Spin wave propagation and detection in YIG films

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Abstract

In 1951 Charles Kittel published an equation relating the frequency at which the magnetization within a magnetic film precesses to the strength of an externally applied magnetic field parallel to the film. This phenomena, known as Ferromagnetic Resonance (FMR), can be adapted to excite spin waves. We study the usefulness and accuracy of this method and find it to be in consistent with both Kittel's theory and other experimentally obtained values of a crucial parameter, gyromagnetic ratio.

Procedure

- Fix resonator at an initial frequency
- Find two voltage ranges (ascending and descending) that correspond to the given field interval
- Apply incremental voltage steps throughout the interval and record signal output
- Repeat sweep at new frequency

Methodology

The process for collecting data on the FMR position and frequency relation was fully automated and improved using LabView virtual instruments. A customizable, versatile application was created to perform field sweeps from given or computed bounds at discrete frequency intervals, additionally saving the data in a user-determined location. Users can also adjust a variety of parameters in an easy-to-use, simplified interface. Data is also visualized while the instrument is running, allowing users to quickly discern if data is useful, continually throughout the collection process. Finally, the software is fully modular and its individual components can be easily integrated into other virtual instruments.

After data was collected, it was analyzed using scientific Python libraries *numpy* and *matplotlib*. Data was read from files exported by the LabView virtual instrument. First, field/voltage pairs were fit onto a line resulting in adjusted, fixed-step field values. This adjusted field data and output signal data was then fit to a Lorentzian curve with multiple parameters, the most important being *H0*, or the FMR position. Once the FMR position was extracted for each distinct frequency, the resulting FMR position-frequency relation was fit to the Kittel equation. The accuracy of the computed (estimated) values for M and γ were used to determine the fitness of the model.

In this experiment, the YIG sample was aligned at 90° with respect to the applied magnetic field. Frequencies 3 GHz to 6 GHz were swept from 0.1 kG to 1.5 kG at 150 MHz intervals.

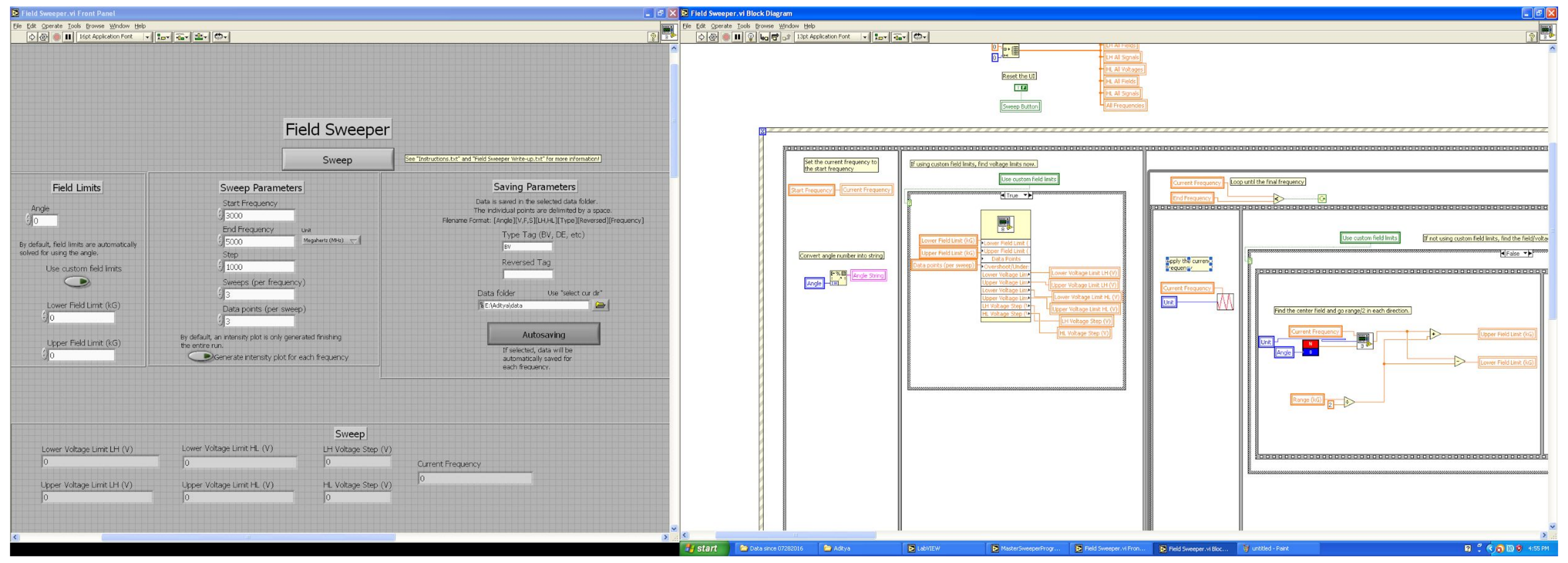

Fig 4.
The LabView front-end interface (left) and block diagram (right).

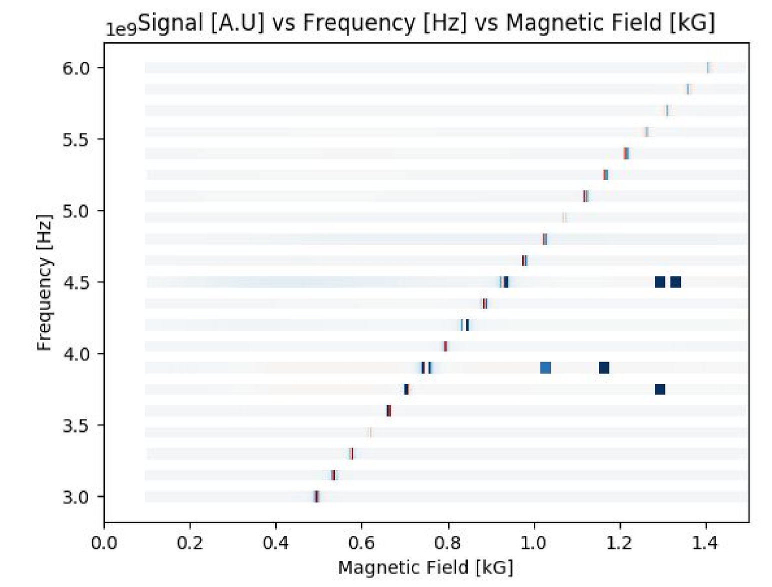

Fig 3.
A plot of the output signal as a function of frequency and magnetic field.

The ascending blue "blips" represent the disturbances in the measurements, indicating the FMR position for every frequency. Blips outside the "staircase" are incorrect measurements and discarded from the dataset before analysis.

Background

Spin waves

In addition to charge, every electron possesses a quantum property known as spin, which can be classified as up or down. Spin waves are formed when the spins of the electrons in a material are aligned using a magnetic field, but deflected slightly in a wave-like manner so as to precess around the field axis.

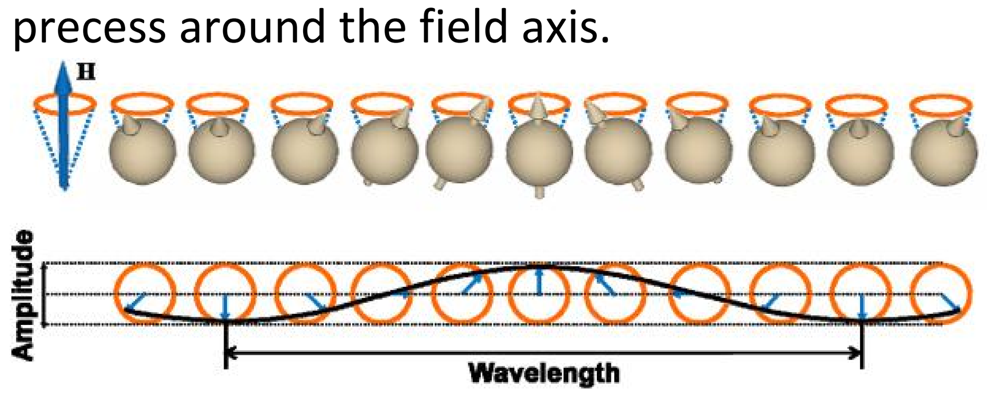

Fig. 1
Electron spin precession

Ferromagnetic Resonance

Ferromagnetic resonance, or FMR, is a technique used to detect spin precession in ferromagnetic materials. Spin waves are induced in a material over some interval of magnetic fields. When the precession frequency of the spins matches the fixed frequency of a microwave generator, there is a clear disturbance in the output signal (see figure 2). The magnetic field which produces this disturbance (known as the FMR position) is governed by the Kittel formula, the accuracy of which we studied and largely confirmed.

Kittel Formula

The Kittel formula is as follows:

$$f = \frac{\gamma}{2\pi}\sqrt{B(B+\mu_0 M)}$$

where f is the resonant frequency, B is the external applied magnetic field, M is the magnetization of the sample, and γ is the gyromagnetic ratio (constant).

Yttrium Iron Garnet

In this experiment, the film in which spin waves were excited is known as YIG - $Y_3Fe_5O_{12}$. YIG is used because it dampens the spin wave much less compared to other practical materials, meaning spin-waves can be observed across centimetre distances.

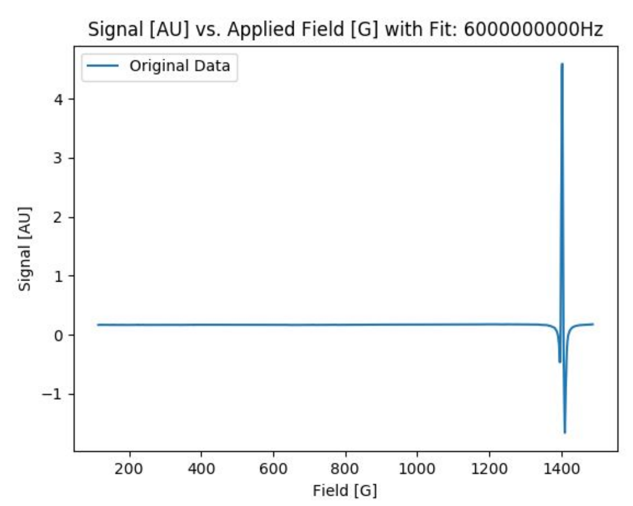

Fig 2.
A plot of the output signal vs magnetic field. FMR position is seen around 1400 G at 6 GHz.

Results and Discussion

Overall, the results were very satisfactory. Computed FMR positions had very low error- the lowest error interval was 0.4%, which is about 4 G. The Kittel fit was just as impressive, with a computed value of 2.8 MHz/G for γ being very close to the reported value of 2.81 MHz/G for the particular film of YIG used in the experiment, on a error of just 2.8%. The estimation of M was also fairly accurate with a computed value of 151 ± 9.2%, well within other measurements made experimentally.

The developed software was a large aid in collecting and analyzing data. The automatically generated intensity plot seen in figure 3 allowed frequencies with "botched" data to be quickly located and discarded from the dataset. The entire data collection process took about 40 hours and required no human input from start to finish. Once data was collected, the Python script was able to automatically generate plots for each frequency with the measured and fitted data, and doing the same for the frequency-FMR position fit.

In conclusion, this experiment yielded:

a. Further confirmation of previously published findings on ferromagnetic resonance and
b. Useful, expandable software to aid in data collection and analysis for future experiments involving ferromagnetic resonance.

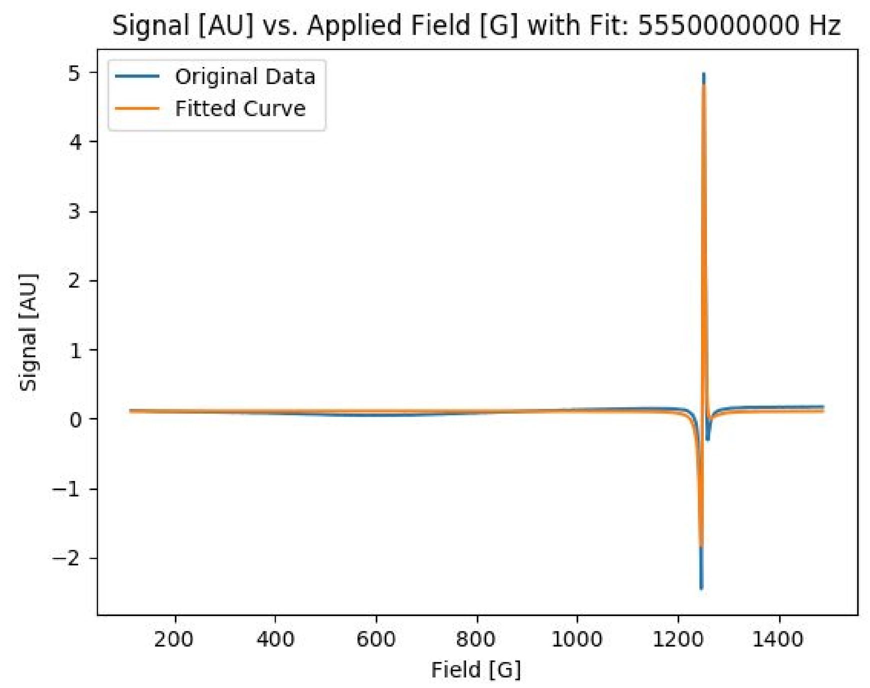

Fig 5.
A fitted curve for output signal vs magnetic field at 5.55 GHz, used to find the calculated FMR position.

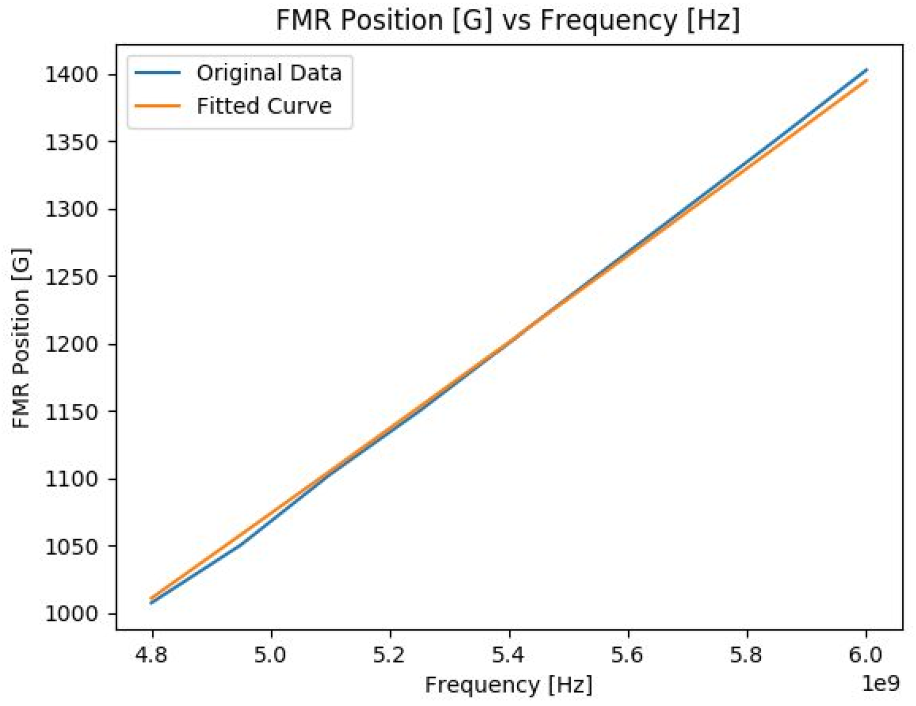

Fig 6.
The fitted Kittel equation used to determine and compare computed values of the gyromagnetic ratio and sample magnetization.