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ABSTRACT
Acoustically-driven ferromagnetic resonance (ADFMR) has recently emerged as a powerful scientific test-bed toward understanding complex interactions between phonons and magnons. In this technique, a traditional surface acoustic wave (SAW) delay-line filter interfaces with a ferromagnetic thin-film which can be driven into precession at the ferromagnetic resonance (FMR) frequency by the SAWs. SAW filters are used extensively in industry, but in the context of ADFMR, their design considerations are largely absent from the literature. We produced a variety of ADFMR devices by systematically changing parameters including the material and the number of pairs of interdigital transducers, the ferromagnetic thin-film growth technique, and the presence or the absence of a capping layer on the ferromagnetic thin-film. We quantitatively compare results by adapting traditional ferromagnetic resonance techniques. This work describes the parameters relevant to the development and optimization of SAW-driven FMR.

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I. INTRODUCTION
Spin wave generation and propagation is an active area of interest, important for its potential applications in logic devices and spintronics.1,2 Crucial goals for spintronic device development include control of the resonant frequency and spin wave mode, maximization of spin wave diffusion length, and nonreciprocity for signal isolation.3,4 Among available methods of spin-wave excitation,2 the most common are inductive techniques in which a microwave current is driven through a strip-line antenna, generating an AC magnetic field.5 Components of this field perpendicular to the external bias field exert a torque on magnetic moments, increasing the precessional amplitude and subsequent collective spin precession, which can result in the absorption of RF radiation detectable by a variety of reflection, transmission, or other measurement methods. An alternative form of spin wave excitation and detection under investigation is acoustically-driven ferromagnetic resonance (ADFMR).1,6–10 This technique is based on the well-established surface acoustic wave (SAW) delay line device combined with ferromagnetic thin films. The underlying principle relies on magnetoelastic (ME) coupling. The elastic strain produced by SAWs drives the magnetization dynamics of the ferromagnetic thin film in the propagation path via ME coupling when the SAW excitation frequency is in resonance with the spin wave frequency under the external bias magnetic field. Similar magnon-phonon interactions have been theoretically and experimentally investigated for bulk acoustic devices.11–13 To observe effective ME coupling in the ferromagnetic thin film, high magnetostrictive property of the ferromagnet is desirable to enhance coupling of the strain waves to magnetization dynamics. SAWs are generated using interdigital transducers (IDTs) on a piezoelectric substrate,1 or more recently on a multiferroic substrate at low temperatures.14 These mechanical strain waves tend to have lower damping than spin waves. As a voltage-driven effect, this is energy-efficient due to the lack of ohmic losses, compared with microwave excitation where electric current-induced magnetic field generates spin excitations. Acoustic excitation techniques are also promising because the speed of sound is about five orders of magnitude slower than the speed of light, resulting in acoustic wavelengths in micrometers at GHz frequencies, and, therefore, local coupling to spin wave excitations with nonzero wavevectors is possible.6 This means that other nonuniform modes can be excited simultaneously. Another advantage is that time-gated measurements as shown in this work can suppress the electromagnetic (EM) radiative interference from the signal to avoid spurious contributions,10 as is important, for example, with spin-pumping experiments. The early work on ADFMR provides the theoretical background and foundation for
experiments using Landau-Lifshitz-Gilbert (LLG) and elastic wave equations. These theoretical expressions lead to the geometrical signature of the ADFMR signal, which can be used to differentiate between types of SAWs (e.g., Rayleigh waves or shear-horizontal waves). Also reported in the literature is the experimental evidence of ADFMR in dilute ferromagnetic semiconductors (Ga, Mn) (As, P) at low temperatures. More practical and application-relevant work shows how spatial and volumetric variations of the ferromagnetic film affect the power absorption at resonance. Further detailed energy flow and quantitative power absorption studies have been reported to understand the practical use of this phenomenon in device applications.

This study is focused on investigating a variety of design decisions in the production of ADFMR devices. We vary choice of the electrode material, the number of IDT finger pairs, the ferromagnetic thin film deposition technique, and the effect of the Au capping layer on the ferromagnetic thin film. We quantitatively compare different ADFMR devices by extracting normalized absorbance data and implementing established FMR analysis techniques. In a power-dependence study, we also note an asymmetry in the ADFMR response which indicates Duhamel oscillation behavior, giving insight into the magnitude of spin precession cone angle during the transmission. This is the first ADFMR report that systematically analyzes key performance criteria of the device design for comparison and optimization.

II. DEVICE DESIGN

An ADFMR device consists of a pair of mirrored split-finger IDTs (see Fig. 1a) on y-cut lithium niobate (LiNbO3) such that SAWs travel between them along the z-axis. IDTs have n pairs of fingers (n = 60 or 100 in this work) with length Lx = 480 μm and minimum separation between the IDTs of 3 mm along the x-axis. The electrode width and spacing is Lz = λ/8 = 1.5 μm which, given the SAW velocity 3488 m/s, leads to a fundamental frequency f1 = 291 MHz. IDT patterning for the metal lift-off process was completed using an image reversal photoresist AZ 5214E and a Karl Suss MA6 mask aligner lithography system. The IDT material was Al or Au with thickness Lx = 70 nm, deposited via sputtering or evaporation.

The split-finger design was chosen because at higher odd harmonic frequencies, it minimizes the destructive interference caused by the reflections within the IDT electrodes. This allowed us to explore a range of frequencies near f1, f3, f5, and f5 = 291, 873, 1455, and 2037 MHz, respectively. The actual optimal transmission frequencies varied within a few megahertz due to fabrication variations and mass loading. In the delay line between IDTs, Lz = 200 μm-thick Ni film was deposited and patterned using the standard lift-off process, with thickness Lz = 500 μm, enough to cover the entire SAW propagation area along x. This thickness Lz was shown to exhibit optimal absorption and damping. For this work, the Ni length Lz was 1.2 or 2.2 mm.

We tested nine devices in three distinct series of device types, which we label as described in Table I.

ADFMR contrast is known to have a linear dependence on length Lz, so we normalize our results in this work to simplify and remove the influence of Lz.

III. TIME DOMAIN MEASUREMENTS

A Tektronix TDS7404 oscilloscope was used in conjunction with a Keysight N5171B signal generator to scan the spectral region of interest for SAWs. A 0.2-μs-wide input pulse was split into two paths, with a reference path traveling directly to an oscilloscope input and a signal path traveling through an ADFMR device with the output then sent to a second oscilloscope input. The oscilloscope was triggered on the reference pulse at time 0, and EM radiation is detectable within the first 0.3 μs. Slower signals from 0.3 to 2.0 μs are acoustic waves traveling through the device as shown in Fig. 2.

At frequencies f1 = 287 MHz, f3 = 862 MHz, and f5 = 1429 MHz, we can see strong signals that appear with a time delay of about
0.85 μs. With a propagation distance from input IDT to output IDT of 3 mm, this indicates an acoustic velocity of 3500 m/s, consistent with the known Rayleigh wave velocity 3488 m/s for z-traveling waves in y-cut LiNbO₃. In addition, we observe a response at around 610 MHz with a velocity 6700 m/s. This velocity is consistent with longitudinal waves, but further investigation is required to verify the nature of this signal. For all signals we observed the triple-time-delay signal of the SAWs which reflected backwards, then reflected again off the input IDT, then arrived at the output, but for the slower Rayleigh waves, this signal is off the scale shown here. The triple transit can be minimized with an appropriate reflector design.

**IV. IDT DESIGN**

Mass loading is a major concern in the design of SAW devices because even the addition of very thin films can significantly alter both frequency and attenuation of SAWs. The mass densities of Al and Au are ρ = 2.7 and 19.32 g/cm³, respectively, thus the total mass of the IDTs depends strongly on the choice of the electrode material. The mass m of the IDT finger material in the path of the SAWs is estimated to be 54 ng for Al or 390 ng for Au, given by $m = 4nL_xL_yL_zρ$. In comparison, the mass of Ni in the propagation path is about 200 ng, given by $m^{Ni} = L_x^{Ni}L_y^{Ni}L_z^{Ni}ρ$. We performed a direct comparison of two similar devices (Au and Al electrodes). Changing the electrode from Au to Al improved transmission efficiency S21 at $f_0$ by a factor of about 1000, which we believe to be due to factors such as the reduction in electrode metal mass, decrease in electromagnetic radiative coupling, and decrease in reflectivity due to improved impedance matching. For ADFMR devices, the choice of IDT electrode metal has a significant impact in terms of the ability of the device to operate at higher harmonics with minimal loss.

A substantial source of loss in SAW devices is EM radiation due to the impedance mismatch at material interfaces. We measured the EM radiation at zero time delay with 1429 MHz input to determine whether the IDT electrode has an appreciable effect. Similar devices using Au or Al electrodes had no noticeable difference in this signal, so we infer that this material choice has an insignificant impact on the radiative properties of the IDTs. Impedance-matching measures were not taken in the design of these devices but should be considered for the future.

In a similar study, we noted that the design of the printed circuit board (PCB) can have a strong impact on the EM radiative signal. Transitioning from early designs to our current microwave waveguide design [Fig. 1(c)] resulted in reducing this EM radiative signal by 1–2 orders of magnitude. Therefore, all further results were obtained with this design, although potential may exist for further improvements in terms of radiative loss from the PCB.

To understand the spectral properties of the IDTs, we varied the input and detected frequency away from the IDT resonance conditions and measured the response. In Fig. 3(a), we see the resulting transmission for the condition where the magnetic layer is fully saturated ($H ≫ H_s$). Each resonance peak was converted to a linear scale and then fitted with a Gaussian approximation (which provided a fit quality of $R^2 > 0.97$ near resonance) as shown for $f_0$ in the inset. Center frequency $f_0$ and half-width $Δf$ were used to calculate a quality factor $Q = f_0/Δf$. The quality factor is a measure of the sharpness of a resonance peak and the maximum power transmitted at resonance. For single-frequency measurements, maximum transmission is desired, which translates to high Q. However, for the study of magnetoelastic spectral behaviors, a delicate balance is required between a broad peak (low Q) and efficient transmission (high Q) to obtain the greatest possible amount of information.

The quality factor of the IDT resonances is shown in Fig. 3(b). The fits for 60-pair devices had Gaussian widths ranging from 1.88 to 2.29 MHz (average 2.09 MHz), but those for 100-pair devices ranged from 1.20 to 1.56 MHz (average 1.37 MHz). This corresponds to a quality factor Q of 680 and 1000, respectively. On the other hand, peak power transmission [Fig. 3(c)] does not show a clear trend as a function of the number of pairs. Further study is necessary to determine how many pairs are optimal. We conclude that the difference between $n = 60$ and 100 is enough to significantly affect the width of the spectral peak, but the minor effect it plays on the overall transmission is overshadowed by other factors, such as variations in the fabrication process or other sources of experimental uncertainty.

**V. INFLUENCE OF Ni THIN FILM ON ABSORPTION**

ADFMR devices studied in this work produced the familiar 4-lobe pattern reported previously. An example is shown in the inset of Fig. 4. As a figure of merit, we extracted the ADFMR contrast (the difference between maximum and minimum signal on this ADFMR plot) and normalized to the length $L_x^{Ni}$ of the Ni. This value is of interest because it signifies how clearly distinguishable the “on” (absorption) and “off” (transmission) states are in a...
FIG. 3. (a) Transmission $S_{12}$ with $H \gg H_0$ for the available SAW spectrum. The operating fundamental frequency and its odd harmonics (287, 862, 1429, and 2000 MHz) are indicated by the vertical dashed lines. Inset: peak transmission at 5th harmonic with Gaussian fit for a variety of devices. Solid curves are 60-pair devices and dashed curves are 100-pair devices. For visibility, each dataset is shown centered at its own individual $f_5$ value. (b) $Q$ factor for each device, grouped by the number of pairs. (c) Peak $S_{12}$ transmission for each device, grouped by the number of pairs.

FIG. 4. ADFMR contrast (difference between “on” and “off” states) as a function of frequency. Device A0 was chosen as a reference to which others could be compared. Blue lines are a guide to the eye. The operating fundamental frequency and its odd harmonics (287, 862, 1429, and 2000 MHz) are indicated by the vertical dashed lines. Inset: example plot of loss as a function of angle $\phi$ (see Fig. 1) for device A0 at $f_5$ showing typical ADFMR characteristics. The angle $\phi_0$ indicates the peak ADFMR signal.
The influence of the magnet length has already been published, so we ignore it in the current work.

To use $A_0$ as a reference, we collected a broad spectrum of data off-resonance (blue data in Fig. 4) and as a result can see that the overall trend increasingly slopes upward over the available range. Off-resonant data show that near $f_1$ and $f_3$, the contrast is nearly independent of the frequency with a gradual positive slope. Near $f_5$, the slope is increased. At higher frequencies, $S12$ is much lower resulting in a lower signal-to-noise ratio. More data would need to be acquired to confirm apparent peaklike behavior near $f_5$. With Ni devices, ADFMR contrast is improved simply by increasing the operating frequency up to and beyond 2 GHz, as has been shown previously.

When looking at the results for other devices at $f_1$ and $f_3$, their behavior systematically falls into 3 groups. The sputtered Ni device C8 has lower contrast (3.45 dB/mm) compared to evaporated Ni devices (group A and B devices). The evaporated films in group A (with the Au capping layer) all performed similarly, but the evaporated films in group B (no capping) all strongly outperformed the others. This indicates that the capping layer inhibits ADFMR performance, probably due to spin-pumping which acts as an additional relaxation channel. This measurement is indicative of the fact that the choice of physical vapor deposition technique strongly impacts the absorption behavior in ADFMR devices. Sputtered and evaporated Ni films have shown notably different behavior. However, we make no claims on whether or not sputtering is a better choice for ADFMR because the quality of sputtered films is highly dependent on the deposition parameters used.

To further examine the differences between the three types of devices, we chose the ADFMR angle $\phi_0$ at which minimum RF transmission occurred to compare normalized data. For a given electrical power input $P_{in}^{\text{film}}$, the total loss $P_{in}^{\text{film}} - P_{out}^{\text{film}}$ is an FMR-like Lorentzian trace with vertical offset $\epsilon_0^{\text{film}}$, where $\epsilon_0^{\text{film}}$ is an ADFMR-independent loss that encompasses reflection from impedance-mismatch, damping, dispersion, diffusion, and mass loading. The loss associated with ADFMR (normalized to the Ni length) is then $\epsilon_0^{\text{film}} = (P_{in}^{\text{film}} - P_{out}^{\text{film}} - \epsilon_0^{\text{film}})/L_{\text{Ni}}$. By substituting loss for transmission $T^{\text{film}} = 1 - \alpha^{\text{film}}$, linearizing $T = 10^{-\alpha^{\text{film}}/10}$, and invoking the relation $T + A = 1$, we can define a linearized ADFMR-related absorbance

$$A = 1 - 10^{-\left(\frac{-A_0 + A_{1-3}}{10}\right)}.$$  

The absorbance data [Fig. 5(a)] were fitted with Lorentzian curves of the form

$$A = \frac{2C}{\pi} \frac{\Delta H}{(H - H_0)^2 + \Delta H^2},$$

where $H$ is the magnetic field strength, $\Delta H$ is the half-width, $H_0$ is the resonant field strength, and $C$ is the area under the curve. These fits for $f_3$ are solid lines in Fig. 5(a), in which we see a clear distinction between the performance of the three device groups A, B, and C. The fitted parameters $\Delta H$ and $H_0$ are used to produce the graphs standard for FMR experiments, as shown in Figs. 5(b) and 5(c).

Table II shows the resulting fitting parameters for harmonics $f_3$ and $f_5$. The contrast discussed previously is related to the maximum value $A_{\text{max}}$ and confirms group B as the device group with the highest ADFMR contrast.

The half-width shown in Fig. 5(b) is described by $\Delta H = \Delta H_0 + 4\pi\alpha / |\gamma|$, where $\Delta H_0$ is the inhomogeneous broadening and $\alpha$ is the Gilbert damping parameter. From the wide spectral view of $A_0$, we can see that the linewidth is superlinear which can be the case, e.g., for two-magnon scattering, or when the field is insufficient to saturate the magnetization. The slope drastically increases for the sputtered Ni device, indicating that the Gilbert damping $\alpha$ is much higher in the sputtered Ni film. A separate study is suggested to systematically compare the influence of ferromagnetic thin film
VI. NONLINEAR POWER DEPENDENCE

An oscillator operating in a nonlinear power regime can be described by the Duffing equation \( x + \dot{x} + ax + bx^3 = \gamma \cos(\omega t) \).

TABLE II. Fitting parameters for Lorentzian normalized absorbance \( A \) of the device groups A, B, and C.

<table>
<thead>
<tr>
<th>Group</th>
<th>( A_{\max} ) (mm(^{-1}))</th>
<th>( f_3 ) (MHz)</th>
<th>( H_0 ) (G)</th>
<th>( \Delta H ) (G)</th>
<th>( A_{\max} ) (mm(^{-1}))</th>
<th>( f_5 ) (MHz)</th>
<th>( H_0 ) (G)</th>
<th>( \Delta H ) (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.24</td>
<td>73</td>
<td>89</td>
<td>0.72</td>
<td>84</td>
<td>129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.37</td>
<td>35</td>
<td>61</td>
<td>0.90</td>
<td>49</td>
<td>116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.23</td>
<td>66</td>
<td>96</td>
<td>0.56</td>
<td>129</td>
<td>270</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The nonlinear component of the restoring force \( \beta \) is equal to 0 when operation is in the linear (low power) regime, and the resonance is symmetric about the center frequency which can be described by a Lorentzian. However, when the power becomes high enough, the symmetry is broken even to the point where hysteretic behavior can occur.\(^{23}\) The power at which this change occurs is known as the Suhl threshold and has been directly observed using MOKE.\(^{24}\) Here, we examined the power dependence of our ADFMR devices to determine the power regime of operation.

In Fig. 6, we show the power-dependent ADFMR behavior for the angle of peak absorption \( \phi_0 \). While increasing the input power from \(-10\) to \(19\) dBm, we fitted each trace with a Lorentzian, then analyzed the residual difference between the data and fit for each power. At higher input powers, we see the shape change as the peak grows more asymmetrical, with the most dramatic change occurring at \(19\) dBm. From these data, we can conclude that our input power can produce a high enough angle of spin procession to be in the Duffing regime (on the order of a few degrees for YIG),\(^{23,25}\) meaning care should be taken to consider the impact of Duffing response in further studies.

VII. CONCLUSION

We have examined several aspects of ADFMR devices, including the IDT electrode material and the number of pairs, as well as magnetic thin film growth methods. We observed ADFMR response in the time domain which showed multiple resonances associated with higher odd harmonics in our split-finger SAW devices. We also noted a faster acoustic wave yet to be associated with ADFMR which we believe originates from longitudinal waves.

By studying ADFMR response over a broadband spectrum, we were able to identify quality factors of our IDTs and conclude that 60-pair IDTs give a broader response than 100-pair without sacrificing peak transmission.

The impact caused by different magnet growth methods was examined, including e-beam evaporation with and without an Au capping layer and sputtering. It was determined that our sputtered film produced a much broader and, therefore, weaker ADFMR response and showed an indication of high damping, and the evaporated Ni with no capping layer gave the most ideal results to date with low damping and a high contrast.

A power-dependence experiment revealed non-Lorentzian behavior which can be attributed to Duffing response, which suggests that the pump power used in this work causes a precession cone angle on the order of at least a few degrees. This shows that the efficiency of the process is sufficient to drive strong spin waves in the magnetic material.

These methods can extend to future, more novel ADFMR devices, providing a way to quickly compare quality and optimize methods. Thus, this work builds on the recent studies and fills in the gaps with a systematic and comprehensive review of the device design process, providing a useful description of the parameters relevant for the development and optimization of ADFMR.

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