of transducers for the AW excitation and reception (that is a common case for many magnetic and acoustic systems), the full potential of the AW nonreciprocity induced by the magnetoelastic interaction cannot be realized [20].

II. PRINCIPLE OF WIDE-BAND NONRECIPROCITY OF ACOUSTIC WAVES

In this work we propose a fundamentally new method to realize wide-frequency-band AW-SW nonreciprocity. It is based on an artificial material, in which the nonreciprocal properties of AW (specifically, surface acoustic wave (SAW)) exist in a much wider frequency range which can exceed several GHz, and, therefore, covers the full band of the SAW applications. The main idea is illustrated in Fig. 1(c). Namely, we propose to couple SAW with SW, which is strongly nonreciprocal, and, for one direction of propagation, has a dispersion characteristic, that is similar to that of the SAW. In such a case the effective coupling between the SW and SAW takes place in a wide frequency region, where the SAW and SW dispersions are similar, instead of a relatively narrow AW-SW hybridization band near the dispersion crossing points, as in the previously used hybridized systems (see Fig. 1(a),(b)).

We consider the possibility of nonreciprocal propagation of surface acoustic waves (SAWs), which are the AWs that are used most often in modern signal processing techniques [21–23]. In addition, the localization of SAWs near the crystal surface makes them sensitive to the properties of thin films adjacent to the acoustic crystal, in particular, to ferromagnetic layers placed on the surface of a crystal [14, 24]. Nevertheless, the above described approach of induced AW-SW nonreciprocity could be used for AWs other than SAW (e.g., Lowe’s waves) by a proper choice of adjacent magnetic structure.

The spectrum of SAW is linear and gapless (see Fig. 2(d)), ω_{SAW} = c_{SAW}|k|, where c_{SAW} is the SAW velocity. Therefore, for the realization of the proposed approach of the wide-band nonreciprocity one needs to find ferromagnetic structure, in which the SW spectrum is nonreciprocal, gapless, and linear (at least, in a certain range of wavenumbers). The structure, which satisfies these requirements, is a synthetic antiferromagnet – a ferromagnetic bilayer with opposite directions of the static magnetization of layers, which can be stabilized by RKKY indirect exchange via a spacer of a proper thickness. The SW spectrum of a synthetic antiferromagnet consists of two branches having different phase relations between the magnetization precession in the layers (Fig. 2(c)), and a set of higher-frequency nonuniform thickness modes (not shown in Fig. 2(c)). Both SW branches are strongly nonreciprocal as long as the static magnetization of the layers lies in plane (or has a nonzero in-plane component) and SW propagates in-plane at a finite angle to the static magnetization, i.e. φ ≠ 0, π (see Fig. 2(a)) [25, 26]. In the ideal case of identical layers and zero external field, the lowest SW branch is gapless and, at sufficiently small values of the SW wavenumber k, has linear dispersion. These spectral properties of SWs in synthetic antiferromagnet are exactly the properties that are needed to match the spectral properties of SAWs.

III. CALCULATION OF WAVE SPECTRA AND PROPAGATION LOSSES

The layout of a structure, in which the above described nonreciprocal SWs can be efficiently coupled with SAW, is shown in Fig. 2(a). It consists of a nonmagnetic acoustic single crystal that supports propagation of SAW (e.g., LiNbO₃, LiTiO₃, etc.) and the adjacent thin synthetic antiferromagnet having magnetostrictive ferromagnetic layers. If the ferromagnetic layers are thin compared to the SAW localization depth (of the order of the SAW wavelength), their presence almost does not affect SAW mechanically. The strain, induced by SAW, freely penetrates into the magnetic layers, where it couples to SWs owing to the magnetostriction effect.

In all the calculations below we used the parameters of a Co/Ru/Co/LiNbO₃ structure with Co being in the fcc or bcc phase; notes on the material choice are presented
magnetizations of the ferromagnetic layers in the structure. Directions of the wave propagation, bias field and

FIG. 2. Frame (a) shows a layout of the proposed artificial structure. Directions of the wave propagation, bias field and magnetizations of the ferromagnetic layers in the x-y plane are shown in (b). Frame (c) shows the SW spectra of the synthetic antiferromagnet in the case of identical layers in zero bias field (Co(15)/Ru(0.9)/Co(15), thicknesses in nm) for different SW propagation directions. Frame (d) shows dispersion of the lowest SW branch at φ = 36° in the ideal case of identical magnetic layers in zero bias field (dashed line) and in the case of slightly different magnetic layers (Co(16)/Ru(0.9)/Co(15)) in B_e = 1 mT bias field. The green line shows the spectrum of SAW in LiNbO_3. Details of the spectral calculation are presented in the Appendix.

below (Sec. IV). Namely, we used the following parameters: saturation magnetization of Co_0M_s = 1.76 T, gyromagnetic ratio γ = 2π × 29 GHz/T [27], exchange stiffness A_{ex} = 2.5 × 10^{-11} J/m [28], Gilbert damping constant α_G = 0.006 [29]. The thickness of the Ru spacer, which corresponds to a local maximum of the RKKY antiferromagnetic exchange, was chosen to be t_e = 0.9 nm. The corresponding constant of the antiferromagnetic interlayer exchange was J = 0.8 mJ/m^2 [30]. The magnetoelastic coupling constants of Co were B_1 = −9.2 MJ/m^3, B_2 = 7.7 MJ/m^3 [31, 32]. The parameters of LiNbO_3 were: Y-cut, Z-propagation axis of SAW, density ρ = 4650 kg/m^3, longitudinal and transversal sound velocities were c_L = 7350 m/s and c_T = 3600 m/s [33], and the corresponding SAW velocity was c_{SAW} = 3361 m/s.

SW dispersion in a synthetic antiferromagnet was considered in [25, 26]. In the case of identical ferromagnetic layers and zero external bias field, the long-wave (small k) approximation of the lowest SW branch yields the following dispersion relation:

\[ \omega_k = \omega_M t_{FM} \left[ \sqrt{\frac{\lambda^2}{t_{FM}} + 1} \frac{\sin^2 \phi}{3} + \frac{1}{2} \sin \phi \text{sign} k \right] |k|, \]

where \( \omega_M = \gamma \mu_0 M_s \), \( M_s \) is the saturation magnetization, \( t_{FM} = t_1 + t_2 \) is the thickness of the ferromagnetic layers, and \( \lambda \) is the exchange length. It is clear, that this dispersion is gapless, \( \omega_0 = 0 \), which reflects the continuous rotational symmetry in the layers’ plane. The SW spectrum is, also, linear, \( \omega_k = c_o |k| \), with the velocity \( c_o \) dependent on the angle \( \phi \) of SW propagation relative to the static magnetization. Finally, the SW spectrum is nonreciprocal, \( \omega_k \neq \omega_{-k} \) (except for \( \phi = 0 \)). The angular dependence of the SW velocity \( c_o \) greatly simplifies the design of the artificial structure, as it allows one to easily match the group velocities of SW and SAW, \( c_o \approx c_{SAW} \), by the selection of a proper propagation angle \( \phi \) (see below). The linearity of the SW dispersion holds up until \( |k| \ll 1/h, 1/\lambda \). At higher wavenumbers the SW dispersion deviates from the linear law, as shown in Fig. 2(d).

In practice, one cannot use this idealized case, since the continuous degeneracy of the magnetic state does not allow one to fix the angle between the \( k \) and \( M \) – it will fluctuate under thermal noise. A possible solution is to use slightly different ferromagnetic layers (in saturation magnetization \( M_1 \) and/or in thickness \( t_1 \)), and apply a weak in-plane magnetic field \( B_e \). If the bias field does not exceed the critical value \( |B_e| < J [(M_2 t_2)^{-1} - (M_1 t_1)^{-1}] \) (see Appendix), where \( J \) is the constant of the interlayer antiferromagnetic exchange (RKKY), the antiferromagnetic state remains stable, and magnetizations of the layer align with the direction of the bias field \( B_e \), so that the net magnetic moment of the bilayer is parallel to \( B_e \). Alternatively, one can utilize a weak in-plane anisotropy caused by the crystal structure of the ferromagnetic material or by the sample shape (see notes on the acceptable anisotropy values in Sec. IV). This in-plane anisotropy would create the same stabilizing effect, as the in-plane bias magnetic field. The presence of weak magnetic field or anisotropy does not drastically change the SW spectrum. It leads to the appearance of a small spectral gap, \( \omega_0 > 0 \), but, apart from a small region near \( k = 0 \), the SW spectrum still follows the linear law (see Fig. 2(d)).

The coupling between the SW and SAW was calculated using the perturbation approach developed in [20]. The coupling coefficient is equal to:

\[ \kappa_k = \frac{2 \cos \phi}{\sqrt{A_k Q_k}} \int \mu(z) [B_1 u_{xz} m_{1y}, \sin \phi + B_2 u_{xx} m_{2y}^*] dz. \]

(2)

Here \( \mu(z) \) defines the direction of static magnetization of the layers relative to the direction of the bias field (i.e., \( \mu = 1 \) within the upper (thicker) layer and \( \mu = -1 \) within the lower layer, otherwise \( \mu = 0 \)), \( m_{1y}(z) \) and \( m_{2y}(z) \) are the in-plane and out-of-plane components of the dynamic magnetization in the SW mode, \( u(z) \) is the strain tensor of the SAW, \( B_1, B_2 \) are the coefficients of magnetoelastic
coupling tensor. Finally, $A_k$ and $Q_k$ are the normalization constants of SW and SAW (see Appendix).

In the vicinity of the surface, the components of the SAW strain tensor satisfy the condition $|u_{zz}| \ll |u_{xx}|$, so that the coupling strength is mainly determined by the first term in the brackets, which is proportional to $\sin(2\phi)\mu(z)m_{IP}(z)$. For the lowest SW mode the in-plane components of the dynamic magnetization in the layers are in opposite phases, $m_{IP,1} = -m_{IP,2}$ (see Fig. 2(c)). Since $\mu_1 = -\mu_2$, it is clear that the contributions from the both layers have the same sign and enhance each other. Thus, both layers can be made from the same ferromagnetic material, i.e., have the same magnetostriction. In contrast, for the coupling of SAW to the higher SW mode, synthetic antiferromagnet should be asymmetric in magnetostriction, e.g., one layer should not be magnetostrictive at all.

The magnetoelastic coupling between SW and SAW is maximum at the magnetization angle $\phi \approx 45^\circ$ for a fixed layer thickness, as it is common for interaction of SAW with thin ferromagnetic layers [14, 24]. Also, the coupling is, expectedly, proportional to the thickness $t_i$ of the layers (at a given $\phi$), as with the increase of $t_i$ the overlapping volume of the SW and SAW is increased. If the layer thickness increases, the match of the SW and SAW dispersion happens at a smaller angle $\phi_i$, because the SW velocity $c_{SW}$ is proportional to the layer thickness.

In general, the increase of the layer thickness with simultaneous decrease of the angle $\phi$ (to satisfy the matching condition $c_{\phi} \approx c_{SAW}$) leads to a small increase of the coupling strength. However, one should be aware that large thickness of the ferromagnetic layers reduces the range of linearity of the SW dispersion, which extends until $kt_i \ll 1$. Thus, the optimal thickness of ferromagnetic layers is determined by an interplay of the desirable strength of nonreciprocity (proportional to the coupling) and the size of the nonreciprocal frequency band (range of linearity of the SW dispersion), and will be different for different possible applications.

In Fig. 3 we present the calculated characteristics of the Co(16)/Ru(0.9)/Co(15)/LiNbO$_3$ artificial structure. For this structure the match of the SW and SAW dispersion characteristics takes place at the angle $\phi = 36^\circ$. It is clear from Fig. 3(a), that the distance between the SW and SAW frequencies in the positive propagation direction ($k_z > 0$) is smaller than, or comparable to the coupling rate $\kappa$ in a wide range of the wave numbers, meaning strong influence of the magnetic layers on the SAW propagation inside all this frequency range. In contrast, for the negative propagation direction the frequency distance between SW and SAW dispersion branches is much larger than the coupling, and the SW and SAW propagate almost independently from each other.

The magnetoelastic coupling between the SAW and SW leads to the formation of hybrid magnetoelastic waves. Their frequencies $\omega_{1,2}$ and damping rates $\Gamma_{1,2}$ are determined by standard relation for coupled waves, namely

$$\omega_{1,2} - i\Gamma_{1,2} = \frac{\omega_{SW} - i\Gamma_{SW} + \omega_{SAW} - i\Gamma_{SAW}}{2} \pm \sqrt{\left(\frac{(\omega_{SW} - i\Gamma_{SW}) - (\omega_{SAW} - i\Gamma_{SAW})}{2}\right)^2 + |\kappa k|^2},$$

(3)

As it was pointed out earlier, the coupling significantly affects the damping rates of the SAW, since a part of the energy of a magnetoelastic wave is dissipated in the magnetic subsystem. This effect is evident from Fig. 3(b), as for a positive propagation direction the damping rate $\Gamma_1$ of the coupled wave drastically increases in comparison to the damping rate of a pure SAW. In the negative propagation direction, for which the spectra of the pure SW and SAW are well-separated, $\Gamma_1$ is much smaller than for the positive propagation direction, and much faster approaches $\Gamma_{SAW}$.

Transmission losses in a SAW transmission line with synthetic antiferromagnet are mainly determined by the coupled magnetoelastic wave with lower damping rate $\Gamma_1$, since the second coupled wave having much larger damping rate $\Gamma_2$ decays completely (below the thermal level) at the length of a typical SAW line. In our artificial material, the variation of the damping rate $\Gamma_1$ with the wave number is much smaller than the width of the excitation spectrum of a typical interdigital SAW transducer. This allows one to get rid of the nonresonant excitation, and to realize the full potential of the SAW nonreciprocity, induced by the magnetoelastic coupling, which is impossible to achieve in other schemes (Fig. 1(a,b)). The propagation losses can be estimated simply as $L = 10 \log(\Gamma_1/\nu)$, where $\nu \approx c_{SAW}$ is the group velocity of the coupled wave and $l$ is the length of the SAW transmission line. As it is clear from Fig. 3(c), the propagation losses are significantly nonreciprocal in a giant frequency band. They differ by more than one order of magnitude for opposite propagation directions in the frequency range of 6.1 GHz (from 0.6 to 6.6 GHz). This giant frequency band of the SAW nonreciprocity is almost 100 times wider than the nonreciprocity regions of that can be obtained using using the traditional methods with point-like spectral crossing. It is important to note, that this giant frequency band of the SAW nonreciprocity covers almost all the range of the possible SAW applications in the microwave signal processing [21].

It is important to note, that the effect of the wide-band SAW nonreciprocity is quite robust respective to the angle $\phi$ between the static magnetization and the wave propagation direction, and perfect alignment of the magnetization direction in not necessary for the experimental observation and utilization of the effect. For example, decrease of the angle $\phi$ in 5 degrees result in the reduction of highly nonreciprocal frequency range (highlighted in Fig. 3) to 4.5 GHz. Moreover, moderate increase of this angle does not lead to a reduction of the nonreciprocity range, but only to a more complex depen-
mechanically. The SAW velocity in LiNbO

\[
\text{d} = \frac{\Delta f}{2\pi c_{\text{SAW}}}
\]

to not significantly affect the SAW propagation me-

\[
\text{and SW (} \Gamma_{\text{SW}} \text{) and SAW (} \Gamma_{\text{SAW}} \text{). Frame (c) shows the frequency dependence of the propagation losses of SAW, coupled to SW, in opposite propagation directions. The yellow shaded area in all panels shows the same region, where the propagation losses for the opposite propagation directions differ by ten times and more. The calculations were made for Co(16)/Ru(0.9)/Co(15)/LiNbO}_3, B_e = 1 \text{ mT}, \phi = 36^\circ.
\]

\[
\text{IV. NOTES ON THE MATERIAL CHOICE}
\]

In this section we briefly discuss the requirements for the ferromagnetic material in the synthetic antiferromagnet multilayer, which should be satisfied for the realization of wide-band nonreciprocity of SAW. Naturally, usual for magnetoelastic devices requirements of a high magnetostriction and sufficiently low magnetic damping (if the magnetic damping significantly exceeds the magnetoelastic coupling \( \kappa \)), the SAW and SW become effectively uncoupled \([20]\) hold in our case too. Specific requirements follow from Eqs. (1, 2). The SW group velocity is proportional to the saturation magnetization and the layer thickness. It is clear that the maximal value of the group velocity, which is realized at \( \phi = 90^\circ \), should be larger than the SAW velocity, maintaining, simultaneously, a reasonably small bilayer thickness in order to not significantly affect the SAW propagation mechanically. The SAW velocity in LiNbO_3 is quite high, \( c_{\text{SAW}} = 3361 \text{ m/s} \), so the saturation magnetization of the ferromagnetic should be sufficiently high too. In particular, nickel, which is commonly used as a magnetostrictive material, is not a good choice in combination with LiNbO_3 due to its relatively low static magnetization \( M_s \). If Ni is used as a ferromagnetic material, the thicknesses of the ferromagnetic layers should exceed 40 nm each to match the SAW dispersion. Instead, Co, Fe, or CoFe alloys are suitable magnetic materials in combination with LiNbO_3. Usage of acoustic crystals having slower SAW increases the variety of acceptable ferromagnetic materials.

Another important requirement concerns the anisotropy of ferromagnetic layers. It is desirable to have vanishing anisotropy in the layers plane. The presence of anisotropy sufficiently increases the SW spectrum gap (frequency at \( k = 0 \)), and it becomes impossible to match SW and SAW dispersions at low frequencies. The sensitivity of the SW spectrum gap to anisotropy field is much higher than to the external field, since the anisotropy has the same effect in both layers (increasing of frequency), while external field acts oppositely. For example, in-plane anisotropy of 2 mT in the studied structure increases the SW spectrum gap to \( \omega_0 = 1.7 \text{ GHz} \) and reduce the range, where SAW propagation losses differ at least in ten times (shown in Fig. 3), from 6.1 GHz to 4 GHz (the range 3.3 – 7.3 GHz). The in-plane anisotropy of 5 mT and more leads to a standard dispersion crossing (shown exemplary in Fig. 1(b)) instead of the dispersion matching, necessary for the wide-band nonreciprocity. Thus, if one uses in-plane anisotropy for the stabilization of magnetization state instead of external field, the anisotropy should be really weak, characterizing by effective anisotropy field below 1 mT. Simultaneously, perpendicular magnetic anisotropy does not have such a critical impact. It simply reduces the SW group velocity; roughly this reduction can be estimated by the substitution \( \omega_M \rightarrow (\omega_M - 2\gamma K / M_s) \), where \( K \) is the constant of the perpendicular anisotropy.

If it is impossible to get rid of a relatively high in-plane anisotropy in fabrication process, its undesirable effect can be eliminated by the simultaneous application of a sufficient in-plane magnetic field. Indeed, a sufficient bias field results in the instability of the antiferromagnetic state, and the in-plane anisotropy simply increases this critical value compared to the isotropic case (Eq. (A10)). Near this point the SW spectrum gap is vanishingly small and SW spectrum can approximately fit the SAW dispersion, although it becomes more complex than the linear spectrum in the isotropic case (Eq. (1)).

\[
\text{V. CONCLUSIONS}
\]

In summary, we demonstrated a way to realize nonreciprocal propagation of SAW in a giant frequency band...
by coupling of SAW to the SWs in a synthetic antiferromagnet having magnetostrictive ferromagnetic layers. In the proposed approach the SW spectrum is nonreciprocal, and is similar to the SAW spectrum: it has a small spectral gap, and is approximately linear in a wide frequency range. These features lead to the coalescence of the SW and SAW spectra for one propagation direction, making magnetoelastic interaction between these waves very efficient in a wide frequency band, which could exceed several GHz. This efficient magnetoelastic interaction leads to the increased losses of SAW due to the energy dissipation in the magnetic subsystem. The calculations lead to the increased losses of SAW due to the magnetostatic interaction between these waves and is similar to the SAW spectrum: it has a small nonreciprocity of the SAW propagation losses in the frequency band exceeding 6 GHz. We believe, that our results open a way for the development of a new generation of wide-band nonreciprocal SAW devices.

ACKNOWLEDGEMENTS

This work was supported in part by the U.S. National Science Foundation (grants No. EFMA-1641989 and No. ECCS-1708982), by the Oakland University Foundation, and by the Ministry of Education and Sciences of Ukraine (project 0118U004007).

APPENDIX – CALCULATION OF SPIN-WAVE SPECTRUM OF SYNTHETIC ANTIFERROMAGNET

The spectrum and spatial profile of spin waves (SWs) in a synthetic antiferromagnet can be found, as usual, by solving the linearized Landau-Lifshitz equation [26, 34]:

\[-i\omega k m_{k,i} = \sum_{j=1,2} \mu_j \times \tilde{\Omega}_{ij} \cdot m_{j,k}.\]  

(A1)

Here \(\omega_k\) is the SW frequency, \(k = k_z\) is the SW wave vector, assumed to be aligned with the x-axis (see Fig. 2a in the main text), \(\mu_1 = -\mu_2 = \cos \phi e_x + \sin \phi e_y\) are the unit vectors of the static magnetizations in the ferromagnetic layers forming a synthetic antiferromagnet, \(m_i = -m_{1p,i} \sin \phi e_x + m_{1p,i} \cos \phi e_y + m_s e_z, i\) are the distributions of the dynamic magnetization (SW profile), and the index \(i = 1, 2\) denotes ferromagnetic layers. The operator \(\tilde{\Omega}\) is defined as:

\[\tilde{\Omega}_{ij} = (\omega_{H,i} + \omega_M \lambda^2 \left( k^2 - \frac{d^2}{dz^2} \right)) I \Delta_{ij},\]  

(A2)

where \(\omega_{H,(1,2)} = \pm \gamma B_e\) is proportional to the static internal magnetic field \(B_e\) in the layers, \(\omega_M = \gamma \mu_0 M_s\), \(\lambda\) is the exchange length of the ferromagnetic material, \(\Delta_{ij}\) is the Kronecker’s delta, \(I\) is the unit matrix. The kernel \(G_k\) of the integral in (A2) is the magnetostatic Green’s function for a ferromagnetic film [34]:

\[G_k = \begin{pmatrix} G_{xx} & G_{xz} \\ 0 & 0 \\ G_{xz} & \delta(z - z') - G_{xx} \end{pmatrix},\]  

(A3)

where \(G_{xx} = (|k|/2) \exp[-|k(z - z')|], G_{xz} = (ik \text{sign}[z - z']/2) \exp[-|k(z - z')|].\)

Equation (A1), containing the exchange differential operator of the second order, should be accompanied by the corresponding boundary conditions for the dynamic magnetization. At the outer surfaces of the ferromagnetic layers \(z_i^{(o)}\) these conditions are:

\[\pm \frac{d m_i}{dz} - d_z m_s e_z \bigg|_{z_i^{(o)}} = 0,\]  

(A4)

while at the inner surfaces \(z_i^{(i)}\) these conditions have the form:

\[\pm \frac{d m_i}{dz} - d_z m_s e_z \bigg|_{z_i^{(i)}} - \frac{J}{\mu_0 M_s^2} \left( m_i |z_i^{(i)} - m_j |z_j^{(i)} \right) = 0.\]  

(A5)

The + and − signs in the boundary conditions correspond to the upper and lower surfaces of the ferromagnetic layers, \(d_z = K_s/(2\mu_0 M_s^2)\) is the standard pinning parameter determined by the surface anisotropy \(K_s\), while \(J\) is the constant of the antiferromagnetic RKKY coupling. All the SW spectra presented in the main text were calculated as a numerical solution of Eq. (A1). The SW norm \(A_k\) is calculated using numerical SW profiles as

\[A_k = i \frac{M_s}{\gamma} \int m_k^* \cdot \mu(z) \times m_k \, dz.\]  

(A6)

The normalization constant \(Q_k\) of SAW, mentioned in Eq. (2), is equal to [20]

\[Q_k = 2\omega_k \rho \int \xi_k^*(z) \cdot \xi_k(z) \, dz,\]  

(A7)

where \(\xi(z)\) and \(\tilde{u}(z)\) are the profile (displacement) and strain tensor of SAW [35], and \(\rho\) is the density of the acoustic crystal.

The analytical dispersion equation Eq. (1), obtained in the long-wave approximation and presented in the main text, was derived under the following assumptions: zero external bias field, antiferromagnetic coupling between the ferromagnetic layers is neglected, the ferromagnetic layers are identical, thin \((k t_s \ll 1)\), and have negligible surface anisotropy, so the thickness distribution of the dynamic magnetization in both layers is assumed to be uniform.

For the derivation of the condition of stability of the synthetic antiferromagnet under the applied external bias field we calculated the frequency of the lowest SW branch...
at $k=0$, which is the lowest frequency in all the SW spectrum. The only approximation in this calculation was the assumption of the uniform dynamic magnetization distribution along the layers thickness, which is valid for $k=0$ for thin layers and/or weak surface anisotropy. The calculated SW frequency at $k=0$ is equal to:

$$\omega_0^2 = \frac{\omega_{11}^2 + \omega_{22}^2}{2} - \omega_{11} \omega_{22} - \left[ (\omega_{11}^2 - \omega_{22}^2)^2 / 4 + \omega_{11} \omega_{22} (\omega_{11} + \omega_{H1} - \omega_{H2}) (\omega_{M2} + \omega_{H2} - \omega_{H1}) \right]^{1/2},$$

(A8)

where $\omega_{11} = \omega_{H1} + \omega_{M1}$, $\omega_{H1} = \gamma B_c + \omega_{J1}$, $\omega_{H2} = -\gamma B_c + \omega_{J2}$, $\omega_{J1} = \gamma J/(M_s t_s)$. This frequency is real ($\omega_0^2 \geq 0$) if

$$\gamma B_c (\gamma B_c + \omega_{J1} - \omega_{J2}) \leq 0,$$

(A9)

which constitutes the condition of stability of the antiferromagnetic state. In other words, for the antiferromagnetic state to be stable the external field should be smaller than:

$$|B_c| \leq J \left| \frac{1}{M_s t_2} - \frac{1}{M_s t_1} \right|,$$

(A10)

and the magnetization direction of the layer with a larger total magnetic moment ($\sim M_s t_i$) should be aligned parallel to the bias field direction. This condition is presented explicitly in the main text.

[10] In [9] wave propagation in forward direction is accompanied by the transformation of the wavefront. If the wave with this modified wavefront had not passed in the return direction, it would be a nonreciprocity. Instead, only wave with initial unmodified wavefront do not pass in reverse direction.


