PRACTICAL SESSION: FERROMAGNETIC RESONANCE

Abstract

Ferromagnetic resonance (FMR) is a spectroscopic technique used to probe the magnetization of ferromagnetic materials. It will be studied through Vector Network Analyzer (VNA) technique on a permalloy (Py) thin film (15 nm thick) sample.

Brief theoretical summary

Magnetization dynamics

If a magnetic field is applied on a series of magnetic moments, they will tend to line up parallel to the field, because they will minimize their magnetostatic energy by doing so. If, in this configuration, the magnetic moments are taken out from this equilibrium stage, they will try to go back to it through the torque produced by the magnetic field:

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma\vec{M} \times \vec{H}_e$$

Where $\vec{M}$ is the magnetization ($\sum m_i$/Unit Volume), $\mu_0$ is the vacuum magnetic permeability, $\gamma = \frac{g\epsilon}{2m_e}$ is the gyromagnetic ratio and $\vec{H}_e$ is the applied field.

In a real ferromagnetic system, a damping term must be added to this “equation of motion”, to describe correctly the behaviour of the magnetic moments involved. For example, Landau Lifshitz Gilbert (LLG) equation considers the damping in the following way:

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma\vec{M} \times \vec{H}_e + \alpha \left( \vec{M} \times \frac{d\vec{M}}{dt} \right)$$

Being $\alpha$ the dimensionless Gilbert damping parameter, that describes a viscous-like damping proportional to the “velocity” of the magnetization. This equation is not taking into account some phenomena, though, e.g. $\alpha$ could be a non constant magnitude for certain values of $\vec{H}_e$ or the frequency of the movement. Here, however, it will be treated as constant.

Ferromagnetic resonance

LLG equation describes the damped motion of a magnetic moment about the direction of an external magnetic field.
If a varying force perpendicular to \( \vec{H} \) is applied over the magnetic moment (like a radio frequency (RF) electromagnetic signal), it can make it precess about the equilibrium direction. Besides, if this force has a frequency similar to the precessional frequency of \( \vec{M} \), that we will call \( \omega_0 \), a maximum of energy absorption by the ferromagnetic sample will be observed. This is when ferromagnetic resonance is taking place, and all magnetic moments will be oscillating in phase.

For the samples we will be using, ferromagnetic thin films, the resonance frequency (the tip of an absorption peak), as a function of \( \vec{H} \) will be given by:

\[
f_0 = \frac{\mu_0 \gamma}{2\pi} \sqrt{(H + H_k)(H + H_k + M_s)}
\]  

Whereas the \( \vec{H} \) width at half height as a function of the frequency of the signal applied will be:

\[
\Delta \vec{H} = \Delta \vec{H}(0) + 1.16 \frac{2\pi \alpha}{\gamma} f
\]

From the experimental data, \( H_k \) and \( M_s \) (uniaxial anisotropy field and saturation magnetization) will be obtained by fitting the resonance frequency to a function like (1), and \( \alpha \) can be obtained from the slope of a linear fit of a set of datapoints representing \( \Delta \vec{H} \) (that can be got from a lorentzian fit, as explained later) as a function of \( f \).

**Experimental technique and setup**

The sample to be studied will be placed on the central conductor of a coplanar waveguide (CPW). The CPW will excite the sample with a time dependent electromagnetic signal, from 50 MHz to 13.5 GHz. Input and output signals from the CPW are sent and received in a VNA. What we will be measuring is the so called \( S_{21} \) parameter. In a two terminal VNA, \( S_{21} \) is a complex number defined as the ratio of the received voltage in port 2 and the input voltage in port 1:

\[
S_{21} = \frac{V_{out}}{V_{in}}
\]

A frequency sweep like this will be carried out at several external magnetic fields, for example from 2250 to -2250 Gs. These magnetic fields will be created by a pair of Helmholtz coils (1345 Oe/A). The current through the coils is supplied by a current source (KEPKO). The experimental setup is the following:
Data analysis

When the measurement process has finished, we will have an array with values of the real and the imaginary part of the $S_{21}$ parameter at every frequency and static field considered in the sweep. Now we can perform a 3D graph to extract information from it. The color scale will represent the real part of the $S_{21}$ parameter and the axes, the frequency and the static field.

Data analysis can be performed with programs like Origin (we will be using version 7.5 here). We import the generated file “Remu.dat” and convert it to a matrix. It will take a long time to do this. When the matrix has been created (it is easy to identify because of the yellow background color of the datasheet), we click on it, so that it is the active window, and we click Plot>>Profiles\Image. A new window will open, and there is a 3D plot (2 axes + color scale), and on top of it, and to the right, two profiles (like the cross section at different points). We will use these two profiles. Each of them is now a 2D graph.

Damping

Firstly we will focus on the one where $H$ is swept and $f$ is kept unchanged. We can select this constant value of $f$ by moving the yellow lines on the 3D plot. What we are interested in is the width at half height of the absorption peaks. To obtain them a lorentzian fit of the peak can be done. The lorentzian fit equation available in Origin is:

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x-x_0)^2 + w^2}$$

Where $w$ is the width at half height. To fit the curve, restrict the active set of points to a small surrounding around the absorption peak. Otherwise (specially if the other peak is included, for example the one present at negative fields, if we are considering that at positive fields) the fit will not be good. By fitting several of these 2D plots, at different values of $f$, now we can plot the different values of $w$ (i.e. $\Delta H$) vs the frequency at which that $w$ takes place. From these graph it is possible to get the value of $\alpha$ (damping) with a linear fit from the slope of the straight line given by equation (1).
Saturation magnetization and uniaxial anisotropy field

From the other profile, with sweeps of $f$ at fixed fields $H$ we will get the experimental values of $M_s$ and $H_k$. To do this, it is necessary to fit a series of data points with the equation (2). To get the experimental points, we must do the same process we did before (for several values of $H$, do a lorentzian fit to find where the tip of the absorption peak is, and therefore find the resonance frequency at different fields). Once several values of $f_0$ have been obtained, it is possible to fit these points with a non-linear fit of the type:

$$y = a \sqrt{(x + b)(x + b + c)}$$

The fitted parameter $b$ is the value of $H_k$ and $c$ is the value of $M_s$. There is really no need of using $a$ as a parameter if its theoretical value is properly given.

References