Experimental setup to perform ferromagnetic resonance studies at the Modern Physics Laboratory

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Abstract: Ferromagnetic resonance (FMR) is a technique used for material characterisation. This work is about the design and the construction of measure system of FMR. The goal is that this setup can be used for FMR measurements by the students of Modern Physics Laboratory as an exercise. To perform this device, use of high magnetic field, microwave and high sensitivity detection technologies will be necessary. Design has been done considering physics principles of magnetism. The saturation magnetization of a 50nm thin layer has been calculated to demonstrate how it works.

I. INTRODUCTION

Ferromagnetic resonance (FMR) is a physical phenomenon, which occurs in ferromagnetic materials. It is about precessional motion of magnetic moments magnetic moment precessional motion around a magnetic field.

If an external magnetic field is applied to a magnetic moment, it will have precessional motions around the direction magnetic field. If the previous magnetic field is applied to a sample, where there are many magnetic moments. All of them will have a precessional motion. Although the treatment is equivalent to the single moment example, more magnetic field contributions will have to be considered in the sample case. Magnetic moments will have a precessional motion around the effective magnetic field ($\vec{B}_{eff}$).

There is a damping term, which is responsible of the decay of the magnetic precessional motion moments. An external energy must be given in order for the system not to decay. It is the point of the ferromagnetic resonance. If an external oscillating magnetic field, much less intense than the continuous one in order to not to change the magnetization, perpendicular to it, is applied with a specific frequency (resonance frequency), it will be able to keep the precessional motion. Some energy from the oscillating field applied will be spent on it. Resonance frequency does not depend on the damping term, but it is important to mention it in order to understand why the sample absorbs without its magnetics moments diverging.

The objective of this work is to design and build a device able to detect the magnetic resonance frequency for different applied magnetic fields. The method used consists on applying an oscillating magnetic field through the sample while a continuous one is applied perpendicularly.

With data about the energy absorbed by the sample, the frequency applied and the continuous magnetic field intensity, ferromagnetic resonance can be calculated.

In short, the goal is to build an economic setup that can be used in the Laboratori de Física Moderna course of the grade in Physics.

II. THEORICAL FRAMEWORK

Magnetic moment, $\vec{\mu}$, can be related with a mechanical angular moment, $\vec{L}$ [1]:

$$\vec{\mu} = -\gamma \vec{L} \, , \tag{1}$$

where γ is the gyromagnetic ratio.

Eq. 1 can be derivate and the result is:

$$d\vec{\mu} + \gamma d\vec{L} + \vec{L} d\gamma = 0 \, , \tag{2}$$

γ is a constant so:

$$d\vec{\mu} + \gamma d\vec{L} = 0 \, . \tag{3}$$

Finally, a precessional equation can be obtained:

$$\frac{1}{\gamma}\frac{d\vec{\mu}}{dt} = \frac{d\vec{L}}{dt} = \vec{\tau} \, , \tag{4}$$

where $\vec{\tau}$ is the torque vector.

A magnetic moment can be studied as a magnetic dipole. A pole undergoes a force $\vec{F} = \frac{\mu}{2}\vec{B}$ (if $\frac{\mu}{2}$ is considered as the pole magnitude), the other pole, however, undergoes an opposite force, so there is no net force. We can consider a rotation axis, which the dipole will turn around. The direction vector between the rotation axis and the pole, $\hat{r}$, is parallel to $\vec{\mu}$, so the torque moment will be: $\vec{\tau} = \vec{\mu} \times \vec{B}$, because only a perpendicular force to $\hat{r}$ will contribute to the rotation, so the equation of motion is:

$$\frac{1}{\gamma}\frac{d\vec{\mu}}{dt} = \vec{\mu} \times \vec{B} \, . \tag{5}$$

Nevertheless, B is, actually, an effective magnetic field, which affects the magnetic moments, so the expression should be:

$$\frac{1}{\gamma}\frac{d\vec{\mu}}{dt} = \vec{\mu} \times \vec{B}_{eff} \, , \tag{6}$$

$\vec{B}_{eff}$ is composed by different parts, the applied field, $\vec{B}_e$, the demagnetizing field, $\vec{B}_d$, the exchange field, $\vec{B}_{ex}$, and the anisotropy field, $\vec{B}_a$ [2].

$\vec{B}_{ex}$ will be 0 if the sample is uniformly magnetized, so the applied continuous field must be strong enough.

Despite of all parts of the effective field, only demagnetizing and applied fields are going to be considered, so:

$$\vec{B}_{eff} = \vec{B}_e + \vec{B}_d \ , \tag{7}$$

The demagnetizing field, $\vec{B}_d$, is about how the sample magnetization affects itself.

For a uniformly magnetized ferromagnet, $\vec{B}_d$, can be expressed as [3]:

$$\overrightarrow{B_d} = -N_{ij} M_j \mu_0 \ , \tag{8}$$

where i,j represent Cartesian coordinates and N are called demagnetizing factors. Our sample could be considered as infinite planes along in X-Y, so its demagnetizing factors are $N_{xx} = N_{yy} = 0$ and $N_{zz} = 1$.

There is a damping process due to the energetic transmission from macroscopic motion to microscopic thermal motion in the form of spin waves, lattice vibrations (phonons) or the thermal excitation of conductive electrons.

Due the difficult treatment of the previous phenomena, only a phenomenological mathematical description will be given. Including the damping term in the motion Eq. 6 and putting it in magnetization terms, Landau–Lifshitz equation is obtained [2]:

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}_{eff} - \frac{\alpha}{M} \vec{M} \times \frac{d\vec{M}}{dt} \ , \tag{9}$$

where ($\vec{M}$) is the sample magnetization.

As it can be seen in this formula, the precessional motion will decay because of the last term of Eq. 9, unless there were an external energy source able to keep the precessional motion.

Since resonance frequency does not depend on damping term of Eq. 9,

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}_{eff} \ . \tag{10}$$

Although anisotropy due to the crystalline lattice is not considered, there is a priority magnetization direction due the sample shape. So just the demagnetization term (ε_d) and Zeeman term (ε_Z), which is proportional to $\vec{B}_e \vec{M}$, will be considered in the sample energy. Considering the sample as an infinite bidimensional plane in X-Y, the (ε_d) is [5]:

$$\varepsilon_d = \frac{1}{2} \mu_0 M_z^2 \ , \tag{11}$$

where (M_z)is the magnetization component that is perpendicular to the sample surface. With Eq. 11, it is deduced that the equilibrium magnetization is just in a direction in the X-Y plane, because there is an energy minimum. So, easy magnetization (priority magnetization), is in the X-Y plane. That is a reason why the continuous magnetic field is applied parallelly to the sample surface. However, in this case, the oscillating field is also applied parallelly to the sample surface. Taking into account Eq. 11, only the Zeeman energy term must be considered, so the magnetic field must be much stronger than the oscillating one to magnetize in the continuous field direction.

Magnetic moment oscillations are considered much weaker but have to be taken into account. So, magnetization ($\vec{M}$) can be considered as:

$$\vec{M} = (M_0 + m_x \, , m_y \, , m_z) \ , \tag{12}$$

(Continuous field applied in X direction)
Finally, according Eq. 12 and Eq. 8, Eq 7 is:

$$\vec{B}_{eff} = (B_e, 0, -m_z \mu_0) \ . \tag{13}$$

Solving Eq. 10 with Eq 13, the resonance frequency, f, will be:

$$f = \frac{\gamma}{2\pi} \sqrt{B_e (B_e + \mu_0 M_0)} \tag{14}$$

III. EXPERIMENTAL DEVICE

An electromagnet is used to apply the continuous magnetic field, which magnetize uniformly the sample and indicates which direction the precessional motion is turning around according to Eq. 13. To measure this continuous field a hall effect sensor is used.

An oscillating magnetic field is also needed to not let decay processional motion, as has been said before. To apply it a Voltage-controlled Oscillator (VCO), which creates microwaves from 1.9GHz to 3.7GHz, is used. These microwaves go to the sample through a coplanar waveguide, shown in Figure 1.

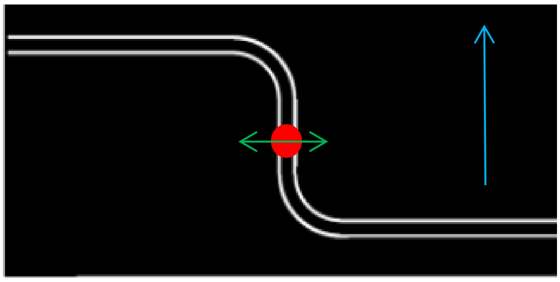

Figure 1: Outline of the coplanar waveguide. Sample position is marked as a red circle.

According to Figure 1, electrical oscillating signal goes through the dark part between white lines (guide), which is conductive. The oscillating magnetic field is circular around the guide. The sample must be placed on the waveguide in order for the oscillating field to go through it, as shown in Figure 1. At the sample position, the oscillating magnetic field generated (green arrow in figure) is parallel to the guide surface and perpendicular to the continuous magnetic field direction (blue arrow).

A microwave intensity detector, which is connected to the end of the waveguide is used to measure the energy that the sample absorbs from the microwave.

To control all the system, an Arduino M0-Pro and some electronic circuits are used among a computer program. The way to use it by the user is just selecting a frequency of the oscillating field between 1.9 GHz and 3.7GHz on the program (Visual Basic). A sweep of the continuous field is automatically performed, while the frequency is being sent. When the sweep ends, a *txt* document is obtained, which includes the frequency of the oscillating field, the intensity of the applied continuous magnetic field, and a magnitude proportional to the power absorbed, which is explained in the following. What is expected to find in the representation of this magnitude depending on the continuous field is a peak at the resonant field at the frequency used.

Electromagnet control:

In order to control to electromagnet intensity, as Figure 2 shows, Arduino sends a PWM signal, which crosses a low-pass filter, because a continuous signal is needed. The intensity source (between 0 and 1.5 A), which is connected to the output of the circuit shown in Figure 2, must be controlled by an input between 0V and 2V, and PWM signal is between 0V and 3.3V, so a voltage divisor is also needed. Finally, in order not to have load effects, a voltage follower is used.

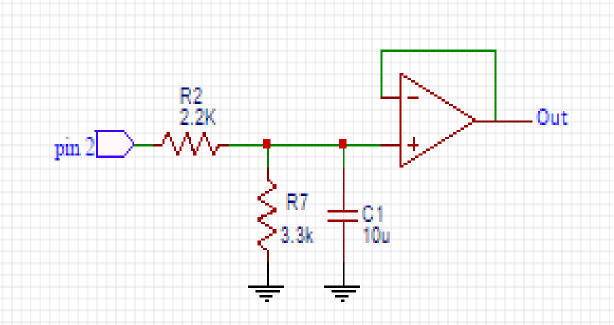

Figure 2: PWM signal from Pin 2 crosses a voltage divisor, a low-pass filter and, finally, a voltage follower before entering the corrent source input.

The magnetic field sweep starts at the maximum magnetic field possible (pin2 at 1023 level). It is done to start the sweep with the electromagnet ferro core magnetically saturated. This is important to be sure that the hysteresis of the core is not important, and the sweep will have the same magnetic intensity values every time. Before the start of the sweep, Pin 2 is on 1023 level for 10 seconds to stabilize the electromagnet coil. The sweep goes from 1023 to 0 level. Steps are of 1 level, and the signal is applied during $50ms$ to stabilize the coil.

VCO control:

The chosen VCO (Minicircuits *ZX95-3800A-S+*) must be fed with 6V. This voltage is obtained with a voltage regulator, which is connected to a 24V source. To control the frequency of the microwave output by the VCO, a voltage from 0V to 21V is needed. This is supplied by the Arduino, with an output signal in the range of 0 – 3.3V that must be amplified (by circuit shown in Figure 3). Although an analogic output from the Arduino is used, signal needs to be filtered to avoid having noise.

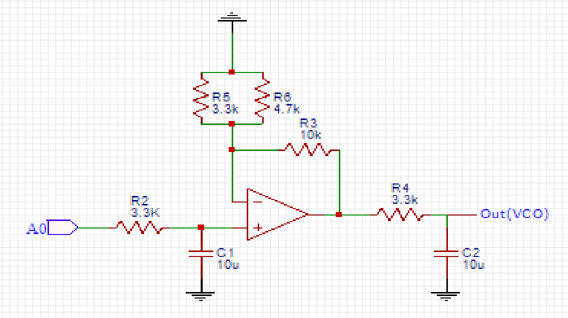

Figure 3: This circuit includes two first order low-pass filter and an analogic amplifier (x 6.15)

In order to know what Arduino voltage level corresponds to every frequency, the VCO connected with Figure 3 circuit must be calibrated. The calibration has been done with a spectrum analyser (HP8565E). An output level was selected on Arduino and the frequency obtained was measured. Figure 4 shows the experimental dependence between frequency and Arduino levels.

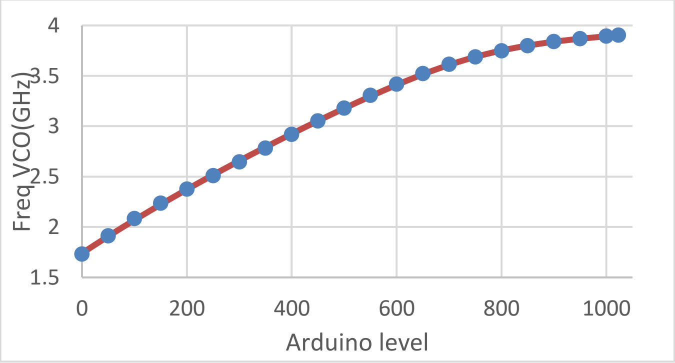

Figure 4: Frequency sent by VCO with its voltage level.

What is needed is the level dependence on frequency to convert the frequency selected by the user into an Arduino level, with which VCO will send the frequency. Experiment dependence found is fitted to the function of Eq. 15, and it is printed in red in Figure 4.

$$Level = -334.5 + freq^{1.51}\left(144.9 + \frac{1}{(4.258 - freq)^{3.267}}\right) \tag{15}$$

Level-Frequency dependence Eq. 15 has not any physical meaning, it is just an experimental calibration.

The uncertainty between put frequency and the real send is: $\Delta f = 0.01GHz$.

Arduino programme waits for a level indication, which is received from the PC, then, the sweep starts. When the sweep ends, Arduino programme waits for another level indication.

Microwave power detector circuit:

A microwave power detector (model Agilent Technologies *8471E*) is used to detect the energy transmitted through the waveguide. What should be detected is the sample energy absorption. It will be detected as a change between transmitted power and a transmission reference detected when the sample does not absorb (high continuous magnetic field applied). First, an intensity level is detected, without absorption, then, that data (a voltage level) is saved as a reference (V_{ref}). Finally, the magnetic field sweep begins. The microwave intensity is detected (V_{in}) during the sweep.

($V_{ref} - V_{in}$) is the proportional to the power absorbed magnitude mentioned before. It is done analogically to obtain the exact point when the maximum absorption occurs.

The output of the intensity detector depends on the sample and frequency used. It is necessary to use a variable amplifier shown in Figure 6 to accommodate this signal to the Arduino input range (0-3.3V).

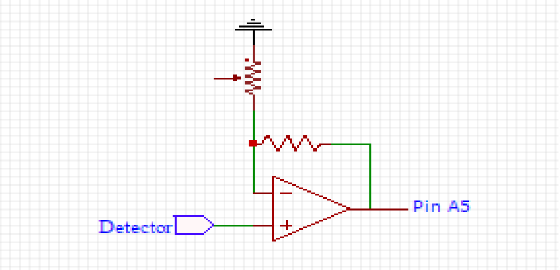

Figure 6: Intensity detector connected to a variable amplifier.

It is necessary to save the input in Pin A5 at high magnetic field as a reference before the sweep. This reference level is sent by Pin 6 while the sweep is performed. The V_{ref} sent is not necessarily the same as the one received by Pin A5, but it is proportional to it because just a proportional to absorbed intensity measure is needed.

The V_{in} is directly obtained from the Figure 6 circuit output. The V_{ref} signal, which is sent by Pin 6, crosses a second order low-pass filter because PWM signal is sent by Pin 6 and a continuous one is needed. Finally, ($V_{ref} - V_{in}$) is done analogically. It is shown in Figure 7 circuit.

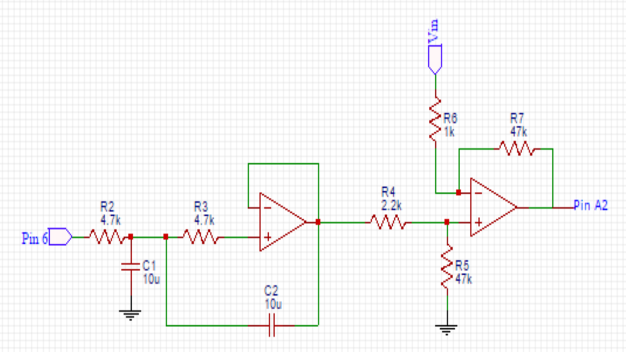

Figure 7: Pin 6 connected to second order low-pass filter and an analogic differential amplifier.

To obtain V_{ref} and ($V_{ref} - V_{in}$), the mean of 100 level values read by PinA5 and PinA2 respectively is done. The aleatory error is reduced by this.

To measure the continuous magnetic field applied a Hall sensor connected to Pin A4 is used. The calibrated sensitivity is 1.21 mV/G

A list of Pin A4, which is connected to Hall sensor, read levels, which are proportional to magnetic field applied, and PinA2 read levels, which are proportional to the intensity absorbed, are communicated to the PC by a USB connection.

The desired Frequency is converted to level using Eq. 15 with a Visual Basic programme. So, wanted frequency must be put on the Visual basic programme, which sends the indication to the Arduino. Data list from Arduino is also processed by Visual Basic programme, which converts Pin A4 levels into magnetic field intensity $B(T)$ with Hall sensor calibration. It creates automatically a folder whose name is the date, where txt documents with the microwave frequency, magnetic field intensity of every sweep steps with its absorption data.

IV. RESULTS

We will show the results of the FMR of a $50nm$ Permalloy thin film. The experiment consists in the measurement of the absorption of energy by the sample at a given frequency as the magnetic field is sweep. Results are shown in Figure 8 as an example.

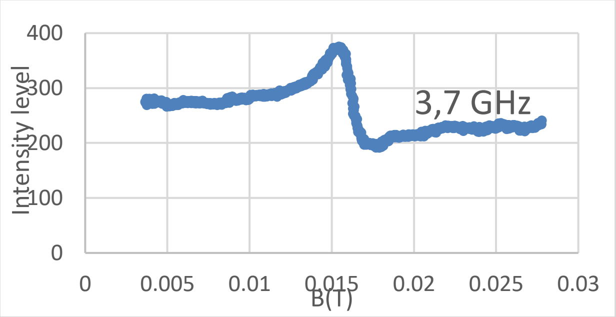

Figure 8: Magnetic sweep dada representation with a 3.7GHz wave sent.

The result is magnitude a proportional to the absorbed intensity. The positive peak will be the maximum intensity absorption, because the signals operation done is ($V_{ref} - V_{in}$). The resounding field can be easily obtained locating the maximum absorption. For the case shown in Figure 8, the resonant field is $B_{3.7GHz} = 15{,}7 \pm 0.7$mT.

We have performed sweeps at 11 different frequencies, from 1.9GHz to 3.7GHz with a step of 0.1GHz between them.

Locating all resounding fields for every sent frequency, the dependence between resonance frequency and its pertinent field can be obtained, as shows Figure 9. The expected theorical dependence is Eq. 15, so f^2 can be represented to calculate M_0 easily.

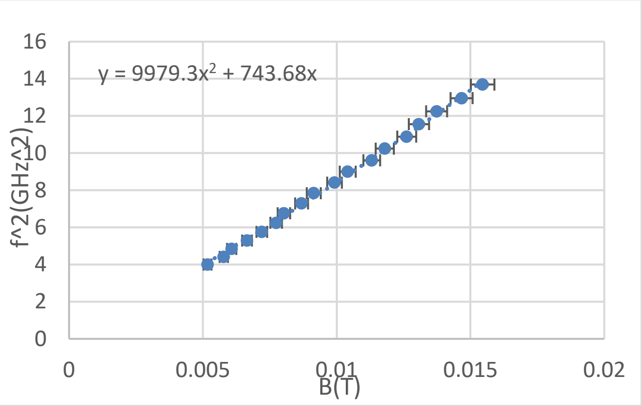

Figure 9: Dependence between resonance frequency and his continuous magnetic field

It can be seen in Figure 9 that the f^2 dependence on B is almost lineal and the error committed in the second power term is too high. So just the first power term is considered.

$$\mathrm{f}^2 \cong (744 \pm 14)\mathrm{B} \tag{16}$$

The gyromagnetic ratio value is well known [6]:

$$\frac{\gamma}{2\pi} = 28.02495164 \text{ GHz/T} \tag{17}$$

According to Eq. 16 and Eq. 17, and taking into account theorical dependence Eq. 14, $\mu_0 M_0$ can be calculated:

$$\mu_0 M_0 = 0.95 \pm 0.02 \text{ T} \tag{18}$$

Permalloy saturation magnetization ($\mu_0 M_0$) depends on the nickel percentage. $\mu_0 M_0$ can change from 0.4T to 1.6T [3]. This measure is perfectly compatible.

V. CONCLUSIONS

The range of the continuous magnetic field applied is between 4mT and 28mT. The oscillating magnetic field frequency range is between 1.9 GHz and 3.7GHz. It can be used to calculate saturation magnetization in samples, whose volume is unknown, if resonant frequency and field are in the range. It can be easily used because just a frequency indication is needed. In addition, materials and electronic components used are economic and can be found easily.

Electronic circuits simplicity is also an advantage. If a different frequency or continuous magnetic field range is needed, components can be changed easily taking into account their supply, their control input, and the output given. If Hall sensor or VCO needs to be changed, the calibration expression has just to be changed on Visual Basic programme.

If gyromagnetic ratio and saturation magnetization are needed to be calculated at the same time, other VCO should be used with larger frequencies than 3.7GHz, as can be seen in the straightness of Figure 9. It should also be taken into account that with maximum continuous magnetic field applied the sample should not absorb microwave power, because transmitted microwave power with maximum magnetic field is taken as a reference.

Due the low price, the easy setup, and the small dimensions, it is suitable for teaching.

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