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RESEARCH ARTICLE

Development of Cylindrical Cavity Resonator Technique for Magnetic Loss Measurement in Yttrium Iron Garnet

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ABSTRACT - Cavity resonators are essential as high-sensitivity sensors, capable of detecting small changes in electromagnetic fields or material properties, owing to their ability to generate strong fields at resonance. However, due to budget constraints limiting access to advanced technology, developing a custom-built cavity resonator can be a more cost-effective alternative to purchasing commercially available resonators. Building on this motivation, a cylindrical cavity resonator was designed and fabricated specifically for microwave loss measurement, focusing on C-band frequencies. The performance of the fabricated resonator was assessed through COMSOL simulations and experimentally validated by measuring transmission loss with a vector network analyzer connected to the resonator, where a spherical yttrium iron garnet (YIG) sample was employed as a tested material. The simulation result of the magnetic field radiation pattern validates the performance and efficacy of the fabricated cavity resonator. The S_{21} parameter measurements revealed a transmission loss of -62.2 dB for the empty resonator, while the YIG-filled resonator exhibited a transmission loss of -57.87 dB under 0 kOe and increased to -23.13 dB when a magnetic field of 0.5 kOe was applied. The increase in transmission loss can be attributed to the changes in the magnetic properties of YIG under the influence of the external magnetic field. This resulted in enhanced resonance conditions where coupling between EM waves and the samples leads to improved resonance conditions and reduced losses, as the alignment of magnetic moments improves the coupling between electromagnetic waves and the materials, which is associated with the ferromagnetic resonance of YIG.

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1. INTRODUCTION

In recent years, researchers and engineers have focused on designing advanced materials and devices for future microwave telecommunications applications. In this context, understanding the interplay between microwave telecommunication performance and microwave losses is essential for optimizing device functionality, ensuring signal integrity, and enhancing technological progress. In microwave applications, the main aspects affecting the microwave losses in the materials are the magnetic characteristics of the materials and the frequency of the electromagnetic (EM) wave propagations [1]. It is well established that different magnetic materials would exhibit varying microwave losses. Lower microwave losses lead to better performance in terms of signal integrity and strength, which is crucial for effective communication [2]. Thus, to assess the microwave losses of these materials, it is crucial to analyze their response to the applied EM wave. This can be interpreted by measuring the reflection and transmission of the EM waves through the materials at particular frequency ranges. When EM wave propagates through a magnetic material, it simultaneously induces magnetic permeability and magnetic loss [3]. These effects are influenced by both intrinsic factors such as phase and crystallinity; and extrinsic characteristics, including morphology, particle size distribution, and defects within the material [4].

In order to measure the microwave loss in the materials, the microwave cavity resonator technique is commonly employed. Cavity resonators are often employed to characterize and optimize the dielectric and magnetic properties of materials at microwave frequencies. The design of the resonator must consider the magnetic losses introduced by the materials it contains. For instance, a resonator filled with a low-loss magnetic material can improve signal transmission and reduce attenuation, making it suitable for high-frequency applications in telecommunications. As compared to other microwave techniques, such as coaxial lines, transmission lines, and free-space techniques, the cavity resonator technique offers superior accuracy and sensitivity for determining the electromagnetic properties of both lossy and low-loss materials [5]. This technique utilizes cavity perturbation theory, which posits that the EM waves which consist of magnetic and electric field disturbance within a cavity resonator remain closely aligned with the field distributions of the

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unperturbed cavity resonator [6]. When a sample is positioned at the centre inside an empty cavity, the resonant frequency and quality factor that dictates the efficiency of the material would be obtained. In this context, the sample volume must be sufficiently small relative to the wavelength of the cavity, where the introduction of the small sample should not change the total stored energy in the cavity. Ideally, the samples should be no larger than one-tenth of the broad wall of the cavity or waveguide in diameter. Making the sample smaller than this dimension will result in a more uniform field throughout the sample. Microwave cavity resonator technique requires a spherical shape sample, in the form of film or disk. The advantage of using the spherical shape sample is the distribution of the demagnetizing field of the sample is homogeneous, thus preventing the linewidth broadening caused by the shape factor of the sample. Moreover, if the sample has magnetocrystalline anisotropy, care must be taken to ensure that the anisotropy field is oriented in the same direction as the applied magnetic field. This is easier with the spherical shape sample where the demagnetizing field, N in the sphere is $N_x = N_y = N_z = 1/3$. Since the sample is very small, the amount of absorbed power is also very small.

The accuracy of the measurement using the cavity resonator technique depends largely on the quality value (Q-value) of the cavity. A high Q-value indicates high accuracy and narrow bandwidth of the measurement, thus manifesting in the overall quality of the cavity resonator. The Q-value of the cavity resonator can be determined by certain conditions during the design process, i.e. metallic material used to fabricate the cavity resonator, coating material for the inner side of the cavity resonator, coupling device between the cavity resonator to the microwave source and the transverse modes of the measurement. During the measurement, when the external circuit is coupled to the cavity resonator, the Q-value of the unloaded cavity will be different from the Q-value of the loaded cavity. To achieve the impedance matching between the external circuit to the cavity, the critical coupling factor, g equals 1 must be complied with. The coupling factor, g is expressed by $g = R/Z_o$ where R is the resistance of the cavity, and Z_o is the impedance of the external circuit. Thus, the Q-value of the cavity should be larger than that of the Q-value of the external circuit. To achieve the over-coupled, the resistance of the cavity must be higher than that of the resistance of the external circuit.

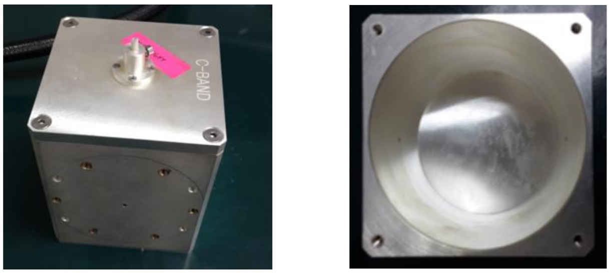
However, commercial cavity resonators are often costly, particularly for specialized applications. Fabricating a custom-built cavity resonator offers a cost-effective alternative, which enables researchers to achieve the required functionality while minimizing the expenses for the measurement. This approach is especially advantageous in academic and research environments, where budget constraints may restrict access to commercial equipment. In this work, a cylindrical cavity resonator has been designed and fabricated to measure the microwave loss of material. Yttrium iron garnet (YIG) is chosen as the material under-tested (MUT) as YIG is widely regarded as a model material for studying the fundamental aspects of magnetism and microwave magnetic dynamics, which is similar to silicon that is essential for semiconductor research or the fruit fly in studying the biological cell [7]. The magnetic properties of YIG are well characterized and highly reproducible, making YIG an ideal candidate for in-depth investigation.

Furthermore, its stable magnetic response, tunable ferromagnetic resonance, and low magnetic loss in the microwave region provide a reliable framework for exploring complex magnetic phenomena. These attributes allow YIG to serve as a foundational material in the research of magnetism, which offers insights applicable to a broad range of magnetic materials and practical applications. This research presented a detailed design of the cavity resonator with supported simulation data. The viability of the fabricated cavity resonator is tested through electromagnetic measurement of transmission loss as a manifestation of the microwave loss, and the mechanisms involved are discussed. The measurement is focused on the C-band frequencies because EM waves interact efficiently with a wide range of materials at the frequencies. This enables accurate determination of magnetodielectric properties which is critical for applications in microwave technologies, including telecommunications and quantum computing where the performance of the material directly impacts the efficiency of the device [8]. Furthermore, the cylindrical cavity resonators operating in the C-band are recognized by international standards of ASTM D2520. This provides a consistent framework to ensure the reliability and reproducibility of the measurements across diverse applications [9].

2. METHODS AND MATERIAL

2.1 Fabrication of the Cylindrical Cavity Resonator

In this work, a cylindrical cavity resonator was fabricated using brass, with the inner wall coated with 99.99% pure silver through an electroplating process. Brass and pure silver were selected for the construction of the cavity resonator due to their high electrical conductivity, which is anticipated to result in a high Q-factor.



(a) (b)

Figure 1. (a) The outer side and (b) the inner side of the fabricated cylindrical cavity resonator

The dimensions of the fabricated cavity resonator were designed to match those of a standard commercial cylindrical cavity resonator used for C-band frequencies. Specifically, the cavity resonator is cylindrical with a height of 6.57 cm and a diameter of 6.75 cm. The fabricated cylindrical cavity resonator is shown in Figure 1.

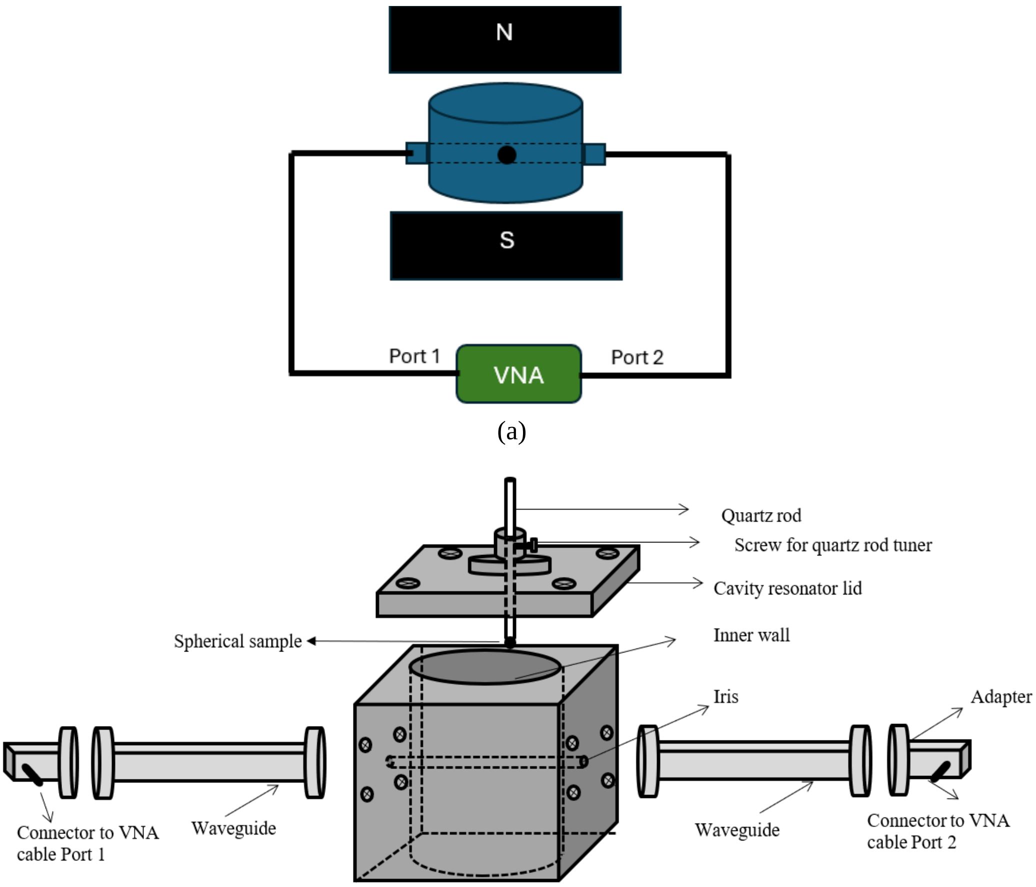
2.2 Yttrium Iron Garnet (YIG) Spherical Sample Preparation

In this work, YIG powder was synthesized using a high-energy ball milling technique. The milling process was conducted for 6 h at 1450 rpm using a SPEX D8000 Mixer/Mill. The milled powder was granulated with 2 wt% polyvinyl alcohol and zinc stearate and pressed under 3 tons of pressure to form a cube-shaped sample. The green sample was sintered at 1400 °C for 10 hours in an ambient air environment. The detailed results of the synthesized sample have been described in our previous works [10]. Next, the sintered sample underwent an air-driven milling process for the fabrication of a spherical-shaped sample. During this process, the air was injected through a small tangential hole into the grinding track and exited through a mesh screen between Perspex plates that cap at both ends of the mill. A small spherical sample with a diameter of 2 mm was produced in a matter of time depending on the hardness of the sample. The dimension of the spherical sample was measured randomly 20 times using a caliper with 0.01 mm uncertainty.

2.3 Electromagnetic Properties Measurement

For microwave loss measurement, a spherical-shaped sample of YIG was used and fitted into the cylindrical cavity resonator connected to the vector network analyzer (VNA) equipment. Before the measurement, the spherical YIG sample was glued and mounted to a quartz rod using a cyanoacrylic low-loss glue. It was then inserted into the fabricated cylindrical cavity resonator where the entire cavity was placed within a magnetic field. A screw that holds the mounted sample to the quartz rod is adjusted to ensure that the sample is perpendicular to the iris and the sample was placed between the center of the poles, such that the DC magnetic field through the sample is uniform.

The transmission loss measurement was conducted using an Agilent PNA-N5227 Vector Network Analyzer at C-band frequencies. The scattering parameter, S_{21} was used to determine the transmission coefficient of the sample. During the measurement, the cavity resonator is positioned under an external magnetic field ranging from 0.0 kOe to 0.5 kOe where the measurement was carried out. The applied magnetic field strength was monitored with a Lakeshore 421 Gaussmeter, with the probe positioned between the magnetic poles. A standard full two-port calibration (SOLT) was performed before the measurement for 201 frequency points. During the measurement, the microwave energy will be transmitted from the VNA to the cavity resonator through an iris and a waveguide as a coupling device. The experimental setup and its corresponding schematic diagram are presented in Figure 2(a) and (b), respectively.



(b)

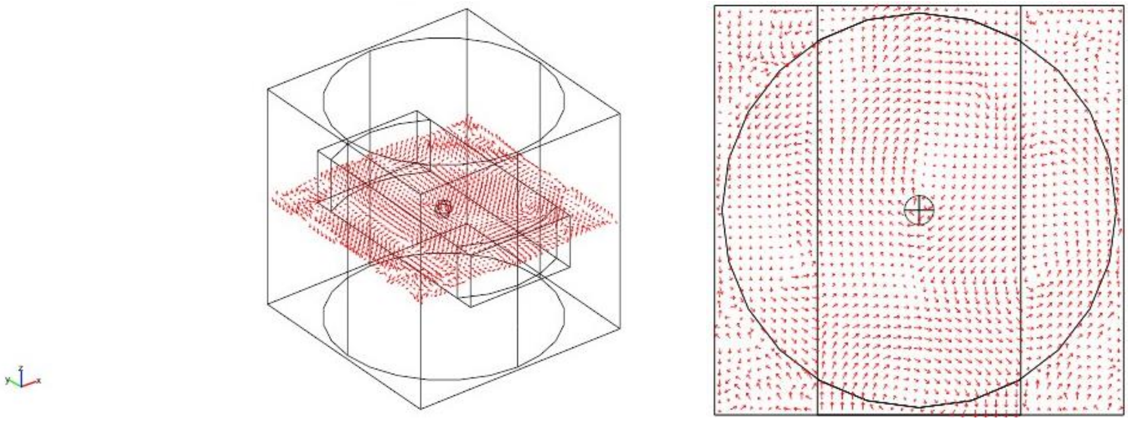
Figure 2. (a) Schematic diagram of the electromagnetic measurement experimental setup; (b) Schematic diagram of the cavity resonator and measurement setup

3. RESULTS AND DISCUSSION

3.1 Simulation of Cylindrical Cavity Resonator

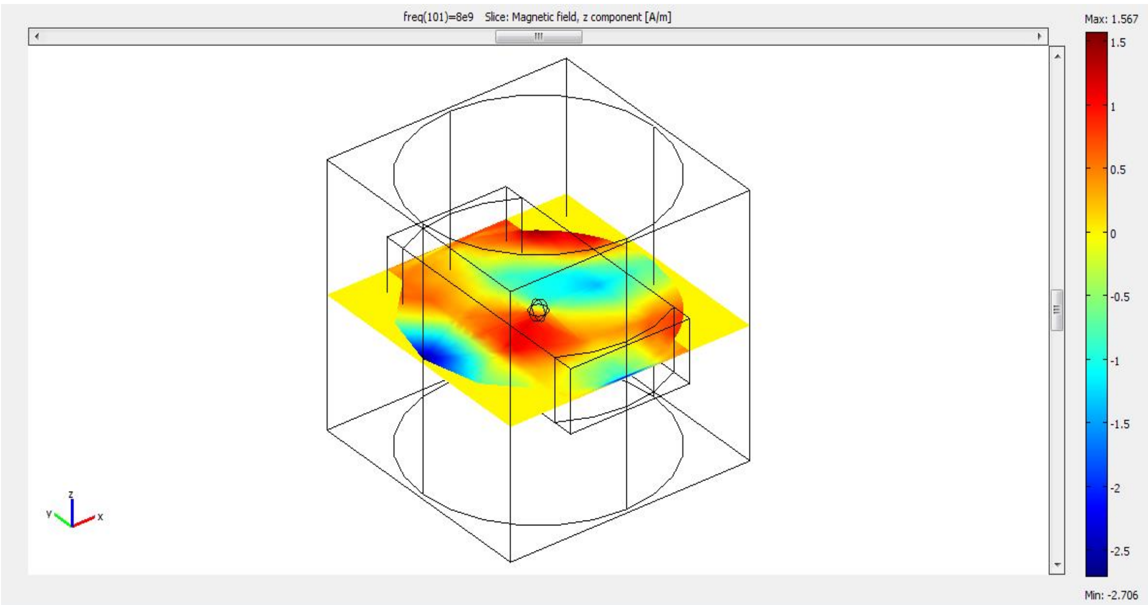
Before it can be used for a microwave loss measurement during the EM wave propagation, it is important to evaluate the radiation pattern in the designed cavity resonator. For that purpose, a simulation using COMSOL Multiphysics software was carried out to analyze the propagation of the EM field through the cavity resonator. In this simulation, the sample is positioned at the center of the cavity resonator to achieve a maximum and uniform magnetic field component. In contrast, the electric field component is effectively nullified. The electromagnetic configuration simulation provides a crucial insight into the behavior of the cavity resonator, particularly in terms of the magnetic and electric field distributions.

The electromagnetic configuration simulation, as depicted in Figure 3 shows that the center position of the cavity exhibits the maximum magnetic field component while simultaneously demonstrating the minimum electric field component intensity. The arrows in the simulation indicate both the magnitude and direction of the electromagnetic field flowing within the cavity resonator, in which when the sample is positioned at the center of the cavity, it satisfies the resonance condition. This alignment is crucial because it maximizes the interaction between the electromagnetic waves and the sample, thus enhancing the measurement sensitivity and accuracy. This is supported by the magnetic field radiation pattern shown in Figure 4. The radiation pattern provides a visual representation of the magnetic field distribution within the cavity resonator. From the pattern, it is evident that the magnetic field distribution is more concentrated at specific regions within the cavity, particularly where constructive interference occurs. This localized concentration of the magnetic field enhances its strength, which is beneficial for detecting small changes in the material properties.



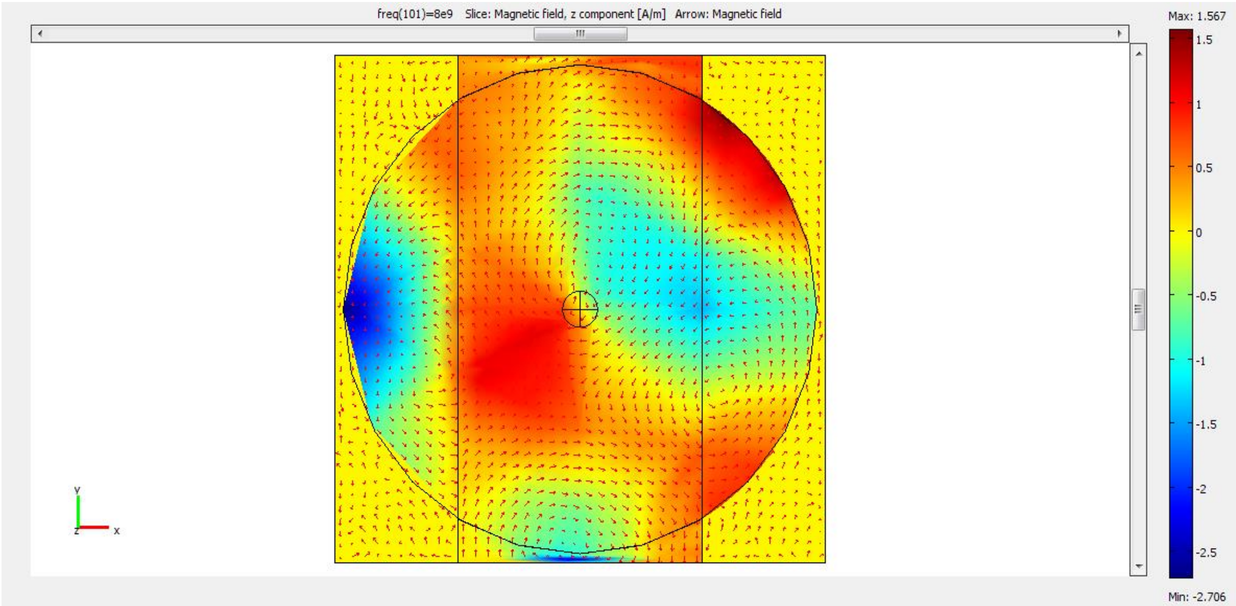
(a) (b)

Figure 3. The electromagnetic configuration simulation of C-Band cylindrical cavity: (a) 3D view; (b) 2D view



(a)

Figure 4. The magnetic field radiation pattern of the cylindrical cavity resonator: (a) 3D view



(b)

Figure 4. (cont.) (b) 2D view

3.2 Experimental Method Validation

The dominant magnetic loss mechanism within magnetic materials at radio and microwave frequency is generally associated with the precessional damping of magnetic spin. Landau-Lifshitz equation commonly describes the microwave loss mechanisms by the damping coefficient, α and the ferromagnetic resonance (FMR) linewidth, ΔH at half power. These two quantities are correlated to one another by the following expression [11]:

$$\alpha = \frac{\mu\gamma\Delta H}{4\pi f'} \tag{1}$$

where f' is the frequency at which the swept field linewidth is measured and $\mu\gamma$ = 2.8 GHz/kOe. In the microwave loss measurement, resonance occurs when the cavity resonator absorbs and stores microwave energy, resulting in no energy being reflected and all the energy being retained within the cavity resonator.

To validate the efficiency of the fabricated cavity resonator, the transmission loss measurements were carried out using a relatively small YIG spherical sample as a material under-tested (MUT). The sample is relatively small as compared to the size of the cavity resonator to prevent perturbation during measurement, otherwise, it will distort the magnetic and electric field. Transmission loss (TL) quantifies the attenuation of signal power as it propagates through a transmission medium. In the context of S-parameters, TL is often expressed in decibels (dB) using the transmission coefficient, S_{21} which represents the ratio of the output signal power between port 2 and port 1 of a two-port network. The relationship between TL and S_{21} is given by the following equation [12]:

$$TL = -20 \log10(|S_{21}|). \tag{2}$$

Figure 5 presents the transmission loss, TL as a function of the external magnetic field for both empty and YIG-filled cavity resonators. The empty resonator exhibits a higher negative transmission loss of -62.2 dB compared to the YIG-filled resonators of -57.87 dB at 0 kOe. A lower negative value of TL in YIG-filled resonators signifies that less power is lost during transmission, where a higher percentage of the signal is transmitted through the material without significant absorption or reflection. This showed that the presence of YIG reduces TL. YIG is known for its low magnetic losses, which contribute to improved transmission characteristics when it fills the cavity. Thus, this allows it to support better wave propagation, resulting in lower attenuation of the transmitted signal. The same trend can be observed in the YIG-filled cavity resonator when subjected to an external magnetic field from 0.0 to 0.5 kOe, where the value of negative TL is drastically reduced from -57.87 dB to -23.13 dB. TL in magnetic ferrites is primarily contributed by hysteresis losses, eddy current losses and residual losses. While hysteresis losses are influenced by the magnetic properties of the material and working frequency, eddy current losses become significant at high frequencies. As the magnetic field strength increases, hysteresis losses tend to increase due to enhanced magnetization, leading to greater energy dissipation within the material [13].

Moreover, the application of the external magnetic field to the YIG-filled cavity resonator modifies the relative permeability of YIG, which in turn influences the EM interactions within the cavity [14]. As the magnetic field strength increases, it promotes better alignment of the magnetic moment in YIG, thereby enhancing the coupling between the microwave fields and the material. This improved coupling leads to a reduction in TL, as evidenced by the observed decrease in negative TL values. This result is expected where the microwave transmission in any material is very much dependent on the structure, geometry, morphology as well as defects existence in the material [15]. During microwave excitations in the sample, lattice vibrations in the form of phonons were created. These phonons are in a higher energy state than the surrounding magnetic system, thus creating spin-wave (magnon) interactions and exchange of energy between phonons and the magnetic system. High crystallinity, single phase, and uniform particle size distribution are desired to obtain a good characteristic of a good microwave transmission [16].

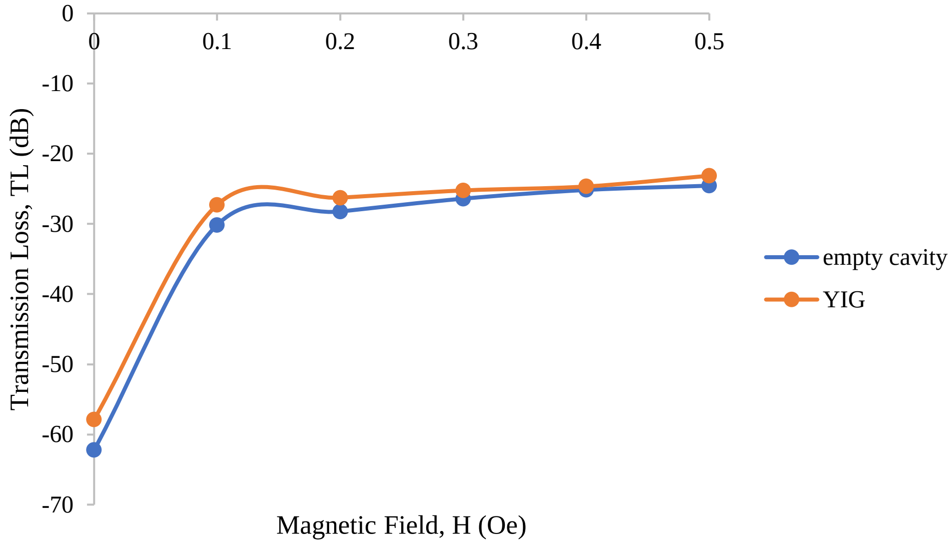


Figure 5. Transmission loss as a function of external magnetic fields of empty and YIG-filled cavity resonators

Figure 6 shows the transmission coefficient, S_{21} as a function of frequency at various external magnetic field strengths of the YIG-filled cavity resonator. A detailed observation at the maximum peak which indicates the resonance frequency, f_r reveals a shift to a lower frequency from 5.64 GHz to 5.46 GHz, as the magnetic field increases from 0 to 0.5 kOe (Figure 7). The application of an external magnetic field caused a shift in the resonance frequency of the cavity resonator, where this behavior is crucial for applications where precise frequency tuning is essential. The resonance occurs when the frequency of the incoming EM waves aligns with one of the natural frequencies of the cavity, enabling efficient energy transfer and reducing energy loss. Based on the results, the ferromagnetic resonance (FMR) linewidth broadening, ΔH of the sample which indicates the magnetic loss can be calculated using the following formula [11]:

$$\Delta H = \frac{\Delta\omega}{\mu_O \gamma} \tag{3}$$

$$\gamma = \frac{g_e \mu_B}{h} \tag{4}$$

where γ is the gyromagnetic ratio, $\Delta\omega$ is the difference of angular frequency of transmission signal S_{21}, μ_o is the magnetic permeability constant in vacuum, h is the reduced Planck's constant $\left(\frac{\hbar}{2\gamma}\right)$, μ_B is the magneton Bohr and g_e is the Lande g-factor. Figure 8 shows the linewidth broadening, ΔH of YIG-filled cavity at various external magnetic fields. It can be observed that ΔH increased from 1.14 Oe to 3.12 Oe. In polycrystalline magnetic materials, linewidth broadening is primarily influenced by magnetocrystalline anisotropy. The presence of porosity within the material induces the demagnetizing effects due to the inhomogeneous internal magnetic field, further contributing to linewidth broadening. The combination of randomly oriented anisotropy between grains, with the demagnetizing field arising from non-magnetic inclusions, grain boundaries, or structural imperfections, leads to the linewidth broadening observed in polycrystalline material [17-19].

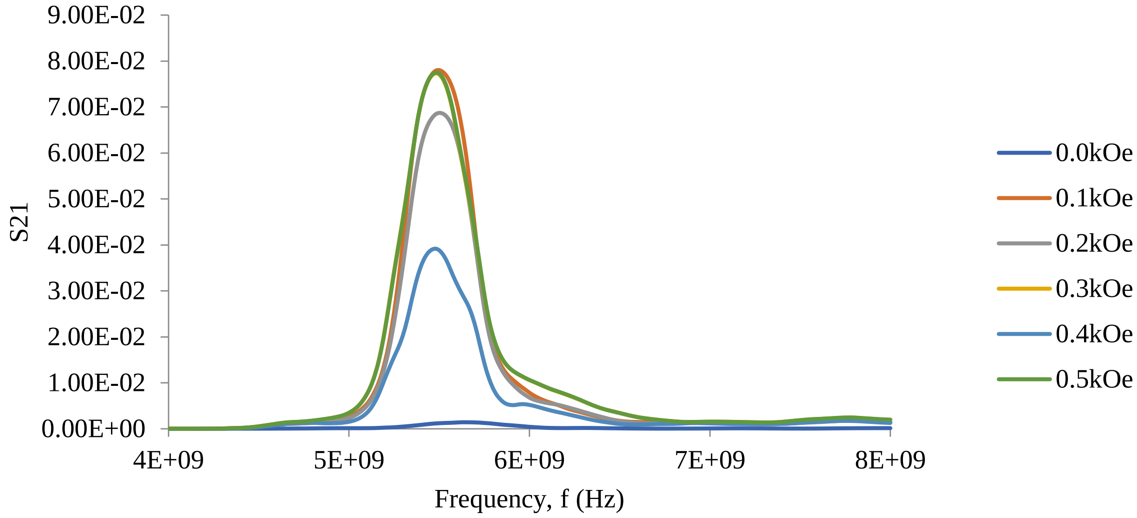


Figure 6. The transmission loss in linear form for YIG-filled cavity as a function of frequency and magnetic field in the C-band frequency

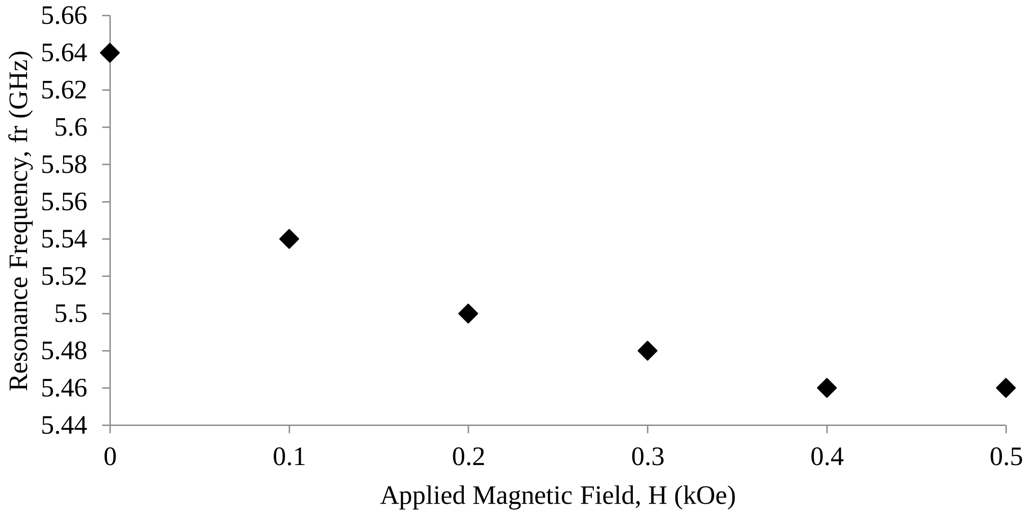


Figure 7. The resonance frequency of YIG as a function of the magnetic field at C-band frequency

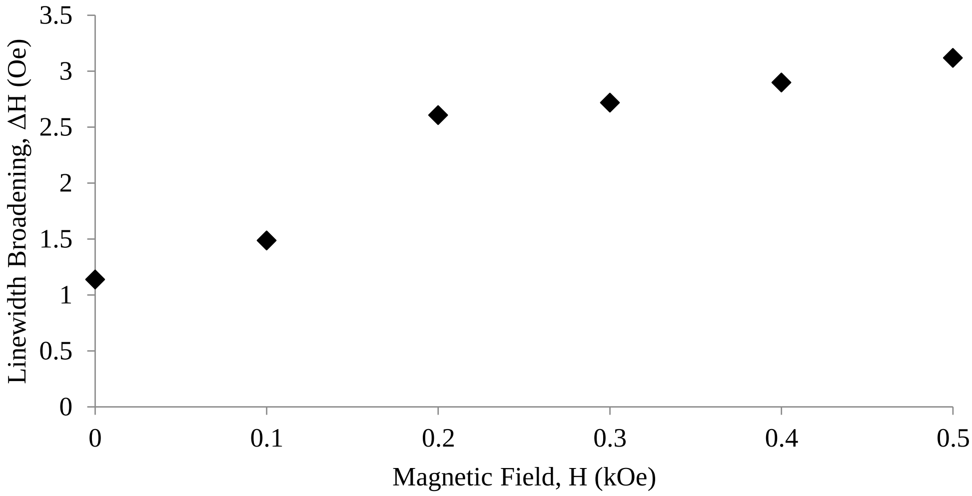


Figure 8. The linewidth broadening as a function of the applied magnetic field for the YIG sample

The efficiency of the cavity resonator is characterized by its Q-factor, with the fabricated empty resonator achieving a Q-value of 30,000. The Q-value is defined by the formula $Q = \frac{2 f_o}{\Delta f}$ where f_o is the resonance frequency, and Δf is the linewidth of the scattering curve [20]. A high Q-value indicates that EM waves can reflect multiple times within the cavity resonator before significant power loss occurs. When a sample is inserted into the cavity resonator, the path length of the EM wave through the material increases, allowing for a more precise evaluation of the energy absorbed by the material. This in turn provides a more accurate characterization of the transmission loss characteristics of the materials.

4. CONCLUSION

In this study, a cylindrical cavity resonator for microwave loss measurement was successfully designed and fabricated. Experimental investigations were conducted using magnetically yttrium iron garnet (YIG) to assess the viability of the fabricated cavity resonator. Transmission loss measurement results revealed a slight difference in transmission loss between the empty cavity resonator and the YIG-filled cavity resonator under zero magnetic field, highlighting the low magnetic loss characteristics of YIG. The same trend can be observed, regardless of the intensity of the applied magnetic field. Scrutinizing the resonance frequency and bandwidth of YIG samples demonstrated narrow linewidth broadening and low transmission loss which underscore its potential in telecommunication devices.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS CONTRIBUTION

R. Nazlan (Conceptualization; Methodology; Formal analysis; Data curation; Investigation; Writing – original draft; Funding acquisition)

F. N. Shafiee (Formal analysis; Data curation; Investigation)

I. R. Ibrahim (Methodology; Writing – review & editing; Validation)

M. A. Jusoh (Validation; writing – Review & editing)

R. A. Ramli (Writing – Review & editing)

F. Esa (Software; Validation; Data Curation)

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