Magnetoelastic effect with Surface Acoustic Waves in Nickel

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Abstract: Surface acoustic waves (SAW) are micrometric strain waves that propagate on the surface of a solid. They are good for a number of applications and have recently been used for their ability to couple with magnetic states in magnetostrictive materials. In this paper we study the SAW absorption of a magnetic material (Nickel) and find the angle dependence between the SAW propagation direction and the magnetic field orientation. We find that when SAW and the magnetic field are perpendicular or parallel there is no power absorption, but a maximum appears at 45 degrees. Furthermore, there is a dependence with the strength of the magnetic field. At high enough fields the magnetic moments are saturated and have enough energy to overcome the coupling generated by SAW, whereas at lower magnetic fields there is SAW attenuation and a maximum appears at a resonant frequency.

I. INTRODUCTION

Modern electronics are largely based on magnetism and use electric current or magnetic field to modify magnetization states. This, results in power loss due to heat and a non-local magnetization variation making it inefficient in small devices. A more power-efficient method to produce changes in the magnetization is by applying strain.

Ferromagnetic materials, such as Nickel, experience changes in shape when magnetized, and this property is called magnetostriction. This effect was first studied by J. Joule in 1842 when he observed a change in shape of ferromagnets under the influence of a magnetic field. This effect is attributed to the rotation of the internal magnetic domains due to a change in the preferred orientation. Furthermore, we can use the inverse magnetostriction effect, also known as magnetoelastic effect, to generate changes in the magnetization when applying strain.

Using elastic materials, such as piezoelectrics, we are able to generate elastic waves on the surface that can produce strain on adjacent materials. These waves are called surface acoustic waves (SAW) and can be generated with a device called an interdigital transducer (IDT). An IDT consists of two interlocking comb-like arrays of metallic electrodes, and are commonly used as filters of frequencies, since the only frequencies they can accept are multiples of the distance between their fingers (Fig. 3(a) shows a representation of an IDT). SAW are used due to their small wavelengths, which makes them perfect for nano and micrometric devices.

Recent studies have shown a variation in the amplitude of propagation of SAW when a magnetic materials is placed on top [1], showing that the magnetic material in fact interacts with the elastic waves. This interaction is made through the coupling between the SAW and the magnetic moments. The latter when placed under the influence of a magnetic field will precess around its axis at certain frequencies. This coupling mechanism has been proven to be a great source for different studies such as acoustic spin-pumping [2, 3]. Acoustic spin pumping can transfer spin current from ferromagnetic materials into nonmagnetic metals and can be converted into charge currents that could be used in many applications.

In this paper we aim to study the interaction between the lattice motion and the magnetization to find how the angle between them affects the magnetoelastic effect. We use a hybrid device composed of a piezoelectric material and a magnetic material. Placing the device inside an electromagnet we apply a magnetic field that will re-orientate the magnetic moments causing them to precess. Then, through IDTs we are able to use the inverse piezoelectric effect to generate a varying strain field that will interact with the magnetic moments producing changes in the magnetization. Furthermore, using a rotatory sample-holder we study the angle dependence of the magnetoelastic effect and the acoustoelectric effect, which is a new-found property in this kind of devices.

II. THEORETICAL BACKGROUND

A. Surface Acoustic Waves

Surface Acoustic Waves (SAW) are elastic waves generated parallel to the surface of an elastic material. The first appearance of SAW was published in a paper by Lord Rayleigh in 1885 [4], where he characterized them as having a longitudinal and vertical shear that could influence contacting layers. The amplitude of propagation of SAW in the neighbouring layer is directly linked to the material's mechanical properties.

The most common way of generating these waves are through Interdigital Transducers (IDT). Sending an AC voltage signal to the one IDT we can generate acoustic

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waves by the inverse piezoelectric effect, where elastic deformations are produced due to a difference of potential between two electrodes of the IDT. An additional IDT will receive these waves and by the direct piezoelectric effect it will transform the elastic deformations into a voltage signal.

The most important characteristic of SAW is the speed propagation. Electromagnetic waves (EMW) have a velocity of 3×10^8 m/s whereas the propagation of acoustic waves on a substrate is approximately $v_s = 4000$ m/s. We can obtain the SAW frequency from the following formula $f_{\mathrm{SAW}} = v_s/\lambda_{\mathrm{SAW}}$ and the λ_{SAW} will be twice the distance between the IDT fingers. Therefore, for the same frequency we will have wavelengths several orders of magnitude smaller than on EMW.

B. Magnetization dynamics

The most accurate representation of the magnetization dynamics in the presence of a magnetic field arises from the Landau–Lifshitz–Gilbert equation (LLG)

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H_{eff}} + \alpha \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \qquad (1)$$

where $H_{\mathbf{eff}}$ is the effective field composed of the external static field, anisotropy field, exchange field and demagnetizing field, γ is the gyromagnetic factor and α is the Gilbert damping parameter. It reproduces a precessing spin around the effective magnetic field axis with a damping component as shown in Fig. 1.

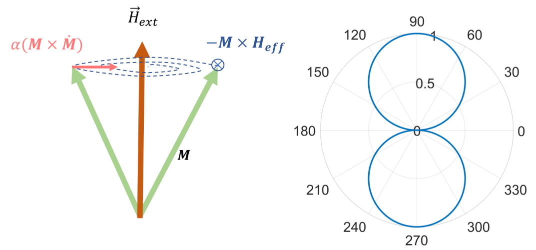

FIG. 1: On the left hand side, is a representation of the magnetization dynamics from the LLG equation. On the right hand side, a polar plot of the first component (torque) as a function of the angle between **M** and $\mathbf{H}_{\mathrm{eff}}$.

A solutions can be found when **M** and $\mathbf{H}_{\mathrm{eff}}$ are parallel, resulting in no torque. When the angle between **M** and $\mathbf{H}_{\mathrm{eff}}$ is different than zero then there will be spin precession and a maximum appears when they are perpendicular. Plotting the first term - the torque - of the LLG equation in polar coordinates and taking the radius as $\dot{M}/M_s$ results in a two-fold shape (Fig. 1). The power absorption will be linked to the precession amplitude, the energy provided by the magnetic field and the SAW frequency.

C. Magnetization coupling with SAW

SAW induce a time-varying strain field on the surface of a solid resulting in tensile ($S_{xx} > 0$) and compressive ($S_{xx} < 0$) phases (Fig. 2). The strain produced in the ferromagnetic material will turn into lattice waves, quantized into phonons, that will interact with the generated spin waves, quantized into magnons, in a phonon-magnon coupling. In this coupling we can observe attenuation of the SAW transmission and a change in the magnetic moment oscillation amplitude proving an interaction between them. It is shown that SAW can generate magnetic waves in Nickel [5], obtaining variations up to 25° between spin orientations at each phase. This oscillating strain and magnetic waves are called magnetoacoustic waves.

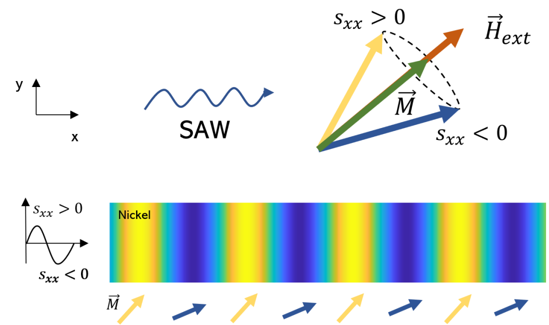

FIG. 2: From top to bottom. This shows the effect of strain phases in the magnetization dynamics. Bellow is a colormap representation of the strain field in which the yellow shows the tensile phase and the blue shows the compressive phase. Under it, we show the magnetization direction in each part of the strain field. We assume a 45° angle between the SAW propagation and the magnetic field.

The generated strain field will add an anisotropic component to the effective field ($\mathbf{H}_{\mathrm{eff}}$) from Eq. 1. Mathematically, we can express that anisotropy energy as a power series of even numbers, since the anisotropy does not change under an inversion of the magnetization ($E_{\mathrm{ani}}(\mathbf{M}) = E_{\mathrm{ani}}(-\mathbf{M})$). Taking the first term we can express the anisotropy energy as

$$E_{\mathrm{ani}} \propto -a\mathbf{M}_{\mathrm{x}}{}^2, \qquad (2)$$

where a is a constant and $\mathbf{M_x}$ is the magnetization value along the SAW propagation direction. The anisotropy field will therefore be

$$\mathbf{H_{ani}} = \frac{\partial E_{\mathrm{ani}}}{\partial \mathbf{M}} \propto -2a\mathbf{M}_{\mathrm{x}}. \qquad (3)$$

This field will give rise to interesting solutions that will be discussed in Section III.B.

III. RESULTS

We started out by measuring the power transmission at 45 degrees between the magnetic field and the SAW propagation direction at different frequencies on a Nickel film with a thickness of 50 nm. We set up the piezoelectric substrate with the Nickel film in between two IDTs in-plane with the magnetic field. We send electrical signals to the IDT 2 with a Programmable Network Analyzer (PNA) which are converted into SAW that will propagate in the piezoelectric. As SAW has a penetration distance comparable to their wavelength we can assume that the whole Nickel film is affected. As the Nickel is placed on top of the piezoelectric, the strain field will produce lattice motions that will couple with the magnetic environment in a phonon-magnon coupling. The PNA will then measure the resulting transmission from IDT 1. The schematics of the setup are shown in Fig. 3(a). In our case we can transmit frequencies of $f_0 = 125$ MHz and their harmonics. A frequency sweep is shown in Fig. 3(b) with the first peak corresponding to f_0.

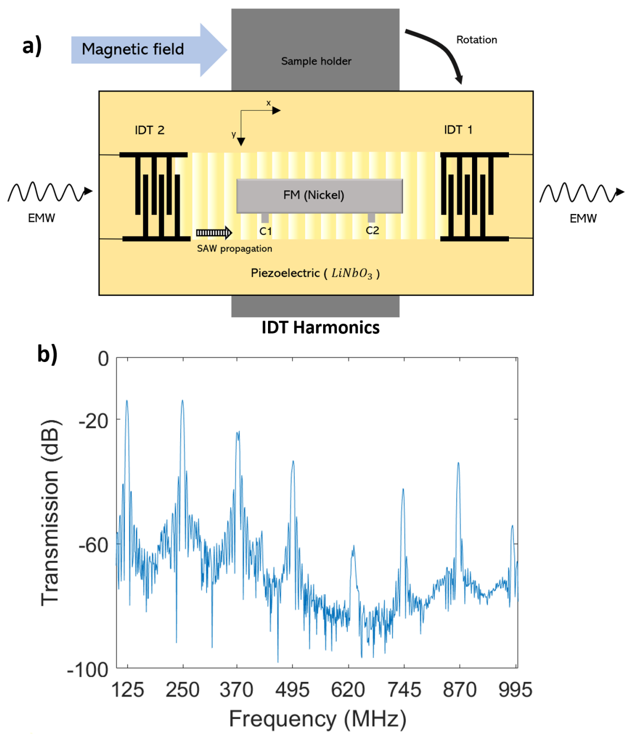

FIG. 3: **a)** Experimental setup. The Network Analyzer sends an electrical signal to IDT 2 and measures the result in IDT 1. SAW travel along the x direction creating longitudinal (s_{xx}) strain in the Nickel film. C1 and C2 are contacts used to measure longitudinal voltage. **b)** Transmission as a function of frequency. Shows the IDT working frequencies, 125 MHz and its harmonics.

A. Magnetoelastic effect

To begin our study we measure the transmission of SAW in the Nickel sample and compare it to a specially manufactured Permalloy (Py) with no magnetoelastic effect. The common composition of a Permalloy is 19% Fe and 81% Ni.

Nickel has magnetostriction and experiences magnetoelasticity. When the field is large enough, the magnetization is saturated and has enough energy to stay in that state ignoring the lattice motions and experiencing no absorption. We use the saturation value to normalize the data so any absorption is detected as a negative SAW transmission (Fig. 4(b)). As we decrease the field we can see that we lose transmission of SAW due to the absorption from the magnetic moments. When the SAW frequency matches the spin precession frequency, there will be resonance and the absorption will be maximum. This is represented as the 2 peaks at ±40 G. When approaching zero magnetic field, at approximately 10 G, a valley appears corresponding to the start of the spin inversion in which the magnetization of the material is 0. This field is called the coercive field (H_c). As we keep increasing the magnetic field we see a symmetric response. The coercive field being at positive 10 G means that the field sweep started at a negative field.

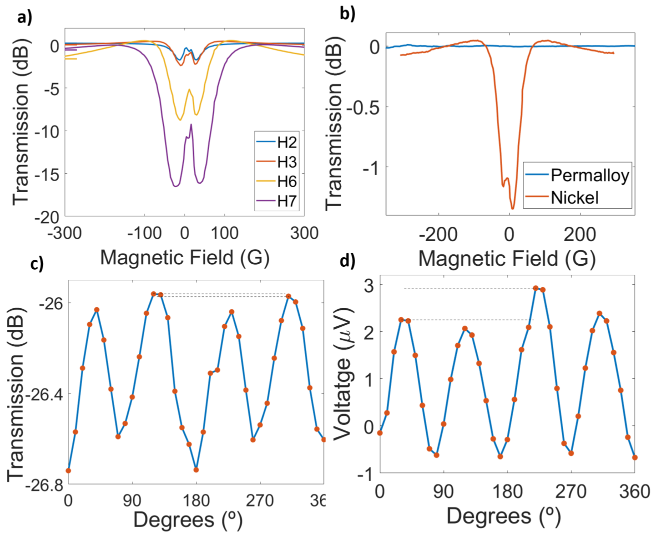

FIG. 4: **a)** Transmission for different harmonics of Ni. **b)** Comparison between the Nickel and Permalloy. Permalloy only shows noise. **c)** Angle dependence of transmission. **d)** Angle dependence of voltage. The dash lines represent the difference between peaks in figures c) and d).

On the other hand, Permalloy does not experience magnetostriction; therefore, there will be no phonon-magnon coupling to change the magnetization. In Fig. 4(b) Permalloy shows some noise and no sign of absorption.

B. Power absorption angle dependence

In Section II.B we explain how an external field produces a torque on the magnetic moments of the Nickel making it precess around the field axes. SAW add another component to the effective field affecting the magnetization. The lattice movement will modify the distance between atoms, which will affect the orbit of the electrons creating anisotropies from dipole-dipole interactions. This effective field will have only one component in the direction of propagation of the SAW and will depend on the magnetization (Eq. 3). We would expect no effect from SAW when it is perpendicular to the magnetization, since there will not be any preferred orientation that minimizes its energy, Fig. 5 shows a representation.

FIG. 5: From left to right. When SAW and magnetization are perpendicular, the magnetization will not have any orientation in which to minimize energy; therefore, it will not move. As the angle changes the lattice motion will have more effect reaching its maximum at 45 degrees.

Using the anisotropy field from Eq. 3 and solving the first component of the LLG equation (Eq. 1), we find 3 important solutions. Taking the SAW propagation on the x axis, then $H_{\text{ani}} = (-2aM_x, 0, 0)$ and taking the magnetization at any direction $M = (M_x, M_y, M_z)$, we find:

1. SAW $\perp$ M: There won't be any H_{ani} since $M_x = 0$; therefore, there will not be any absorption.
2. SAW $\parallel$ M: H_{ani} is at its maximum, but there will not be any torque ($\tau = -\mathbf{M} \times \mathbf{H}_{\text{ani}} = |M||H_{\text{eff}}| \sin\theta$) resulting in no absorption.
3. SAW at 45° from M: Maximum absorption.

These solutions can be visualized in Fig. 6. From a physics point of view, when **M** and SAW are perpendicular the magnetization will not have any direction in which the energy will be lower; therefore, it will remain static and no absorption will occur. At an angle different from 0 or 90, the magnetization will have a lower energy state when rotated along the SAW axis.

Using the setup shown in Fig. 3, we can control the angle of the sample-holder with a screw that can move the sample 1° in either direction. We start by measuring the power transmission at 45° (between the SAW propagation and magnetic field) for different harmonics, and we rotate 10° for each collection of data. We end up with a four-fold butterfly-shaped dependence as we expected

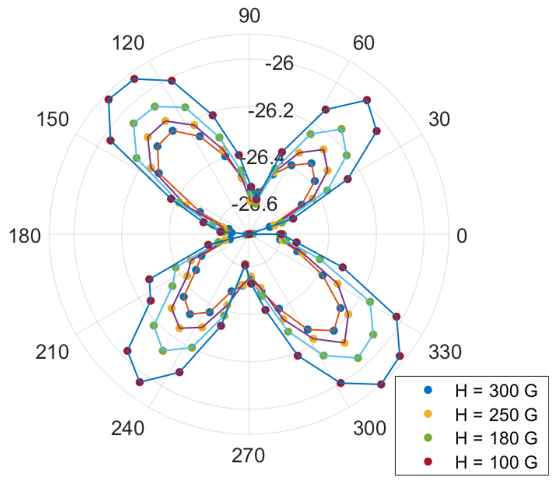

FIG. 6: Experimental data on the angle dependence of transmission at different magnetic fields for the third harmonic (H3: 375MHz).The radius shows the power transmission value in dB and goes from -26 dB to -26.6 dB.

(Fig. 6) reaching a maximum at 45 degrees. Additionally, there is field dependence. As the field decreases there is more power absorption due to the spin having less energy to stay in one direction.

C. Acoustoelectric effect in FM

Recent studies have shown a new property produced by the magnetoelastic effect [6]. A longitudinal voltage appears when SAW propagates through the Nickel film. Using the same experimental setup (Fig. 3) and a lock-in system connected to the signal generator, we can synchronize the AC electrical signal to the internal frequency of the lock-in and measure the longitudinal voltage from the contacts C1 and C2. With the lock-in system we can obtain voltage signals as low as $10^{-7}V$ by multiplying the output signal by the input signal to neglect any noise and filter the signal frequency that we want. Since the voltage depends on the SAW power absorption we expect to obtain the same butterfly-like figure. As it is a recent study there are many missing experiments to determine the exact answer to what generates this voltage but we can theorize that there are two current components; an AC and a DC.

- The DC component is the electrons moving in the SAW propagation direction.
- The AC component is the "wiggling" of the electrons due to an AC resistance change. As shown in Fig. 6(b) the strain field will excite the spin at different amplitudes that will cause a time-varying resistance in the form of a sinusoidal.

There is a clear association between the magnetoelastic effect and the induced voltage, when more power is

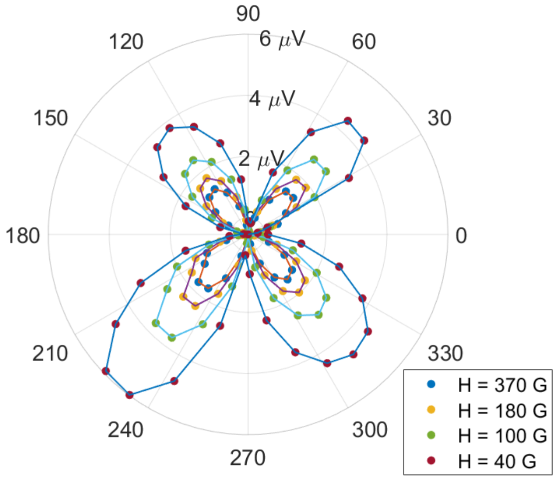

FIG. 7: Longitudinal voltage (V_{xx}) at different angles and magnetic field for the third harmonic (H3: 375 MHz). The radius shows the voltage magnitude and goes from 0 to 6 μV.

absorbed and the spin amplitude is maximized the voltage is maximized. A difference between Fig. 6 and Fig. 7 can be observed, there seems to be a preferred direction for the SAW that results in a non-reciprocity between peaks. This difference is marked with dashed lines in Fig. 4(c) and (d). Non-reciprocity in Ni films has been studied thoroughly in the past [7], in our case the effect is very subtle in the SAW transmission results, but can be clearly seen in the voltage. As Nickel is a conducting metal; therefore, we should take into consideration the free electrons since the SAW will couple with their cyclotron motion and can affect the results.

IV. CONCLUSIONS

We provide an overview of the basic characteristics of SAW and describe the phonon-magnon coupling that results in changes in the magnetization. We studied how the angle between the SAW propagation direction and the magnetic field affects the absorption and therefore the magnetoelastic effect. Furthermore, we find the expected behaviour at high and low magnetic fields, exhibiting more magnetoelastic effect at lower fields due to the lower energy provided to the magnetic moments. Finally, we mention the acoustoelectric effect, a new-found property of magnetostrictive materials resulting in a longitudinal voltage and find a similar behaviour as the SAW transmission. Further studies should focus on the difference in peak magnitude (non-reciprocity). At a constant magnetic field a change in SAW propagation and induced voltage can be produced by changing the angle between the SAW and magnetic field leading to useful applications. Furthermore, it would be interesting to study these effects at higher frequencies, ranging in the GHz, since it would give a faster magnetization state switch. Coupling between the lattice motion created from the SAW and the magnetic state pave the way for faster and more efficient devices and give rise to research opportunities.

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