

Strongly Coupled Spin Waves and Surface Acoustic Waves at Room Temperature

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Here, we report the observation of strong coupling between magnons and surface acoustic wave (SAW) phonons in a thin CoFeB film constructed in an on-chip SAW resonator by analyzing SAW phonon dispersion anticrossings. We employ a nanostructured SAW resonator design that, in contrast to conventional SAW resonators, allows us to enhance shear-horizontal strain. Crucially, this type of strain couples strongly to magnons. Our device design provides the tunability of the film thickness with a fixed phonon wavelength, which is a departure from the conventional approach in strong magnon-phonon coupling research. We detect a monotonic increase in the coupling strength by expanding the film thickness, which agrees with our theoretical model. Our work offers a significant way to advance fundamental research and the development of devices based on magnon-phonon hybrid quasiparticles.

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Hybridization between two systems can be characterized by a comparison of the coupling strength g and the relaxation rates of each system κ_1 and κ_2 . When $g/\max(\kappa_1, \kappa_2) > 1$, the hybridized state is in the strong coupling regime [1]. In the case of coupling of magnons and other waves, reducing the magnon relaxation rate is experimentally challenging, thus increasing g is the most efficient route to realize strong coupling. The most straightforward approach to achieve higher coupling strength is increasing the number of spins coupled in phase to the desired mode [1]. This approach is typically done for magnons coupling to photons in cavity magnonics experiments by increasing the volume of the magnet [2]. The rationale behind this approach lies in the relatively spatially homogeneous microwave cavity modes throughout the magnet, especially for magnets significantly smaller than the microwave wavelength (\sim mm).

However, in the context of magnon-phonon coupling research, this approach is not always straightforward as the magnon and phonon are not necessarily in phase across the sample, and thus the magnon-phonon coupling depends nontrivially on the sample geometry. For instance, in a spherical magnet, the magnon-phonon coupling decreases with the volume [3–5]. Nonetheless, one can circumvent this apparent limitation by choosing an appropriate geometry for the magnetic medium: a thin film with a much

smaller thickness than the involved acoustic wavelength. Since it supports spatially uniform spin and acoustic waves across the film thickness, the coupling strength recovers its characteristic monotonic increase with the expansion of the film thickness. Hence, the thin film limit allows us to explore the dependence of magnon-phonon coupling on the number of spins. In order to make it possible, it is crucial to attain independent control over the phonon wavelengths and the geometry of the magnetic material.

Several studies demonstrated magnon-phonon coupling [6–9], and some studies experimentally observed strong magnon-phonon coupling [10–13]. However, the strong dependence of the phonon wavelength on the dimensionality of the active magnetic layer within the structure [7,9,11,12] imposes limitations on the ability to separately control the phonon wavelength and the size of the magnet, hindering the realization of the thin film limit. One viable approach to accomplish this limit is injecting surface acoustic waves (SAWs) with variable wavelengths into the magnetic material as has been researched over the past two decades [14–25]. Especially, Refs. [20,23] employed a two-port SAW resonator that consists of SAW generation and detection devices enclosed by distributed Bragg reflectorlike stripes, forming an acoustic cavity [26,27]. This device design allows driving acoustic modes with any

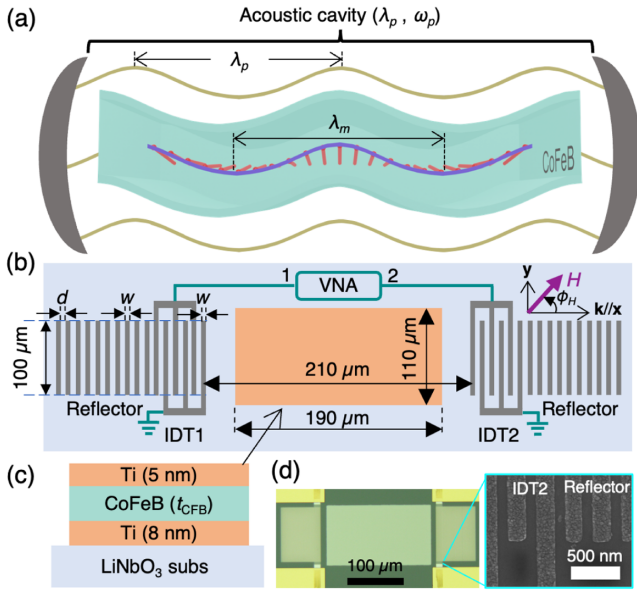


FIG. 1. (a) Schematic illustration of strong magnon-phonon coupling in an acoustic cavity that confines phonons with a wavelength λ_p and a frequency ω_p . The yellow curves denote acoustic waves (phonons) created within the acoustic cavity and the red arrows represent magnetization dynamics. The phonons propagating through a CoFeB thin film excite a spin wave (magnon), which is represented by the purple curve, with a matched wavelength $\lambda_m = \lambda_p$. (b) Schematic top view of the device structure used in this research. IDT1 and IDT2 include 20 pairs of Al stripes and each set of reflectors includes 200 Al stripes. IDT1 and IDT2 are respectively connected to port1 and port2 of a vector network analyzer (VNA). (c) Schematic side view of the Ti/CFB/Ti stack. (d) Optical (left) and scanning electron microscope (right) images of one of the devices used in this study.

wavelength λ_p (frequency ω_p) enabling coupling to magnons at the wavelength $\lambda_m = \lambda_p$ by spin wave resonance (SWR), as depicted in Fig. 1(a), circumventing the reliance of λ_p on the material geometry. However, despite successfully reduced phonon loss and enhanced coupling strength using acoustic cavities, strong coupling between magnons and SAW phonons was not achieved [20,23]. This is because experiments on the coupling between magnons and SAW phonons mostly utilize Rayleigh-SAWs, which exhibit limited magnetoelastic coupling into the film thickness direction, limiting the attainable coupling strength [22]. On the contrary, shear-horizontal (SH)-SAWs enable a significantly stronger magnetoelastic coupling through a magnetic film, thus efficiently having a larger coupling strength [22].

In this Letter, we demonstrate the strong coupling between magnons and SH-SAW phonons caused by SAW-driven SWR in a $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ (CFB) thin film on a 128° Y-cut LiNbO_3 (128-LN) substrate at room temperature by measuring anticrossing of SAW phonon dispersion, an indication of strong interaction [28]. We generate SAWs

using a nanostructured high-frequency acoustic cavity significantly smaller than previous reports in the field [20,23]. The anticrossing behavior is only detected when the angle between the SAW propagation and an applied in-plane magnetic field, ϕ_H , is around 0° . In contrast, the previous results that utilized acoustic cavity structures [20,23] detect magnon-phonon coupling only at $\phi_H \sim 45^\circ$, consistent with the behavior of SWR driven by SH- and Rayleigh-SAWs, respectively [15,22], confirming that our device corresponds to the former. Despite the smaller contribution of SH-SAWs compared to Rayleigh-SAWs on 128-LN [29–32], the improved mechanical coupling between SH- and Rayleigh-SAWs within the well-defined periodic gratings of our acoustic cavity led to an enhancement of SH-SAWs [33,34]. Furthermore, by the realized thin film limit as mentioned, we successfully estimated the magnon-phonon coupling strength (g values) of samples with the same device structure but varying CFB thicknesses (t_{CFB}) by fitting the observed anticrossing with our theoretical model. Our study reveals a monotonic increase in g with increasing t_{CFB} , which agrees with our expectation and our magnon-phonon coupling model. This increase of g allowed us to achieve strong coupling; $g/\max(\kappa_m, \kappa_p) > 1$, where $\kappa_{m(p)}$ is the magnon (phonon) relaxation rate, for devices with $t_{\text{CFB}} \geq 20$ nm.

To generate SAWs, we utilized interdigital transducers (IDTs) that can generate and detect SAWs on a piezoelectric substrate [26]. We fabricated acoustic cavity devices including $\text{Ti}(8\text{ nm})/\text{CFB}(t_{\text{CFB}})/\text{Ti}(5\text{ nm})$ layers on a 128-LN substrate, as shown in Figs. 1(b) and 1(c), where the parameters inside the parentheses exhibit the thickness of each layer. For the IDTs and the acoustic reflectors, we deposited 35-nm-thick Al. Each Al stripe of an IDT has a length of $120\ \mu\text{m}$ and a width of w . Each Al stripe of the acoustic reflectors has a length of $100\ \mu\text{m}$ and the same width as the IDT stripes, w . All metallic stripes of the IDTs and the acoustic reflectors are separated by a distance d . The scanning electron microscope image in Fig. 1(d) shows the measured values of w and d : $w = 175 \pm 8\ \text{nm}$; and $d = 125 \pm 4\ \text{nm}$. After the fabrication of the acoustic cavity, we patterned a $190\ \mu\text{m} \times 110\ \mu\text{m}$ rectangle between the two IDTs. The Ti/CFB/Ti layers are sputter-deposited to the rectangle pattern. We fabricated samples with the same structure but different $t_{\text{CFB}} = 10, 20, 25, 30,$ and $35\ \text{nm}$.

SAW transmission ($|S_{21}|^2$) is measured using a vector network analyzer (VNA) while applying an external in-plane magnetic field H , where the angle between H and the SAW wave vector \mathbf{k} is described by ϕ_H . This transmission is shown in Fig. 1(b). When H is far enough from the resonant field of SWR driven by our SAW frequency, the SAW spectrum shows the phonon signal without contributions from magnons, which remain unexcited. Such a situation is shown in Fig. 2(a), which depicts $|S_{21}|^2$ of the sample with $t_{\text{CFB}} = 20\ \text{nm}$ out of magnetic resonance when

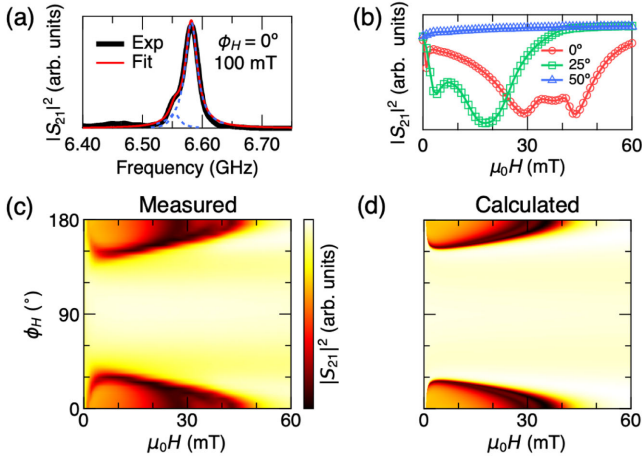


FIG. 2. SAW measurement results of the sample $t_{\text{CFB}} = 20$ nm. (a) Measured SAW transmission signal ($|S_{21}|^2$) by VNA in the frequency domain. An in-plane magnetic field of 100 mT is externally applied in a direction parallel to the SAW propagation, which is far from the resonant field of SWR driven by our SAW frequency as shown in (b), thus the transmission signal displays only the phonon response. The black curve exhibits the measured spectrum, and the red curve shows the multiple Lorentzian fitting. The blue dashed curves show the individual Lorentzian peaks of the fitting. (b) $|S_{21}|^2$ at the frequency of 6.58 GHz as a function of the amplitude of the externally applied in-plane magnetic field ($\mu_0 H$). The in-plane field angles (ϕ_H) of each curve are shown in the legend. (c) $|S_{21}|^2$ at the frequency of 6.58 GHz as a function of $\mu_0 H$ and ϕ_H . (d) Calculated SAW transmission with the same setup as (c).

$\mu_0 H = 100$ mT and $\phi_H = 0^\circ$. The resonant frequency of the strongest SAW peak is $f_r = 6.58$ GHz. The designed wavelength of the SAW (λ_r) is determined by the designed structure of our acoustic device; $\lambda_r = 2(w + d) = 600$ nm. Using these parameters, one can calculate the SAW velocity as $v = f_r \lambda_r = 3,950$ m/s. This value aligns with the typical SAW velocity propagating on the crystal x axis of 128-LN [35].

In addition to the main resonance, we found one more peak on the lower frequency side of the main resonance [see the fitting to two Lorentzian peaks in the blue dashed curves in Fig. 2(a)]. The presence of these two peaks originates from the existence of two modes allowed within our cavity device. A detailed explanation of the origin of the two SAW peaks can be found in Sec. 1 of Ref. [36]. This Lorentzian fitting is used to extract the phonon linewidth δ_p to estimate the phonon relaxation rate below.

The SAW transmission out of magnetic resonance decreases when H approaches the resonance field condition since the phonons are used to excite magnons [14,15,19,20,41]. Figure 2(b) shows the absorption of $|S_{21}|^2$ of the main SAW peak in Fig. 2(a) when $\phi_H = 0^\circ$, 25° , and 50° . Figure 2(c) shows $|S_{21}|^2$ as a function of $\mu_0 H$ and ϕ_H . In the case of a typical magnetoelastic coupling excited by a Rayleigh-SAW, the absorption amplitude shows

maximum when $\phi_H = 45^\circ$ [14,15,19–21,25,37,41,42]. However, our results indicate that the maximum absorption across all ϕ_H ranges at $\phi_H \sim 25^\circ$ and no absorption was detected when $\phi_H > 30^\circ$. This is because the magnon dispersion is raised to a higher frequency due to the dipolar field and does not meet the phonon dispersion at $\phi_H > 30^\circ$ (Fig. 8 of Ref. [36]). Note that the in-plane uniaxial magnetic anisotropy of our CFB film [43] aligned in-plane perpendicular to \mathbf{k} causes the dips of SAW transmission around $\mu_0 H = 0$. Assuming the uniaxial magnetic anisotropy and the magnon-phonon coupling strength obtained by experiments (see below) allow us to calculate the SAW transmission as a function of an external in-plane magnetic field. As shown in Fig. 2(d), the calculation agrees well with the measured result. A detailed description of the calculation can be found in Sec. 5A of Ref. [36].

The distinct observation of anticrossing, represented by split features in SAW absorption, becomes most pronounced when $\phi_H \sim 0^\circ$. This splitting does not originate from Rayleigh-SAWs, commonly considered the dominant one in SAWs generated on a 128-LN substrate, which show the maximum magnetoelastic coupling when the angle between \mathbf{k} and the magnetization, described as ϕ , is 45° and no magnetoelastic coupling when $\phi = 0^\circ$. On the other hand, SH-SAWs show the maximum magnetoelastic coupling when $\phi = 0^\circ$ or 90° [15]. While in our device, the strain of Rayleigh-SAW, ϵ_{xx} , is larger than that of SH-SAW, ϵ_{xy} (Fig. 2(c) of Ref. [36]), and ϵ_{xx} decreases abruptly away from the surface [22]. Therefore, ϵ_{xx} faces a limitation in terms of penetration depth, which results in an insufficient coupling strength to observe magnon-phonon anticrossing. On the contrary, ϵ_{xy} has a larger penetration depth, making the associated coupling strength dominant [22].

Having clarified the origin of the coupling, we now focus on the magnon-phonon coupling at $\phi_H = 0^\circ$, where the magnetoelastic coupling is dominated by SH-SAW. Figure 3(a) shows the SAW transmission signal $|S_{21}|^2$ of the sample with $t_{\text{CFB}} = 10$ nm as a function of frequency and $\mu_0 H$, and Fig. 3(b) the SAW transmission spectrum when $\mu_0 H = 100$ mT. As we mentioned above, a SAW peak exists at a lower frequency side to the main peak, giving rise to multiple anticrossing features. However, as each SAW mode couples only to the magnon mode with its same wave number, each SAW branch shows a single anticrossing. Therefore, we focus on anticrossing of one mode per device to estimate its coupling. We first fit the phonon branches in ω - H dispersion taken by the local maximum of the SAW spectrum [see the marker in Fig. 3(b)] at each field with our magnon-phonon coupling model:

$$\omega^2 = \frac{\omega_m^2 + \omega_p^2}{2} \pm \frac{1}{2} \sqrt{(\omega_m^2 - \omega_p^2)^2 + (2\delta\omega_{\text{bare}}^2)^2}, \quad (1)$$

where ω_m and ω_p are the magnon and phonon resonant frequencies. The derivation of Eq. (1) and the definition of

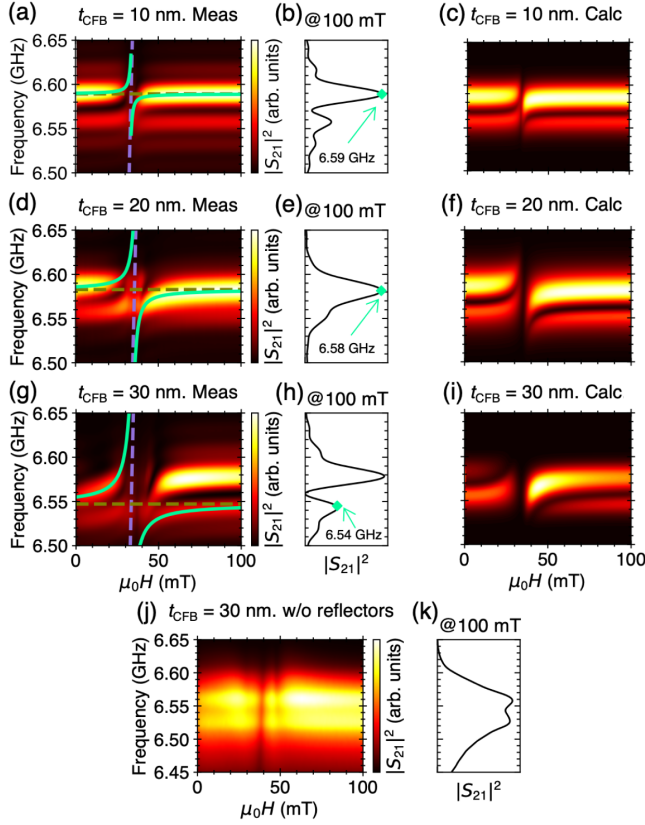


FIG. 3. SAW transmissions when the external magnetic field is applied in the direction of SAW propagation; $\phi_H = 0^\circ$. (a),(b) SAW transmission signal ($|S_{21}|^2$) of the sample with $t_{\text{CFB}} = 10$ nm under (a) various amplitudes of the magnetic field $\mu_0 H$ and (b) $\mu_0 H = 100$ mT. The green marker in (b) represents the local maximum used for the anticrossing fitting, shown as the green curves in (a). (c) Calculated SAW transmission of the sample with $t_{\text{CFB}} = 10$ nm as a function of the frequency and $\mu_0 H$. (d)–(i) Same as (a)–(c), but measurements and calculations of the samples with (d)–(f) $t_{\text{CFB}} = 20$ nm and (g)–(i) $t_{\text{CFB}} = 30$ nm. (j),(k) $|S_{21}|^2$ of the sample with $t_{\text{CFB}} = 30$ nm, but in the absence of acoustic reflectors (j) under various $\mu_0 H$ and (k) $\mu_0 H = 100$ mT. The purple and khaki dashed curves in (a), (d), and (g) indicate the calculated magnon (SWR) and phonon dispersions, respectively, as Fig. 8(a) of Ref. [36].

$\delta\omega_{\text{bare}}$ can be found in Sec. 4 of Ref. [36]. The anticrossing fitting is shown in Fig. 3(a) as green curves. The design of our SAW devices fixes the wave number $k = 2\pi/\lambda_r$, precluding the direct characterization of the ω – k dispersion; however, a schematic of the ω – k dispersion indicating the working area of our device can be found in Fig. 6 of Ref. [36].

From the parameters obtained by the fitting, we reproduce the anticrossing detected by SAW transmission spectra using our SAW transmission model. We modeled two phonon modes coupling to each magnon mode corresponding to its wave number. For the details of the model, see Sec. 5 of Ref. [36]. As a result, the SAW transmission is well reproduced as shown in Fig. 3(c).

Furthermore, in Figs. 3(d)–3(i), we present the same analysis as shown in Figs. 3(a)–3(c) but for the samples with $t_{\text{CFB}} = 20$ and 30 nm. Especially for the sample with $t_{\text{CFB}} = 30$ nm, it is notable that the upper phonon branch of the main SAW peak in Fig. 3(g) is vaguely visible at $\mu_0 H \sim 0$; however, it is no longer detectable at $0 < \mu_0 H < 40$ mT, as this peak shifts out of the frequency range of our cavity due to a redshift given by the strong mode interaction. Therefore, we fitted anticrossing of the peak at 6.54 GHz in Fig. 3(h) to obtain the parameters as shown in Fig. 3(g). The results and calculations of samples with other t_{CFB} are shown in Fig. 9 of Ref. [36].

Additionally, a device with the same structure as used in this experiment but without the presence of the acoustic reflectors does not show any anticrossing as shown in Figs. 3(j) and 3(k). This is due to the considerably higher phonon relaxation and smaller coupling strength originating from smaller SH-SAW when there is an absence of reflectors that form an acoustic cavity (Secs. 2 and 3B of Ref. [36]). The reason for the significant enhancement of SH-SAWs by the presence of acoustic cavity is the mechanical scattering of Rayleigh-SAW into SH-SAW within the periodic gratings of our acoustic cavity [33,34].

Lastly, we present the magnon-phonon coupling estimation in the devices with varying CFB thicknesses. Figure 4(a) shows the coupling strength g as a function of t_{CFB} taken by the anticrossing fittings in Fig. 3 and Fig. 9 of Ref. [36] with Eq. (1) and Eqs. (9), (12) of Ref. [36]. While our magnon-phonon coupling model (Sec. 4 of Ref. [36]) predicts $g \sim \sqrt{t_{\text{CFB}}}$, this prediction does not hold true, as shown in Fig. 4(a), due to variations in the effective magnetoelastic coupling coefficient b with changes in the thickness of the ferromagnetic layer. It is known that b is determined by contributions of the bulk (b_v) and surface (b_s) magnetoelastic couplings [44–46] as $b = b_v + b_s/t_{\text{CFB}}$. Figure 4(b) shows b as a function of the inverse of t_{CFB} , determined by the values of g and Eq. (12) of Ref. [36].

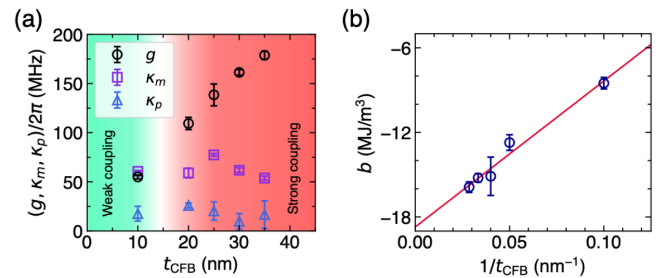


FIG. 4. (a) The coupling strength (g , the black curve) and magnon (κ_m , the purple square) and phonon (κ_p , the blue triangle) relaxation rates as a function of the thickness of the CFB layer. (b) The effective magnetoelastic constant as a function of the inverse of the thickness of the CFB layer. The solid line exhibits the surface magnetoelastic coupling fitting. The data points and error bars of (a) and (b) are the mean and s.d. of measurements of three or more different devices, respectively.

The fitting of b with the surface magnetoelastic coupling shown as a solid line yields $b_v = -18.7 \text{ MJ/m}^3$ and $b_s = 104 \text{ mJ/m}^2$, where the values are in agreement with the known values for CFB [46].

Next, to evaluate the attainment of strong coupling we estimate the relaxation rates of magnons (κ_m) and phonons (κ_p). To obtain κ_m , we used the Gilbert damping α of our CFB films as $\kappa_m = \omega_m \alpha$. The Gilbert damping is measured by ferromagnetic resonance using coplanar waveguides (see Sec. 6 and Fig. 10 of Ref. [36]). For κ_p , we obtain the linewidth of $|S_{21}|^2$ peaks (δ_p) by Lorentzian fittings as shown as the dashed curves in Fig. 2(a) and determine $\kappa_p = 2\pi\delta_p$. The estimated relaxation rates of devices with varying t_{CFB} are depicted alongside the coupling strength in Fig. 4(a). For the devices with $t_{\text{CFB}} \geq 20 \text{ nm}$, $g > \kappa_m, \kappa_p$, i.e., strong coupling is achieved. However, for the devices with $t_{\text{CFB}} = 10 \text{ nm}$, $\kappa_m > g$, thus it is not in the strong coupling regime.

To summarize, we achieved strong coupling between magnons and SAW phonons in $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ thin films thanks to the use of an acoustic cavity constructed by a two-port SAW resonator. SAW phonon anticrossings are observed when an external magnetic field is applied parallel to the SAW propagation direction. By fitting anticrossings with our theoretical model, we estimated the coupling strength of our devices. For the devices with $t_{\text{CFB}} \geq 20 \text{ nm}$, we confirmed the achievement of strong coupling. The variety in selecting magnetic materials and the usage of well-established SAW devices will pave the way to explore magnon-phonon strong coupling physics with on-chip devices at room temperature. This could be a significant asset toward integrating magnons within GHz-frequency quantum technological platforms, which is currently difficult due to the large wavelength mismatch and resulting weak coupling between microwaves and magnons. Our work offers the potential solution for establishing such couplings via mediating phonons, which have been demonstrated to be efficient interfaces with solid-state qubits [47], superconducting qubits [48,49], and other quantum systems in the GHz domain [50]. Moreover, it holds the potential to offer insights into studying coherently coupled magnon-phonon hybridized quasiparticles [22,51] enabling the development of magnetic field-controlled acoustic devices and less lossy magnon-based information processing devices. Having observed anticrossing through SAW signals, the potential for further advancements, such as magnetoelastic wave detection using techniques like Brillouin light scattering [9,52], is a promising avenue for exploration.

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