Acoustic attenuation in magnetic insulator films: dynamical phase-field simulations

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Abstract

A magnon and a phonon are the quanta of spin wave and lattice wave, respectively, and they can hybridize into a magnon polaron when their frequencies and wavenumbers are equal. Guided by an analytically calculated magnon polaron dispersion, we perform dynamical phase-field simulations to investigate the effects of magnon polaron formation and magnetic damping on the attenuation of a bulk acoustic wave in a magnetic insulator film. It is found that a stronger magnon-phonon hybridization leads to a larger attenuation, whereas the largest attenuation occurs under an intermediate magnetic damping coefficient. The simulations also demonstrate a dynamic rotation of the acoustic wave polarization by almost 90° and a dynamic magnetic-field control of acoustic wave antennation, which have potential applications in nonreciprocal acoustic devices.

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I. Introduction

This article is concerned about the propagation and attenuation of an acoustic wave in a ferromagnetic film. Although the underlying theories are well-established (e.g., refs. [1–4]), time-domain simulations of the acoustic wave attenuation in ferromagnetic films have remained scarce (a brief survey of relevant computational works is provided in Section II). In particular, a quantitative understanding of how the coupled magnon-phonon dynamics influences the acoustic attenuation remains elusive. When an acoustic wave (its quanta is an acoustic phonon) propagates in a ferromagnetic crystal, it can excite a spin wave (its quanta is a magnon) via the magnetoelastic coupling [5]. At the same time, the spin precession will induce secondary acoustic waves due to the magnetostrictive stress [6–9]. To accurately predict the attenuation of a propagating acoustic wave in a ferromagnetic crystal, it is imperative to consider such coupled magnon-phonon dynamics, as well as the damping from both the lattice and spin subsystems. For example, let us consider a (001) yttrium iron garnet (Y₃Fe₅O₁₂, or YIG) film that has an equilibrium magnetization \( \mathbf{m}_0 \) along +z stabilized by a bias magnetic field \( \mathbf{H}^{\text{bias}} \) applied along the same direction. A continuous bulk acoustic wave \( \varepsilon_{xy}(z,t) \), which is generated by a piezoelectric transducer [8–10], propagates into the YIG film from its bottom surface (\( z = 0 \)), and an adjacent gadolinium gallium garnet (Gd₃Ga₅O₁₂, or GGG) substrate works as the sink of the acoustic wave, as shown in Fig. 1a. For an in-plane-magnetized (001) YIG film (\( \mathbf{m}_0 \) is within the \( xy \) plane), only a transverse acoustic wave such as \( \varepsilon_{xy}(z,t) \) and \( \varepsilon_{yz}(z,t) \) can rotate the local magnetization and excite a spin wave due to the symmetry of the magnetoelastic anisotropy field [11,12]. In particular, when the frequencies \( f \) and wavenumbers \( k \) of the injected acoustic phonons are equal to the \( f \) and \( k \) of the magnons, the acoustic attenuation is predicted to be the strongest due to the magnon-phonon hybridization [1]. The formation of such hybridized state (known as magnon polarons [13–16]) will induce an anticrossing in the dispersion relation of the acoustic phonon and the exchange-coupling-dominated magnons. Figure 1b shows the analytically calculated \( f-k \) relations of transverse acoustic (TA) phonons and exchange-coupling-dominated magnon in the (001) YIG film under different \( \mathbf{H}^{\text{bias}} \). Figure 1c shows the \( f-k \) relation of the magnon polaron at the low-\( k \) anticrossing at \( \mathbf{H}^{\text{bias}} = 2605 \) Oe, where the dispersions of the TA phonon and magnon cross at the point \( (k_0, f_0) = (2.6 \, \mu \text{m}^{-1}, 10 \, \text{GHz}) \), which is also known as the exceptional point in such hybrid magnon-phonon system [17]. Details of the analytical calculation are shown in Supplementary Material 1.

At the anticrossing, an acoustic wave injected into a ferromagnetic crystal can be converted to a magnetoelastic wave (its quanta is a magnon polaron), the energy of which is distributed in both the spin and lattice subsystems and transferred back and forth between them [18]. In this case, the acoustic wave attenuation is strongly influenced by both the elastic damping and magnetic damping of the ferromagnetic crystal as well as the strength of the magnon-phonon hybridization. For a crystal with negligible macroscopic motion in the body, the elastic loss mainly arises due to the internal friction [19,20]. The magnetic loss can arise from different magnon damping processes that involve coupling of magnons to non-uniformity (e.g., the two-magnon scattering [21,22]), phonons, photons [4], and/or the plasmons (quanta of free electron gas) [1,4,23,24]. Such phonon-magnon-phonon-plasmon coupling is illustrated in Fig. 1d. Both the elastic damping and magnetic damping critically influence the formation of magnon polaron. For example, for materials with high magnetic damping such as CoFe₂O₄, a recent computation has shown that a magnon polaron cannot form even if the \( f \) and \( k \) of the injected acoustic wave match those of the spin wave [8]. Furthermore, for a bulk acoustic wave propagating along the thickness direction of a ferromagnetic film (see Fig. 1a), the film needs to be thick enough to provide sufficient time for the magnon
polaron formation. Such a minimum time requirement is difficult to predict with analytical theories and should be more convenient to extract from time-domain simulations. In this article, we computationally investigate how the magnon polaron formation and the magnetic damping affect the attenuation of a propagating bulk acoustic wave in a ferromagnetic insulator film. The polarization rotation of transverse acoustic wave induced by magnon-phonon interaction [10] is also investigated. Real-time magnetic-field-controlled acoustic wave attenuation by magnetically shifting the exceptional point (see Fig.1b-c) is also shown.

II. Dynamical Phase-field Model

To accurately model the attenuation of an acoustic wave in a ferromagnetic film, we use a recently developed dynamical phase-field model that considers the coupled dynamics of acoustic phonons, magnons, photons, and plasmons in magnetic thin-film heterostructures [25]. For the present problem, it is not necessary to consider the coupling to the dynamics of photons because the radiation magnetic field produced by the magnons is negligibly small (See Supplementary Material 2). It is also not necessary to consider the coupling to the dynamics of plasmons since the YIG is an electronic insulator. In our model, the magnetic damping is described by the effective magnetic damping coefficient $\alpha$ in the Landau-Lifshitz-Gilbert (LLG) equation, the same as that in standard micromagnetic simulations. Thus far, there exist only a few advanced micromagnetic models that consider the coupled dynamics of magnons and phonons (or spin-lattice dynamics more generally) [6–9,26–29], but time-domain simulations of the magnon polarons formation and its influence on acoustic wave attenuation have not yet been reported. Here we use two criteria to determine the formation of a magnon polaron in a ferromagnet. First, the amplitudes of the acoustic and spin waves should display periodic, alternative variations in real space, a phenomenon known as coherent beating oscillation [16] that resembles the oscillation of coupled pendulums. Second, the wavenumber of an injected acoustic wave that has the value of the exceptional point should split into two values ($\Delta k \neq 0$, see Fig. 1c) upon the magnon polaron formation. Although YIG is a ferromagnet, the antiparallel magnetic moments of the Fe atoms at the tetrahedral and octahedral sites of its unit cell are always collinear, yielding a net magnetization of ~5$\mu_B$ per formula unit ($\mu_B$ is Bohr magneton). Therefore, for long-wave perturbations with wavelengths much greater than the unit cell size of YIG (~1.2 nm [22]) such as the GHz acoustic waves, it is rational to treat the YIG as a ferromagnet [8]. In this case, the evolution of the normalized local magnetization $\mathbf{m}$ in the YIG is governed by the LLG equation,

$$\frac{\partial \mathbf{m}}{\partial t} = -\frac{\gamma}{1+\alpha^2} \mathbf{m} \times \mathbf{H}^{\text{eff}} - \frac{\alpha\gamma}{1+\alpha^2} \mathbf{m} \times (\mathbf{m} \times \mathbf{H}^{\text{eff}}),$$

(1)

where $\gamma$ is the gyromagnetic ratio and $\alpha$ is the effective magnetic damping coefficient. The total effective magnetic field $\mathbf{H}^{\text{eff}}$ is a sum of the magnetocrystalline anisotropy field $\mathbf{H}^{\text{anis}}$, the Heisenberg exchange coupling field $\mathbf{H}^{\text{exch}}$, the magnetic dipolar coupling field $\mathbf{H}^{\text{dip}}$, the bias magnetic field $\mathbf{H}^{\text{bias}}$ (fixed along $+x$ in this work), the magnetoelastic anisotropy field $\mathbf{H}^{\text{mel}}$. The mathematical expressions of $\mathbf{H}^{\text{anis}}$ and $\mathbf{H}^{\text{dip}}$ (both are a function of $\mathbf{m}$), $\mathbf{H}^{\text{exch}}$ (a function of $\nabla^2 \mathbf{m}$), and the $\mathbf{H}^{\text{mel}}$ (a function of $\mathbf{m}$ and local strain $\varepsilon$) are provided in our previous work [25]. The injected acoustic wave $\mathbf{e}(z,t)$, which is considered to be spatially uniform in the $xy$ plane, excites spin wave $\mathbf{m}(z,t)$ via the $\mathbf{H}^{\text{mel}}$. Therefore, the coupled transport of acoustic and spin waves occurs along the $z$ axis and can be modelled in a one-dimensional (1D) system [8,9,25]. The strain is
calculated as $\varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) (i,j = x,y,z)$ and the evolution of the mechanical displacement $\mathbf{u}$ is described by the elastodynamics equation [20,30],

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = -\nabla \cdot \left( \mathbf{\sigma} + \beta \frac{\partial \mathbf{\sigma}}{\partial t} \right),$$

(2)

where stress $\mathbf{\sigma} = c(\varepsilon - \varepsilon^0)$; $\rho$, $\beta$ and $c$ are the mass density, stiffness damping coefficient and elastic stiffness, respectively, for the (001)-oriented YIG or GGG. The $\varepsilon^0$ is stress-free strain caused by the magnetization via magnetostriction, and $\varepsilon_{ii}^0 = -\frac{3}{2} \lambda_i^{100} \left( m_i^2 - \frac{1}{3} \right)$, $\varepsilon_{ij}^0 = -\frac{3}{2} \lambda_i^{111} m_i m_j$, with $i,j = x,y,z$, where $\lambda_i^{100}$ and $\lambda_i^{111}$ are the magnetostrictive coefficients of the magnetic phase. For a magnetic film where all physical quantities are assumed to be uniform in the $xy$ plane, the full expansion of Eq. (2) is given as,

$$\rho \frac{\partial^2 u_x}{\partial t^2} = \left( 1 + \beta \frac{\partial}{\partial t} \right) \left( c_{44} \frac{\partial^2 u_x}{\partial z^2} + B_2 \frac{\partial (m_i m_j)}{\partial z} \right),$$

(3a)

$$\rho \frac{\partial^2 u_y}{\partial t^2} = \left( 1 + \beta \frac{\partial}{\partial t} \right) \left( c_{44} \frac{\partial^2 u_y}{\partial z^2} + B_2 \frac{\partial (m_i m_j)}{\partial z} \right),$$

(3b)

$$\rho \frac{\partial^2 u_z}{\partial t^2} = \left( 1 + \beta \frac{\partial}{\partial t} \right) \left( c_{11} \frac{\partial^2 u_z}{\partial z^2} + B_1 \frac{\partial (m_i^2)}{\partial z} \right),$$

(3c)

where $B_1 = -1.5 \lambda_i^{100} (c_{11}^{M} - c_{12}^{M})$ and $B_2 = -3 \lambda_i^{111} c_{44}^{M}$ are the magnetoelastic coupling coefficients of the magnetic phase. Equation 3(a-c) indicates that the precession of local magnetization can generate secondary acoustic waves via the terms related to $B_1$ and $B_2$, namely, the magnetoelastic stress. The injection of the continuous bulk acoustic wave $\varepsilon_{xz}(z,t)$ is simulated by applying a time-varying mechanical displacement boundary condition in the form of a sinusoidal wave, $u_x(z=0, t) = u_{\text{max}} \sin(2\pi f_{\text{app}} t)$, at the bottom surface ($z=0$) of the YIG film. The entire YIG/GGG heterostructure is discretized into a 1D system of computational cells along the $z$ axis, with a cell size $\Delta z = 2 \text{ nm}$ (only slightly larger than the unit cell of YIG). Central finite difference is used for calculating the spatial derivatives. All equations are solved simultaneously using the classical Runge-Kutta method for time-marching with a real-time step $\Delta t = 20 \text{ fs}$. The magnetic boundary condition $\partial \mathbf{m} / \partial z = 0$ is applied on the surfaces of the YIG film. When solving the Eq. (2), the continuity boundary conditions of mechanical displacement $\mathbf{u}$ and stress $\mathbf{\sigma}$ (see details in [11]) are applied at the YIG/GGG interface. The absorbing boundary condition $\frac{\partial u_i}{\partial z} = -\frac{1}{v} \frac{\partial u_i}{\partial t} (i=x,y,z)$, is applied at the top surface of the GGG layer to make it a perfect sink for acoustic waves. Here $v$ is the transverse sound velocity for $u_x$ and $u_y$, and the longitudinal sound velocity for $u_z$. Moreover, our model is GPU (Graphics Processing Unit) accelerated to achieve high-throughput simulations in a computational system of the order of $10^5$ cells and millions of numerical time steps.

The materials parameters are summarized below. For the (001) GGG [31], the elastic stiffness coefficients $c_{11} = 285.7 \text{ GPa}$, $c_{12} = 114.9 \text{ GPa}$, $c_{44} = 90.2 \text{ GPa}$ and mass density $\rho = 7085 \text{ kg m}^{-3}$. For the (001) YIG [8,32,33], $c_{11} = 269 \text{ GPa}$, $c_{12} = 107.7 \text{ GPa}$, $c_{44} = 76.4 \text{ GPa}$ and $\rho = 5170 \text{ kg m}^{-3}$; gyromagnetic ratio $\gamma = 0.22 \text{ rad MHz A}^{-1} \text{ m}$; the saturation magnetization $M_s = 0.14 \text{ MA m}^{-1}$ (or $5\mu_B$ per YIG formula unit); the exchange coupling coefficient $A_{ex} = 3.26 \text{ pJ m}^{-1}$; the magnetocrystalline anisotropy coefficient $K_1 = 602 \text{ J m}^{-3}$; the magnetoelastic coupling coefficients
$B_1 = 0.3 \text{ MJ m}^{-3}$ and $B_2 = 0.55 \text{ MJ m}^{-3}$. The stiffness damping coefficient of the (001) YIG is assumed to be same as that of the GGG, $\beta = 3 \times 10^{-15}$ s. The value of $\beta$ is obtained by fitting the experimentally determined characteristic decay length of a GHz transverse acoustic wave (~ 2 mm) in (001) GGG [15] through analytical calculation and elastodynamics simulation (see details in Supplementary Material 3).

III. Results and Discussion

Let us consider a continuous acoustic wave $\varepsilon_{xz}$ with an amplitude of $10^{-5}$ ($u_{\text{max}}=1.224 \text{ pm}$) and a frequency $f_{\text{app}}$ of 10 GHz is injected into the in-plane-magnetized (001) YIG film at $t=0$ ps. Figure 2a shows the spatial profile of the acoustically excited spin wave, represented using $m_s(z)$, at the moment ($t=52$ ns) when the acoustic wave had travelled for 200 $\mu$m along the $z$ axis. As seen, there exists several nodes where the spin wave amplitudes show local minima. Compared to the spatial profile of the acoustic wave $\varepsilon_{xz}(z)$ at the same moment (in the bottom panel of Fig. 2a), it can be found that the local minima of the spin wave correspond to the local maxima of the acoustic wave at the same positions, and vice versa. Such periodic, alternative variation in the amplitudes of the spin wave and acoustic wave, which was not predicted in magnetic systems with relatively large intrinsic magnetic damping coefficient ($>10^{-2}$) [6–9], is known as the coherent beating oscillation [16] and indicates the formation of magnon polarons. The appearance of such coherent beating oscillation necessarily requires considering the generation of secondary acoustic wave via the magnetostrictive stress (see Eqs. 3a-c), as shown by the control simulation (see Supplementary Material 4). The formation of magnon polarons is also indicated by the wavenumber splitting for both the spin wave and the acoustic wave. As shown in Fig. 2b, two distinct wavenumbers of 2.57 $\mu$m$^{-1}$ and 2.64 $\mu$m$^{-1}$ appear in the spectra of both the $m_s(z)$ and the $\varepsilon_{xz}(z)$ profiles at $t=52$ ns. These two wavenumber values agree well with the analytically predicted 2.56 $\mu$m$^{-1}$ and 2.64 $\mu$m$^{-1}$ (c.f., Fig. 1c), which demonstrates the high numerical accuracy of our dynamical phase-field model.

The wavenumber splitting/shift caused by the magnon polaron formation (denoted as $\Delta k$) is also indicated by the horizontal double-headed arrows in Fig. 1c: when the $f$ and $k$ of the injected acoustic wave match the values at the exceptional point (10 GHz, 2.6 $\mu$m$^{-1}$), $|\Delta k|$ is the largest ($=0.04$ $\mu$m$^{-1}$). To numerically demonstrate this analytical prediction, we vary the frequency of the injected acoustic wave ($f_{\text{app}}$) from 9.8 GHz to 10.2 GHz in the simulations. It is found that the $\Delta k$ extracted from the simulations agree well with the analytical prediction under all frequency values investigated, as shown in Fig. 2c. Figure 2d further shows the attenuation ratio (denoted as $h$) of the injected acoustic wave $\varepsilon_{xz}(z,t)$ as a function of its frequency, which is calculated as $h=1-\int_0^d \varepsilon_{xz}(z)^2dz/\int_0^d \varepsilon_{xz}^{\text{uni}}(z)^2dz$. The integration evaluates the elastic energy of the entire acoustic wave packet. $\varepsilon_{xz}^{\text{uni}}(z)$ refers to the acoustic wave profile simulated by omitting the magnetostrictive stress, which is utilized as the reference (see its profile in Supplementary Material 4). $d=200$ $\mu$m is the acoustic wave packet length. As shown in Fig. 2d, $h$ is the largest (~90%) when the frequency $f_{\text{app}} = f_0 =10$ GHz, and the variation trend of $h$ with $f_{\text{app}}$ is similar to that of $|\Delta k|$.

To understand the formation of magnon polarons in the time-domain, the spatiotemporal profile of the mechanical displacement component $u_s(z,t)$ in the (001) YIG film is shown in Fig. 3a, where the frequency of the injected acoustic wave $\varepsilon_{xz}(z,t)$ is 10 GHz. It is noticeable that the number of nodes, in which $u_s(z,t) \sim 0$, in the acoustic wave packet grows with time. The appearance of the first node occurs at $t=9.6$ ns, which is the minimum time required for the magnon polaron formation.
The spatial profiles of the $\varepsilon_{xc}(z,t)$ at $t=7.8$ ns, 13 ns, and 26 ns, which are shown in Fig. 3b and also marked by horizontal dashed lines in Fig. 3a, display 0, 2 and 4 nodes, respectively. The wavenumber spectra of these spatial profiles are shown in Fig. 3c, where the single peak wavenumber at 2.6 $\mu$m$^{-1}$ splits to two different ones in the case of $t=13$ ns and 26 ns. This also indicates the magnon polarons formation.

Another notable feature associated with the formation of magnon polarons is the polarization rotation of a transverse acoustic wave, which was predicted [1] and experimentally demonstrated in single-crystal YIG over sixty years ago [10]. However, time-domain simulation of the acoustic wave rotation caused by the magnon polaron formation has remained scarce. According to Eq. 3(b), the $y$-component of the mechanical displacement $u_y(z,t)$ will be generated by the precession of local magnetization (see Supplementary Material 5 for the spatiotemporal distribution of $u_y(z,t)$), which in turn rotates the polarization of the injected transverse acoustic wave. As shown in Fig. 3d, the polarization angle $\theta$ reaches up to $90^\circ$ when $u_y(z,t)$ approaches zero (cf., Fig. 3a). This observation is consistent with the definition of the polarization angle, which is given by $\theta(z,t) = \text{atan}(|u_y(z,t)|/|u_x(z,t)|)$. Such acoustic wave polarization rotation offers potential applications in non-reciprocal acoustic devices [34]. Figure 3e further shows the temporal evolution of the attenuation ratio $h$ of the injected acoustic wave $\varepsilon_{xc}(z,t)$. As seen, after the magnon polaron forms at $t = 9.6$ ns, the increase of the $h$ is much slower, thereby demonstrating the significant influence of the magnon polaron formation on the acoustic attenuation in the time domain.

The above results are based on an ultralow effective magnetic damping coefficient $a=8\times10^5$ for high-quality (001) YIG single crystal [35]. Now we discuss the influence of the effective magnetic damping on the magnon polaron formation and the acoustic wave attenuation. The frequency of the injected acoustic wave is fixed at 10 GHz. Figure 4a shows the spatial profiles of the $\varepsilon_{xc}(z)$ in the YIG films with magnetic damping $a = 0.001, 0.002$ and 0.1 at $t=52$ ns, by which the acoustic wave had propagated for 200 $\mu$m, and the corresponding wavenumber spectra are shown in Fig. 4b. In all three cases, the $\varepsilon_{xc}(z)$ only shows a moderate attenuation in region near $z=200$ $\mu$m, where the acoustic wave had just arrived and started to transfer its energy to the spin subsystem. However, if looking at the first 50 $\mu$m of the acoustic wave packet ($z=0$-50 $\mu$m), where the phonon and magnon had interacted for long enough time (up to 52 ns), the two key features of magnon polaron formations, coherent beating oscillation and wavenumber splitting, exist only in the case of $a = 0.001$. This is because a larger magnetic damping would dissipate a larger amount of energy and ultimately suppress the magnon polaron formation. Although coherent beating oscillation can still be seen in the last 50 $\mu$m of the wave packet (where $z=150$-200 $\mu$m) at the moment of $t=52$ ns, this oscillatory profile would eventually disappear. Taken together, these results indicate that a sufficiently small effective magnetic damping coefficient ($a < 0.002$ herein) is necessary for the magnon polarons formation. This is consistent with the fact that the formation of magnon polarons with non-zero $k$ has thus far been observed only in low-damping magnetic insulator such as YIG [16,36]. Figure 4c presents the attenuation ratio $h$ of the acoustic waves $\varepsilon_{xc}(z,t)$ as a function of the $\alpha$ where the $f_{\text{app}}$ varies from 9.8 GHz to 10 GHz. Given that the strength of magnon-phonon hybridization (proportional to $|\Delta k|$) gradually increases to its maximum when $f_{\text{app}}$ reaches 10 GHz (see Fig. 2c), we can draw two conclusions. First, the stronger the magnon-phonon hybridization is, the higher the acoustic attenuation. This is because stronger hybridization enables converting more elastic energy of the acoustic wave into the magnetic energy. Indeed, the curve with $f_{\text{app}}=10$ GHz is above the other curves with lower $f_{\text{app}}$ in Fig. 4c. Second, when the $f_{\text{app}}$ is fixed, the $\alpha$ with
an intermediate value leads to the highest acoustic attenuation. A larger \( a \), on one hand, leads to weaker magnon-phonon hybridization (smaller \(|\Delta k|\), see Fig. 4b) and hence lower acoustic attenuation. On the other hand, a larger amount of magnetic energy would dissipate to the surrounding in the form of waste heat when \( a \) is larger. In other words, there would be fewer amount of energy returned from the spin subsystem to the lattice subsystem, which leads to higher attenuation. Due to these two competing effects, the maximum antennation ratio \( h \) appears at an intermediate value of \( a \). For example, \( h \) reaches its peak of 96.5\% at \( a=0.001 \) when \( f_{\text{app}}=10 \) GHz.

The simulation results in Fig. 4c show that the \( h \) can be tuned by controlling the magnetic damping and the strength of magnon-phonon hybridization (denoted by \(|\Delta k|\)). Furthermore, \(|\Delta k|\) can be tuned by shifting the frequency of the exceptional point \( f_0 \) (Fig. 1b) through the variation of the bias magnetic field \( H^{\text{bias}} \). Therefore, it should be possible to achieve dynamic control of the acoustic attenuation by simultaneously applying a dynamic magnetic field \( H^{\text{Dyn}} \). Such phenomenon was experimentally demonstrated over fifty years ago [37], but time-domain simulations have remained elusive. Here, we simulate the propagation of a 10-GHz-frequency continuous acoustic wave \( \varepsilon_{xz}(z,t) \) across a (001)YIG(20 \( \mu \)m)/GGG(acoustic sink) under the \( H^{\text{Dyn}} \), a fixed \( H^{\text{bias}} \) (= 2000 Oe), and a fixed \( a=8\times10^{-5} \). Figure 5 shows the time-domain evolution of the strain \( \varepsilon_{xz}(z,t) \) in the GGG at 500 nm above the YIG/GGG interface under three different \( H^{\text{Dyn}} \), whose temporal profiles are also plotted. In all three cases, when \( H^{\text{Dyn}} \) reaches its maximum, the exceptional point frequency \( f_0=f_{\text{app}}=10 \) GHz. If such resonant condition can last for long enough time (that is, \( \geq 9.6 \) ns), the magnon polaron would form, and thereby induce more significant acoustic attenuation. As shown in Fig. 5a, the influence of \( H^{\text{Dyn}} \) on the acoustic wave amplitude is not appreciable when the peak value of \( H^{\text{Dyn}} \) is only held transiently. However, when \( H^{\text{Dyn}} \) is held for longer time at its peak value, the decrease in the acoustic wave amplitude is more significant, as shown in Fig. 5b. When the duration of this pulsed \( H^{\text{Dyn}} \) is long enough to enable the formation of magnon polarons, significant acoustic wave attenuation occurs over the entire ‘ON’ phase of the pulsed \( H^{\text{Dyn}} \) with clear feature of beating oscillation, as shown in Fig. 5c. Such time-domain simulations therefore allow one to design the shape, duration, and amplitude of the dynamic magnetic field to achieve the desirable level of acoustic attenuation at any given location of a heterostructure.

IV. Conclusions

In conclusion, our time-domain simulations show that (1) the acoustic attenuation in magnetic insulator films is proportional to the strength of magnon-phonon hybridization, which can be indicated by the magnitude of wavenumber shift \(|\Delta k|\); (2) the attenuation is the strongest when the effective magnetic damping coefficient \( a \) takes an intermediate value. Moreover, for a continuous bulk acoustic wave that has a frequency near the frequency of the exceptional point (that is, the strong coupling regime), we have shown that the duration of the magnon-phonon interaction needs to be long enough (at least 9.6 ns in the main example) to ensure the formation of magnon polarons. More detailed analyses indicate that such a threshold duration is inversely proportional to the magnetoelastic coupling coefficient (see Supplementary Material 6), and increases when the \( a \) gets larger (see Supplementary Material 7). However, if the \( a \) is too large, the formation of magnon polaron would not be possible since the enhanced energy dissipation would suppress the coherent energy transfer between the spin and lattice subsystems [17]. Based on the strong magnetic-field sensitivity of the \(|\Delta k|\) in the strong coupling regime, we also demonstrate a significant dynamic tuning of the acoustic wave attenuation with a dynamic magnetic field.
Overall, our time-domain numerical simulations, implemented based on an in-house GPU-accelerated dynamical phase-field model, enable a fast and accurate prediction of the spatiotemporal profile of an acoustic wave in heterostructures based on magnetic insulator films. Such simulations can therefore guide the materials and heterostructure engineering to achieve on-demand dynamic magnetic-field control of acoustic attenuation, which could potentially be utilized to develop nonreciprocal acoustic devices such as an isolator [37]. Moreover, although a bulk transverse acoustic wave is considered in this work, the theoretical and numerical analyses can be extended to bulk longitudinal acoustic waves and surface acoustic waves as well as more complex magnetic heterostructures (e.g., superlattices, nanostructure arrays) [12,17,34,38,39]. Finally, beyond the magnetic systems, we note that the enhanced acoustic attenuation due to the magnon-phonon hybridization is analogous to the enhanced acoustic attenuation in ferroelectrics near the Curie temperature, which results from the interaction between the acoustic phonons and softened optical soft mode phonons [40–42].

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Figure 1. a, Schematic, not to scale, showing a piezoelectric (PE)/ferromagnet (FM)/substrate heterostructure, where the substrate is a sink for the continuous transverse acoustic wave $\varepsilon_{xz}$. A bias magnetic field $H_{bias}$ is applied along $+x$ to stabilize a spatially uniform initial magnetizations $m^0$ along the same direction. b, Analytically calculated dispersion relations of transverse acoustic (TA) phonon (blue) and exchange-coupling-dominated magnons (red) in (001) YIG films under $H_{bias} = 2605$ Oe, 13025 Oe, and 26050 Oe, where $k\parallel z$. c, Magnon polarons at the low-wavenumber ($k$) anticrossing between the TA phonon and the magnon branches under $H_{bias} = 2605$ Oe. The formation of magnon polarons shifts the wavenumber of the injected acoustic wave by an amount indicated by $\Delta k$. $|\Delta k|$ is the largest at the exceptional point $(k_0, f_0) = (2.6 \, \mu m^{-1}, 10 \, GHz)$. d, Schematic of phonon-magnon-photon-plasmon coupling in a FM material. The phonons and magnons interact via the magnetoelastic coupling, the strength of which is indicated by $b$; magnons and photons interact via the dipolar coupling (whose strength is represented by $g$); the coupling strength of the photons and plasmons is represented by the plasmon frequency $\omega_p$. In this work, the magnon-photon and photon-plasmon couplings are negligible; see details in text.
Figure 2. a, Spatial profiles of the spin wave $m_y(z)$ and the acoustic wave $\varepsilon_{xz}(z)$ in a 200-µm-thick (001) YIG film at $t = 52$ ns. $t=0$ ns is the moment that the acoustic wave propagates into the YIG film from its bottom surface ($z=0$). The inset shows the enlarged profile of the $m_y(z)$ in the last 50 µm. The local minima in the spin wave packet and the local maxima in the acoustic wave packet are connected using dashed lines. b, Wavenumber spectra of the spin wave (top panel) and the acoustic wave (bottom panel), obtained by performing Fourier transforms on the $m_y(z)$ and the $\varepsilon_{xz}(z)$ profiles shown in (a). c, Analytically calculated (solid lines) and numerically simulated (circles) wavenumber shifts $\Delta k$ of the magnon polaron as a function of the frequency of the injected acoustic wave ($f_{app}$). d, Simulated acoustic wave attenuation ratio $h$ (see definition in the main text) as a function of the $f_{app}$. The length of all acoustic wave packets is 200 µm.
Figure 3. a, Spatiotemporal profile of mechanical displacement component $u_x(z,t)$ in a 200-µm-thick (001) YIG film within $t = 0$-52 ns. $t=0$ is the moment that the acoustic wave propagates into the YIG film from its bottom surface ($z = 0$). b, Spatial profiles of the $e_{xz}(z,t)$ at $t = 7.8$ ns, $t = 13$ ns, and $t = 26$ ns, and c, their wavenumber spectra. The corresponding time moments and the spatial width of the wave packets are labeled using dashed lines in (a). d, Spatiotemporal profile of polarization angle $\theta$ of transverse acoustic wave. The inset illustrates the definition of the $\theta$. e, The acoustic wave attenuation ratio $h$ as a function of the traveling time of the acoustic wave.
Figure 4. a. Spatial profiles of the acoustic wave $\varepsilon_{xz}(z)$ in a 200-µm-thick (001) YIG film at $t = 52$ ns with effective magnetic damping $\alpha = 0.001$, 0.002, and 0.1, and b. their wavenumber spectra. The wavenumber spectra are obtained by performing Fourier transforms on the first 50 µm of the $\varepsilon_{xz}(z)$ profile in (a). c. The acoustic wave attenuation ratio $h$ as a function of $\alpha$, under different frequencies of the injected acoustic wave ($f_{app}$). The length of all acoustic wave packets is 200 µm.
Figure 5. Temporal profiles of the dynamic magnetic field $H_{\text{Dyn}}$ (red) and strain $\varepsilon_{xz}(t)$ (black). The $H_{\text{Dyn}}$ is held at its peak value of 605 Oe for (a) 0 ns, (b) 5 ns, and (c) 50 ns. $\varepsilon_{xz}(t)$ is taken from the location in the GGG layer that is 500 nm above the YIG/GGG interface. $H_{\text{bias}}=2000$ Oe. Both the $H_{\text{Dyn}}$ and the $H_{\text{bias}}$ are applied along the $+x$ direction.