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Study of the Ferromagnetic Magnetite Resonance (Fe_3O_4) Forms of Thin Films Using Micromagnetic Simulation

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Abstract. Fe_3O_4 is the strongest magnet among other iron oxides. Magnetite Fe_3O_4 is applied as a permanent magnet. The hysteresis curve of the permanent magnet Fe_3O_4 has a coercivity field that is not too large so that the material has a good chance to be applied as an absorbent material for RADAR waves. Micromagnetic simulations were carried out on Fe_3O_4 material in the form of thin film against hysteresis curves and ferromagnetic resonances at various thickness variations and side length variations, and the relationship was seen with changes in the bandwidth of the radar wave absorption frequency if the thickness variation of the simulated material had the same multiple as the experimental material. The thickness variations in this study were 60 nm, 90 nm, and 120 nm, where the variations in the experiment were 0.6 mm, 0.9 mm, and 1.2 mm. Micromagnetic simulation runs were performed to obtain the hysteresis curve and resonance frequency of the Fe_3O_4 material. The simulation results show that the resonant frequency increases with increasing thickness (fixed side length). Meanwhile, the relationship between the resonant frequency and the side length of the thin film is inversely related. Changes in the resonant frequency of Fe_3O_4 material are closely related to changes in the absorption frequency band of Fe_3O_4 material. The hysteresis curve obtained shows that the Fe_3O_4 material is a hard magnetic material. Changes in the resonant frequency of Fe_3O_4 material are closely related to changes in the absorption frequency band of Fe_3O_4 material. The hysteresis curve obtained shows that the Fe_3O_4 material is a hard magnetic material. Changes in the resonant frequency of Fe_3O_4 material are closely related to changes in the absorption frequency band of Fe_3O_4 material. The hysteresis curve obtained shows that the Fe_3O_4 material is a hard magnetic material.

Keywords: Fe_3O_4, Ferromagnetic Resonance Frequency, Micromagnetic Simulation

Introduction

Radar detection technology has grown rapidly every year. This technology has been delivered to a new material, namely Radar Absorbing Material (RAM). RAM is a material that can absorb electromagnetic waves. An object coated with RAM will not be detected by Radio Detection and Raging (RADAR) because this material absorbs reflections and absorbs microwaves. The types of materials used as wave absorbers are dielectric and magnetic material [1]. Magnetic materials depend on magnetic losses. Magnetic losses are a state of loss of the magnetic field of a material and in general this value depends on the magnetic permeability of the material. An example of a material that has high permeability and can be used as an absorber of electromagnetic waves is iron oxide. This material is found in the form of minerals in the form of magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), and hematite (α-Fe_2O_3).

Research on the absorption of electromagnetic waves has been carried out by Shofiyatun experimentally to determine the effect of layer thickness on radar wave absorber [2]. From this research, it was found that the change in the absorption frequency bandwidth of the material to radar waves is proportional to the increase in thickness of the Fe_3O_4 material.

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This research uses Magnetite Fe_3O_4 which is iron oxide which is widely used commercially. The purpose of this study was to determine the effect of thickness variations and side length variations in the Fe_3O_4 material on the resonant frequency and to see its relationship with changes in the absorption frequency band width of the radar waves if the variation in the size of the simulated material has the same multiple as the experimental material.

Theoretical Background

Magnetite has the strongest magnetism among other iron oxides so that it is widely applied in everyday life [3]. Magnetite has a spinel crystal structure with a cubic-shaped unit cell consisting of 32 oxygen ions, of which the gaps are occupied by Fe^{2+} and Fe^{3+} ions (Figure 1). In the tetrahedral there are eight Fe^{3+} ions in each cell because it is in the middle of the tetrahedron where the four corners are occupied by oxygen ions. The remaining eight Fe^{3+} and eight Fe^{2+} ions are in the octahedral, because the oxygen ions around them occupy the corners of an octahedron occupied by the six oxygen atoms [4]. As with magnetic materials in general, the magnetic properties of magnetite, which are included in ferromagnetic materials, can be determined using the hysteresis curve [5]. The amount of coercivity determines whether the material is classified as soft magnetic or hard magnetic. Materials that have a coercivity of more than 10 kA/m (Hc > 10 kA/m) are called hard magnetic, while materials with a coercivity of less than 1 kA/m (Hc < 1 kA/m) are called soft magnetic [6].

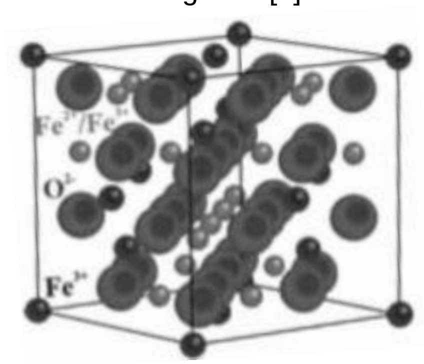

Figure 1. Magnetite unit cell

Ferromagnetic resonance (FMR) is the frequency at which the relative response amplitude is maximum. FMR occurs because magnetic materials oscillate when exposed to a field that oscillates periodically. The performance of magnetic-based devices is influenced by magnetization reversal and ferromagnetic resonance (FMR) which can increase the speed of reading and writing data on the device [7].Research on magnetization reversal and FMR has been published experimentally or simulated by providing an external magnetic field or pulse signal. Measurements using an FMR tool are carried out by placing the sample in a microwave resonant cavity and the sample is in the form of a thin layer as shown in Figure 2.

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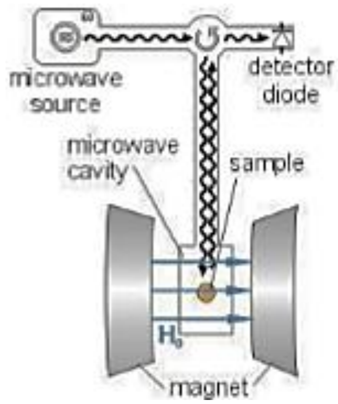

Figure 2. The principle of measurement using an FMR instrument is applied to microwaves or radio in the direction perpendicular to the magnetic field

The theory development regarding FMR is carried out based on the relative orientation of the sample shape between H and M. Magnetization has an important role in the influence of the shape of ferromagnetic materials on the resonance process. The equation regarding the dynamics of magnetization in FMR measurements in the form of the relationship between the external magnetic field, magnetization and demagnetization factors, can be written as follows [8]:

$$\omega = \frac{\gamma}{2\pi}\sqrt{[H_0 + H_k + (N_y - N_x)M_s]^2} \quad (1)$$

Materials and Methods

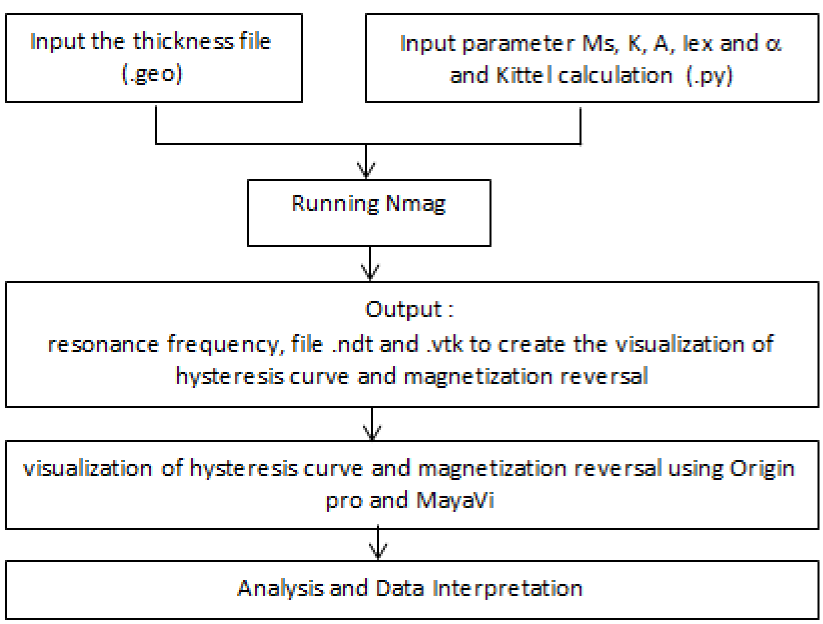

Figure 3. Research flow diagram to obtain hysteresis curve and resonance frequency of Fe_3O_4 material

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The material used in this study is a hard magnet in the form of Magnetite (Fe_3O_4). Fe_3O_4 material has a geometry in the form of thin film. The parameters used for the micromagnetic simulation consist of: saturation magnetization, anisotropy constant, and exchange constant. The cell size used is based on the exchange length size of the Fe_3O_4 material with a damping factor of 0.05. This simulation uses two types of variations, namely the thickness and length of the thin film side to find the hysteresis curve and resonance frequency.

Table 1. Fe_3O_4 material parameter for micromagnetic simulation data input

Parameter	Score
Ms	[2]8.68 x 105 A / m
A	[5]1.2 x 10^{-11} J / m
K	[5]-1.1 x 10^4 J / m3
Α	[5]0.05
Iex	8.7 nm

A. Simulation analysis to obtain resonant frequency with variations in thickness and side length of the Fe_3O_4 material

Simulations to obtain resonant frequency values with variations in thickness and side length were carried out by inputting thickness and side length variations in the file (.geo) and material parameters (Ms, A, K, Iex, α) and Kittel's calculations in Equation 1 in file (. py). Then the file is run using Nmag. The output of this process (.frek) contains the resonant frequency value. The amplitude used to get the value of the resonant frequency through simulation is 1000 A / m.

B. Analysis to determine the relationship between the simulation results of Ferromagnetic Resonance (FMR) with changes in the bandwidth of the radar wave absorption frequency

Simulation for determining the correlation between ferromagnetic resonance (FMR) simulation results with changes in frequency band widthdone by providing various thickness variations on the thin film. The thickness varied in the experiment 0.6 mm, 0.9 mm, and 1.2 mm. Meanwhile, in the simulation, the thickness varied from 60 nm, 90 nm, and 120 nm. Then from these results it can be seen whether the simulation results of Ferromagnetic Resonance (FMR) have a relationship with changes in the bandwidth of the radar wave absorption frequency if the simulated material size variation has the same multiple as the experimental material.

Results and Discussion

Hysteresis Curve

The magnetic properties of a material can be seen from the hysteresis curve. The hysteresis curve is a curve that shows the relationship between the magnetization (M) that occurs in a material and the external magnetic field (H). Figure 4 is the hysteresis curve of the Fe_3O_4 material obtained in this simulation.

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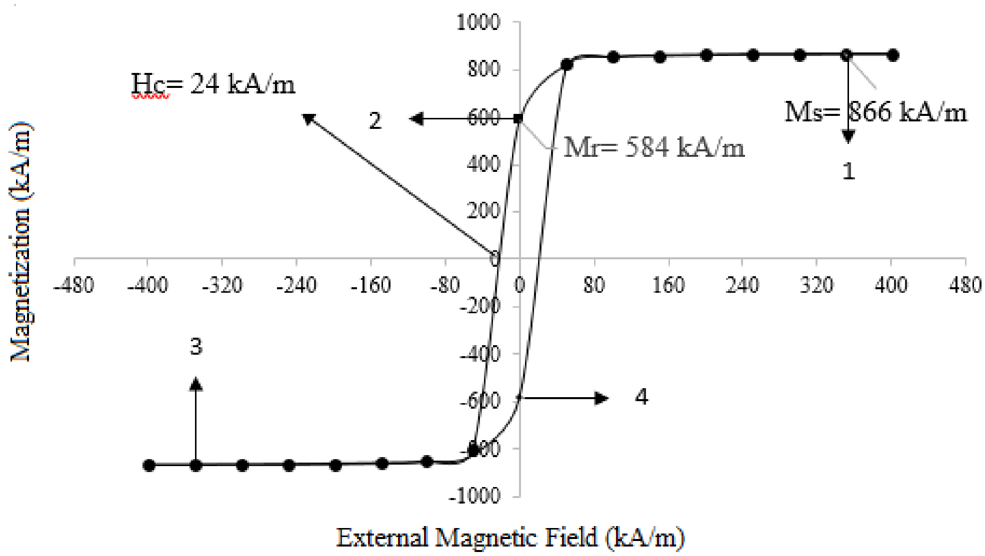

Figure 4. Fe_3O_4hysteresis curve

The change in magnetization in the material occurs with the addition of the external magnetic field. The external magnetic field will continue to increase so that the magnetization reaches a saturation state as shown in Figure 4 number 1 with a magnetic value of 866 kA/m. After reaching the saturation point, the magnetization will reach a remanence state as shown in Figure 4 number 2 with a magnetization value of 584 kA/m. This process is continued by reversing the direction of the magnetic field H given and continuously increasing so that the magnetization value becomes zero. The value of the external magnetic field given when the magnetization reaches zero is called the coercivity field. The simulation results show that the coercivity field is 24 kA/m where Hc > 10 kA/m so that information is obtained that the material Fe_3O_4 is hard magnetic [9].

Ferromagnetic Resonance Frequency

Ferromagnetic resonance (FMR) is the frequency at which the relative response amplitude is maximum. FMR occurs because magnetic materials oscillate when exposed to a field that oscillates periodically. The performance of magnetic-based devices is influenced by magnetization reversal and ferromagnetic resonance (FMR) which can increase the speed of reading and writing data on the device [7]. The ferromagnetic resonance frequencies are obtained in the GHz range using micromagnetic simulations.Table 2 is the result of the resonant frequency generated through Kittel's simulation and calculations. Kittel's calculation is used as a comparison or reference for the truth of the simulation results according to theory. Based on Kittel's calculations, the greater the thickness given to the material, the greater the resonant frequency.

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Table 2. The magnitude of the ferromagnetic resonance frequency (FMR) with respect to thickness variations with a fixed side length

No.	Thickness (nm)	Side length (nm)	Ratio	FMR calculated by Kittel (GHz) *	FMR simulation result (GHz)
1.	60	15	4	10.4	10.4
2.	90	15	6	11.9	11.4
3.	120	15	8	12.5	12.3

The results obtained in Table 1 then graphed the relationship between FMR and various thicknesses of the Fe_3O_4 material. Figure 5 explains that the greater the thin film thickness of the Fe_3O_4 material (fixed side length), the greater the resonant frequency. This is because the greater the thickness of the material, the greater the magnetic material content. The results obtained are in accordance with the theory, where the thickness of the material given is proportional to the resulting resonant frequency.

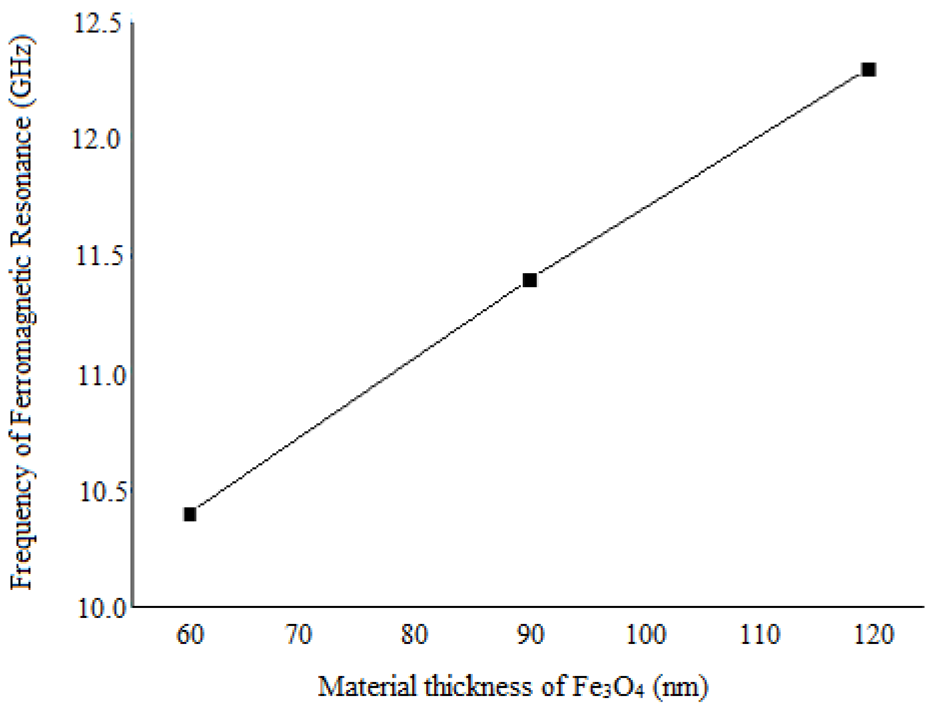

Figure 5. Graph of the resonance frequency relationship to thickness variations

The simulation results obtained in this study indicate that the increase in the resonant frequency of the material is proportional to the increase in thickness of *thin film* Fe_3O_4. If these changes are further analyzed, there is a correlation between the results of simulation research and experimental research conducted by Shofiyatun [2]. The thicker the layer, the higher the frequency value and the wider the absorption band.

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Table 3. The magnitude of the ferromagnetic resonance frequency (FMR) for variations in side length with a fixed thickness

No.	Side length (nm)	Thickness (nm)	Ratio	FMR simulation result (GHz)
1.	60	15	4	13.7
2.	90	15	6	12.7
3.	120	15	8	12.6

Table 3 is the result of the frequency generated through micromagnetic simulations with variations in side length values. In the table, it can be seen that the greater the side length, the smaller the frequency. This is because the spin position becomes more irregular as the side length of the Fe_3O_4 material increases. The results obtained in this study are in accordance with previous research conducted by Moh. Imron, where the greater the diagonal value or side length of the material, the smaller the resulting frequency [10].

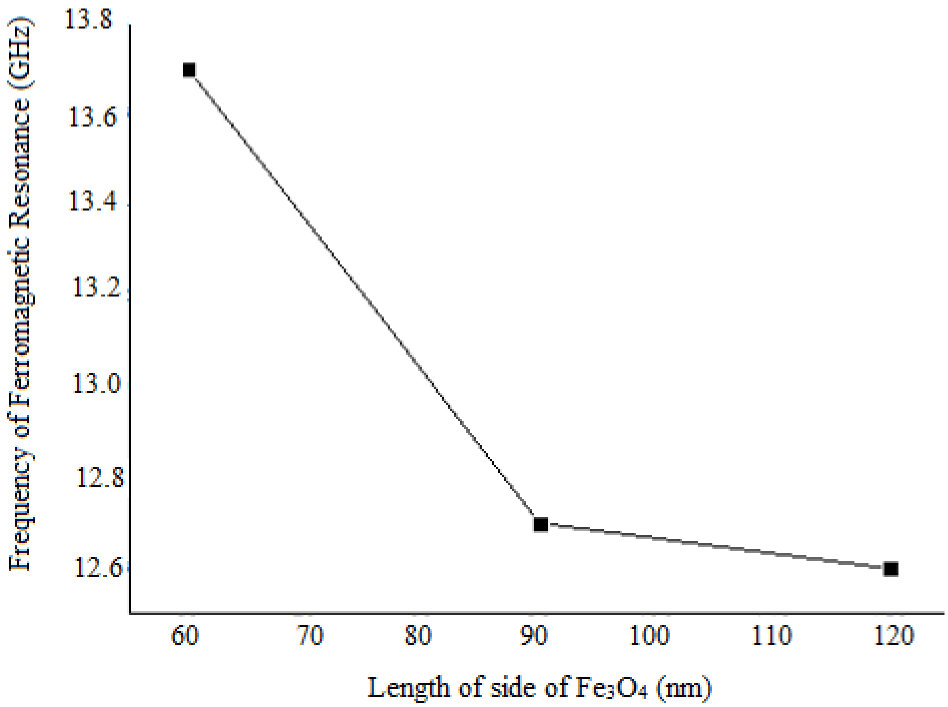

Figure 6. Graph of the resonance frequency relationship to the variation in length of side of Fe_3O_4

Figure 6 shows the relationship between the resonant frequency of the material and the length of the thin film side of the Fe_3O_4 material at a fixed thickness value of 15 nm. The graph explains that the greater the length of the thin film side of the Fe_3O_4 material (fixed thickness), the smaller the resonance frequency obtained. It can be said that the value of the side length is inversely proportional to the resulting frequency.

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Conclusions

The results obtained in this study are variations in thickness (fixed side length) and variations in side length (fixed thickness) which can affect the ferromagnetic resonance frequency of the Fe_3O_4 material produced. The value of the resonant frequency increases with increasing thickness of the material. Meanwhile, the variation in side length (fixed thickness) results in a smaller frequency value as the side length increases.

The simulation results of Ferromagnetic Resonance (FMR) have a relationship with changes in the absorption frequency band width of the radar waves if the simulated material size variation has the same multiple as the experimental material, where the change in the absorption frequency band of the material to radar waves is proportional to the increase in thickness of the Fe_3O_4 material. From this, we can say that the change in the resonant frequency of the Fe_3O_4 material is closely related to the change in the absorption frequency bandwidth of the Fe_3O_4 material.

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