Measure of SAWs' propagation in magnetoelastics

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Abstract: In this paper we go in depth in the study of the propagation of surface acoustic waves (SAWs) and its coupling with magnetoelastic materials (nickel, in our case). We found that the transmission coefficient of SAWs, propagating in a piezoelectric-magnetoelastic hybrid device, depends on the magnetic field and that there is a similarity with the classic ferromagnetic resonance (FMR). We also observed that there is a delay of 0.25m/s of the SAW's velocity due to the absorption from the magnetoelastic material.

I. INTRODUCTION

When thinking of changing the electric and magnetic properties of materials we have customarily used the effects of directly applying electric and magnetic fields to our samples of interest. In this paper, an alternative way is employed. In 1880, the brothers Jacques and Pierre Curie discovered piezoelectricity, the property of some solid materials to exhibit a change in their electric polarization when a mechanical stress is applied. The reverse effect is also possible and will be the one responsible for creating the surface acoustic waves (SAWs) we will work with in this paper (see section II.A).

Piezoelectricity and SAWs are nowadays used in a wide range of fields. The ability of piezoelectric materials to create potential differences allow them to work as some kind of power source, like in a cigarette lighter. They are also used as small motors, for ultrasound imaging in medical procedures and as sensors in microphones or musical instruments. SAWs can be used in electronic devices working as filters and sensors, but also in areas like microfluidics, where the transferred energy from the SAWs can perturbate the fluid.

On the other hand, in 1865 Emilio Villari discovered the inverse magnetostriction effect, or magnetoelastic effect, which is analogous to piezoelectricity. It is the property of ferromagnetic materials to exhibit a change in magnetization when a mechanical stress is applied. Magnetoelastic materials are used as force sensors, naval sonars or industrial vibrators, transformers, etc.

In our sample we will combine these two effects. If we deposit a film of ferromagnetic material on top of a piezoelectric substrate, we could be able to change the magnetization of the film by applying a varying electric field to the substrate. That is exactly the configuration we will have in our experiments and we will be interested in studying the propagation of the SAW travelling through the piezoelectric-magnetoelastic hybrid device as a function of an external magnetic field.

II. THEORY

A. Surface acoustic waves (SAWs)

Surface acoustic waves are deformation waves at the surface of a crystal, which can travel macrometric distances [1].

SAWs can be easily created with interdigital transducers (IDTs), electrodes in the shape of a comb that can generate acoustic waves with the electric signal that arrives to them and vice versa, when located on a piezoelectric substrate. As a consequence, we will be using them both as an emitter and a receiver of signal.

When coupled with another material, SAWs can change their amplitude and velocity, because of the absorption and dissipation of energy. That is exactly what we will be measuring in this paper. The lattice deformation of the piezoelectric substrate caused by SAWs also deform the material in contact and, if it is a magnetoelastic sample, due to the magnetoelastic effect explained above, it can change, locally, the magnetization of the sample and create spin waves (SW).

B. Spin Waves (SW)

Spin waves are the dynamic perturbation of magnetization that occur in magnetic materials (chpt. 11.1.5 of [6]).

In our case, we get to create spin waves in our ferromagnetic material due to the surface acoustic waves travelling through the piezoelectric substrate. These SWs will locally change the magnetization of the sample and, because of their coupling with SAWs [2], it will affect the propagation of the original waves and thus letting us study their transmission coefficient and their change in velocity.

SW can also be induced when performing a ferromagnetic resonance (FMR). In ferromagnetic materials, the magnetic moments of the sample can precess around an applied magnetic field with a frequency f, that depends on the external field and magnetization of the sample. In a FMR procedure, the ferromagnetic material absorbs radiation of that f.

III. EXPERIMENTAL DATA

A. The sample

Our sample is composed of a 10nm nickel film (ferromagnetic material) deposited on a $LiNbO_3$ piezoelectric substrate, between two interdigital transducers. By means of these IDTs the SAWs are induced on the piezoelectric substrate. One of the IDTs is working as an emitter and the other one detects the signal passing through the sample (receiver).

The IDTs receive a large range of frequencies for the electromagnetic waves we apply, but they can only work at the ones that obey the relation $f = \frac{nv}{d}$, where d is the space between each electrode, n is an integer number and v is the velocity of the SAWs in our substrate ($v = 3980\ m/s$) [1].

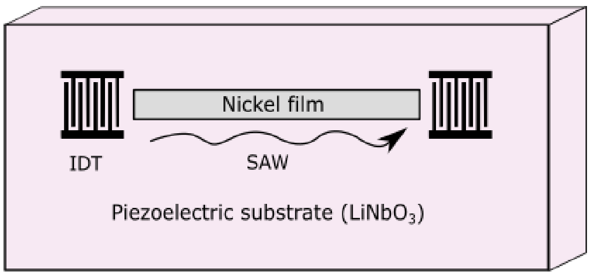


FIG. 1: Diagram of our sample.

B. Experimental setup

Our sample is always placed in the interior of an electromagnet. The latter produces the magnetic field we need using a current source, which controls the field by modifying the intensity passing through the wires. The magnitude of the field that is being applied is measured by a Hall probe placed inside the magnet. The current source, along with the probe, is connected to a computer and controlled by a Labview programme.

For the FMR and the measurements of the transmission coefficient of the SAWs (S_{21}), we use a Network Analyser (PNA) that provides the electromagnetic waves (microwaves) to excite the SAWs in our sample, by dint of the IDTs. When studying the SAWs' velocity we make use of an oscilloscope and a pulse generator. All these tools are also connected to the computer and to the Labview programme.

The aforementioned experiments are described in the following sections.

C. S_{21} measurements

The first part of the experiments is to measure the transmission coefficient of the SAWs travelling through the sample, S_{21}. The procedure is to first generate the microwaves with the PNA that arrive to the sample and create SAWs. Once the acoustic waves have crossed the whole sample, the second IDT converts them into electromagnetic waves that arrive back to the PNA. The PNA calculates the S_{21} parameter as a division of the signal that has been received and the one that has been emitted. We do the quotient because we are working with decibels (logarithmic scale).

As we explained before, the IDTs only work at certain frequencies, so first of all we plot the transmission coefficient, S_{21}, as a function of the frequency to detect which are the frequencies we will be able to work with during all our experiments (see FIG. 2).

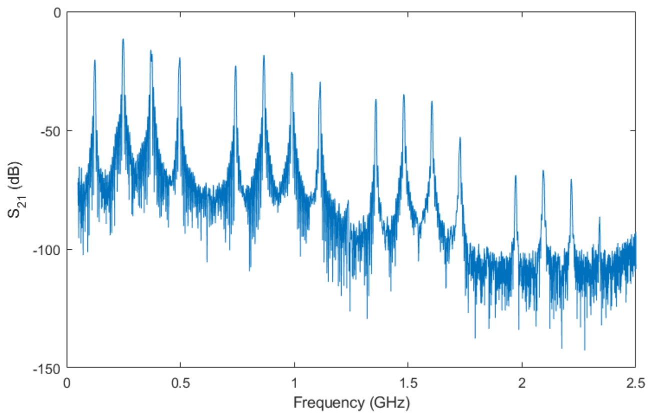


FIG. 2: S_{21} as a function of the frequency for a field $H = -0.1T$.

To obtain the S_{21} measurements in FIG. 2 and the following ones in this section, a gating method has been applied. The IDT acting as a receiver detects the SAW that has been produced by the other IDT but it also detects the direct transmission of the electromagnetic wave through the air and some other less intense bounces of the SAW with the wires or sample borders. Because we only want to focus on the direct transmission of acoustic waves, and knowing that these are orders of magnitude slower than the electromagnetic ones, we perform a gating technique. Also via the Network Analyser we do the Fourier transform and, filtering in the time domain, we eliminate the first signal that arrives to the IDT, corresponding to the electromagnetic wave.

From the labview programme we send orders to the current source to do a sweep of the magnetic field, from -0.1 T to 0.1 T, and for each interval we do another sweep for the frequencies, from 50 MHz to 2.55 GHz, by means of the Network Analyser.

Due to the presence of the nickel film, part of the waves' energy is absorbed and we want to study its dependence with the magnetic field. Now it can be plotted, for each working frequency of the IDT, the transmission coefficient, S_{21}, as a function of the magnetic field.

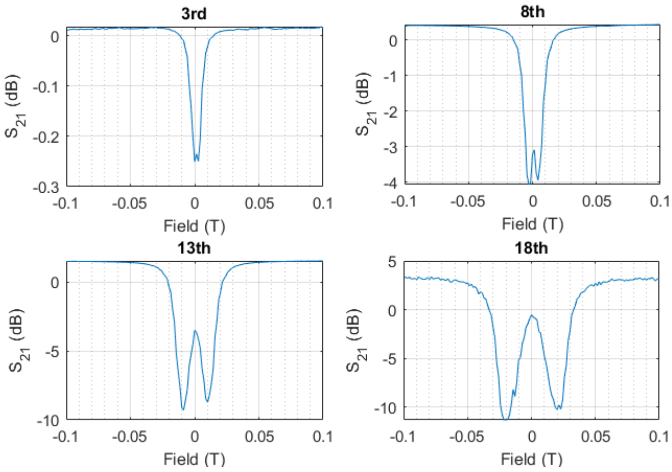


FIG. 3: Transmission coefficient as a function of the applied magnetic field. We plot only the 3rd, 8th, 13th and 18th harmonics.

We can observe in FIG. 3 that at the higher fields there is no absorption. Absorption is produced when the magnetic momentum of the nickel can oscillate around the direction of the applied field, but if it is too strong the magnetization will not be able to move at all and so no energy will we passed from the SAW to the nickel.

For the first harmonics we can only observe one peak of absorption at around 0T, but as long as we increase the frequency, we distinguish two peaks that keep separating from each other but are approximately at the same absolute value of the magnetic field. The difference in the two peaks' height is studied in [4]. In general, the magnitude of the absorption also increases with the frequency.

From the data in FIG. 3, the depth of the peaks and the magnetic field at which this abrupt drop occurs can be measured, as shown in FIG. 4.

D. Ferromagnetic resonance (FMR)

Ferromagnetic resonance consists in the absorption of electromagnetic waves, at certain frequencies and depending on the applied magnetic field, from a ferromagnetic material. This phenomenon is described by the Landau-Lifshitz-Gilbert equation (chpt. 13 of [5]).

As we are studying the absorption of SAWs through the nickel film it is interesting to perform a FMR on the same sample we have been working with to compare the effects. This time, as we only want the electromagnetic wave signal, and not the one from the SAW, we do another time domain gating but this time taking just the first signal we receive.

As we can observe in FIG. 5, for the low frequencies, the values for the FMR are overlapped. This could be

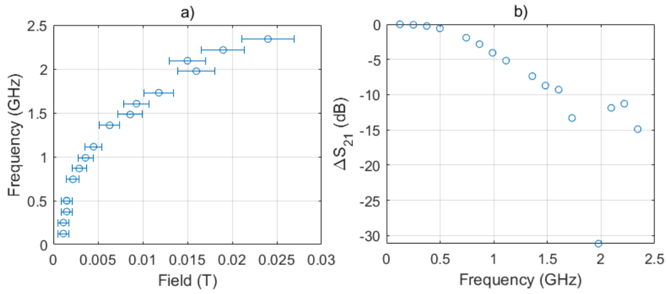


FIG. 4: (a) The magnetic field at which the maximum absorption occurs for each frequency with error bars. The error is calculated as the 10% of the field's value plus half the resolution in our data, $\delta H = 0.1H + 0.0005$. (b) Absorption as a function of the frequency.

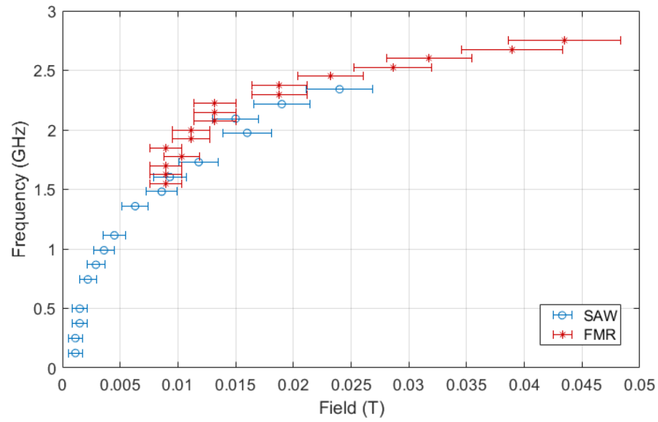


FIG. 5: Comparison of the peak's magnetic field between the FMR and the SAW driven absorption with error bars.

due to the procedure of the FMR (not applying direct electromagnetic waves to the nickel sample) or some signal noise.

For the FMR, as we do not have the limitation in frequencies that the IDTs provide, we have more clear data in higher frequencies which we do not show because cannot be compared with the data with SAWs.

The results obtained in sections II.C and II.D support the ones also studied in [3], with the same sample and experimental setup.

E. Velocity delay

For this section we use a pulse generator and an oscilloscope that can read electromagnetic waves up to, approximately, 1 GHz. The generator sends modulated wave pulses (continuous waves multiplied by a square signal) to the oscilloscope and to our sample. The signal that goes directly to the oscilloscope will be used as a reference for the measurements that will be carried out on the one that goes through the sample and will be, therefore, modified by the magnetic state of the nickel.

What the oscilloscope measures is the amplitude and the phase of the wave in comparison with the reference one. From this, the transmission coefficient, T, (converting the voltage to decibels to compare it with the results of the PNA) and the time and velocity delay (converting the phase delay in degrees to nanoseconds or meters per second) is obtained. This measurements will be performed as a function of the magnetic field (see FIG. 6).

The formulas being used for converting are:

$$\mid \Delta t \mid = \frac{\mid \Delta\theta \mid}{360 \cdot f} \qquad \frac{\mid \Delta v \mid}{v} = \frac{\mid \Delta t \mid}{T} \tag{1}$$

and

$$\mathrm{T(dB)} = 20\log\left(\frac{V}{1\,volt}\right) \tag{2}$$

The velocity of the SAWs, $v = 3980$ m/s, is the one measured in a $LiNbO_3$ substrate with no magnetic material attached, which should correspond to the measure at high magnetic fields in our experiments, where there is not any absorption from the nickel.

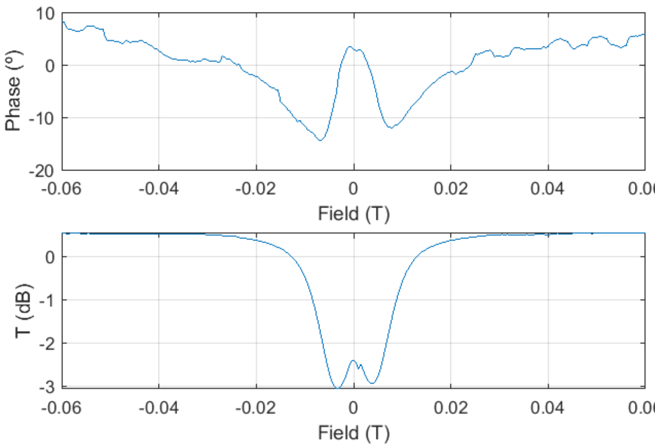
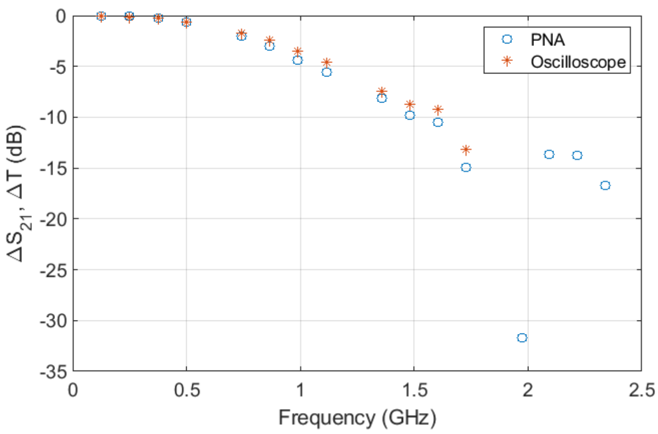


FIG. 6: Measurement of the phase and S_{21} for f = 0.9881GHz.

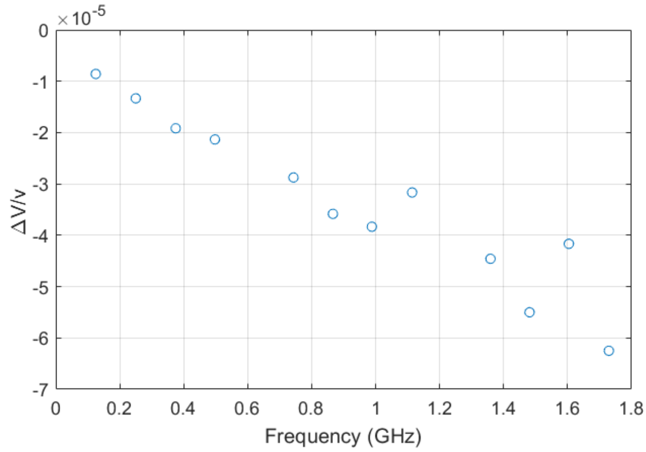
As for the changes in velocity, when looking directly at the oscilloscope, we observe that when the absorption occurs (near low values of the fields), because of the transferred and dissipated energy, the SAW becomes slower and so it arrives later to the receiver IDT.

However, in FIG. 6 we can observe that the peaks in the phase and transmission coefficient occur at different values of the magnetic field, but the behaviour is pretty similar.

Now we obtain these measurements for each frequency of the IDTs. This time we will only be able to work with the first twelve frequencies, since we have the limitation of the oscilloscope.



(a)



(b)

FIG. 7: (a) Comparison between the depths of the absorption. (b) Velocity delay of the SAWs as a function of the frequency.

We expect and observe that the depth of the absorption peaks are the same as the ones measured with the PNA, as we are measuring the same magnitude (see FIG. 7a).

FIG. 7b shows that there is an increase in the velocity delay at higher frequencies.

IV. CONCLUSIONS

A general clarification on this work is that there has not been found a theoretical model behind this phenomena in the literature. Therefore, no fitting has been done on any of the results.

- The first and most important result is that the transmission coefficient of the surface acoustic waves has a strong dependence on the magnetic field. We are able to couple the SAWs with the spin waves on the nickel film in order to perturb its magnetic state and for it to be able to absorb part of the SAWs' energy. There is an increase in the absorption peaks at higher SAWs' frequencies.

- The results show that there is a similarity with the SAW's field dependence and the FMR's. In both cases there is an absorption peak that varies its position with the applied magnetic field. The data is not clear enough at the lower frequencies of the FMR, which are the ones the SAWs work at. This difference could be due to the fact that we are not applying microwaves directly to only our nickel film. We are working with the same sample setup and getting only the part of the direct transmission of the signal through air, which doesn't create SAWs. This implies that there is less signal that arrives to the nickel. If we had data at higher frequencies for the SAWs experiments, we could maybe be able to compare the results more accurately. Another way to approach the problem would be to perform a FMR with just a sample of nickel (without the piezoelectric substrate) connected to a coplanar guide which would provide electromagnetic waves directly to the sample.

  This discussion of whether the SAWs' and FMR's results should be similar is still on. In both cases we are exciting a resonant frequency and, as a consequence, producing absorption from the magnetic material, only with different procedures. From this point of view, the results of the experiments would seem to have to be the same.

- Working with a SAW velocity of 3980m/s, we observe a maximum change in velocity of 0.25m/s ($\frac{\Delta v}{v}$ = 6.25·10^{-5}), that corresponds to 0.075ns of time delay. This is a small difference but it also indicates that there is an absorption of energy from the nickel film that affects the acoustic wave travelling through. Another important factor to take into consideration is that the depth of penetration of the SAW in the $LiNbO_3$ substrate is about 10μm, which is 10^3 times larger than the thickness of the nickel film (10nm). Thus, the nickel is only in contact with a small part of the wave and it is only capable of absorbing energy from the most superficial part of it.

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[1] Foerster M., Statuto N., Casals B., Hernández-Mínguez A., Finizio S., Mandziak A., Aballe L., Hernàndez J. M. Macià F., "Quantification of propagating and standing surface acoustic waves by stroboscopic X-ray photoemission electron microscopy", *J. Synchrotron Rad.* **26**, 184-193 (2019).

[2] Foerster M., Aballe L., Hernàndez J. M. Macià F. "Subnanosecond magnetization dynamics driven by strain waves", *MRS Bulletin* **44**, pp. 854-859 (2018).

[3] Ortells M. "Magnetization modification through magnetoelastic effect in a thin Nickel film" (2019).

[4] Sasaki R., Nii Y., Iguchi Y. Onose Y. "Nonreciprocal propagation of surface acoustic wave in Ni/LiNbO3", *Phus. Rev.* B **95**, 020407(R) (2017).

[5] C. Kittel, *Introduction to Solid State Physics*, (John-Wiley Sons, 2005, 8th. ed.).

[6] J. Stöhr, H. C. Siegmann, *Magnetism. From Fundamentals to Nanoscale Dynamics*, (Springer, Berlin, 2006).