

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**MICROWAVE PHOTON-MAGNON COUPLING IN PLANAR
GEOMETRY FOR QUANTUM TRANSDUCTION**

MORTEZA VAFADAR YENGEJEH
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF PHYSICS

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PROF. DR. BULAT RAMI

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GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

KUANTUM DÖNÜŞÜMÜ İÇİN
DÜZLEMSEL GEOMETRİDE MİKRODALGA
FOTON-MAGNON EŞLEŞMESİ

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DANIŞMANI
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2023



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SUMMARY

Transferring quantum information from systems that work at microwave regimes to other quantum systems that are far apart from each other requires optical channels to minimize the issue of the decoherence effect. The intermediate systems that can interact with microwave photons of quantum systems as well as with photons in the optical communication band (~ 200 THz) are hybrid quantum systems (HQS). One promising approach for achieving this transduction is through a magnon-based HQS, utilizing the collective spin excitation (magnon) modes. Having the advantages of broad conversion bandwidth, low-temperature operation, and high tunability over other HQSs, encourages ongoing research in this field to improve the efficiency of this conversion process. Yttrium iron garnet (YIG) material is used for magnon sources since it is a ferrimagnetic insulator with a high spin density that can interact coherently with microwave and optical photons. More recent studies have primarily focused on planar geometries of magnon-based hybrid systems, as they offer enhanced photon-magnon coupling, and can be fabricated using well-established microfabrication techniques. The objective of this thesis is to explore the potential of magnon-based quantum transduction with planar structure solutions. The thesis will primarily concentrate on developing new designs for planar microwave resonators, investigating their photon-magnon coupling strength through numerical simulations, and experimentally demonstrating their effectiveness. Within this work, we propose and verify the performance of microwave planar resonators containing a YIG thin film positioned above a through-hole feature. The presence of the hole in the resonator structure enables perpendicular passage of the pumping and signal lights, facilitating efficient coupling between external optical resonator modes and magnon modes. Strong microwave photon-magnon coupling was initially achieved with numerical simulations which later the identical results confirmed experimentally at room temperature.

Key Words: Quantum Transducer, Magnonics, Photon-Magnon Coupling, YIG, Microwave Resonator, Planar Geometry

ÖZET

Mikrodalga rejiminde çalışan sistemlerden kuantum bilgisini uyumluluğun (coherence) kaybetmeden uzakta olan diğer kuantum sistemlere aktarmak için optik kanallara ihtiyaç duyulur. Kuantum sistemlerin mikrodalga fotonları ile optik iletişim bandındaki (~ 200 THz) fotonlarla etkileşime girebilen ara sistemler, hibrit kuantum sistemleridir. Bu dönüşümü başarmak için umut verici bir yaklaşım, kolektif spin uyarı (magnon) modlarını kullanan bir magnon tabanlı hibrit kuantum sistemdir. Diğer sistemlere göre geniş dönüşüm bant genişliği, düşük sıcaklıkta çalışma ve yüksek ayarlanabilirlik avantajları, dönüşüm verimini artırmak için bu alanda devam eden araştırmaları teşvik etmektedir. İtiryum demir garnet (YIG) malzemesi, mikrodalga ve optik fotonlarla uyumlu bir şekilde etkileşebilen yüksek spin yoğunluğuna sahip ferrimanyetik bir yalıtkan olduğu için magnon kaynakları için kullanılır. Daha yeni çalışmalar, güçlü foton-magnon eşleşmesi ve mikrofabrikasyon teknikleri kullanılarak üretilebilecekleri için öncelikle düzlemsel geometrilere odaklanmıştır. Bu tezin amacı, düzlemsel yapı çözümleriyle magnon tabanlı kuantum dönüşümün potansiyelini keşfetmektir. Öncelikle düzlemsel mikrodalga rezonatörleri için yeni tasarımlar geliştirmesi, sayısal simülasyonlarla foton-magnon eşleşme gücünü araştırması ve etkinliklerini deneysel olarak kanıtlaması odaklanacaktır. Bu çalışma kapsamında, dielektrik plaka üzerinde hazırlanan ve optik giriş için deliği bulunan bölgeye YIG ince filmi konulan düzlemsel mikrodalga rezonatörlerin geliştirilmesi ve performansının doğrulanması amaçlanmıştır. Rezonatör yapısındaki deliğin varlığı, harici optik rezonatör modları ile magnon modları arasında verimli bir eşleşmeyi kolaylaştırarak optik pompalama ve sinyal ışınlarının mikrodalga rezonatöre dik olarak geçişine imkan vermektedir. Güçlü mikrodalga foton-magnon eşleşmesi, ilk sayısal simülasyonlarla elde edilmiş olup daha sonra aynı sonuçlar oda sıcaklığında deneysel olarak doğrulanmıştır.

Anahtar Kelimeler: Kuantum Dönüştürücü, Magnonik, Foton-Magnon Eşleşmesi, YIG, Mikrodalga Rezonatör, Düzlemsel Geometri

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LIST of ABBREVIATIONS and ACRONYMS

<u>Abbreviations and Acronyms</u>	<u>Explanations</u>
α	: Gilbert damping constant
$a (a^\dagger)$	: Photon annihilation (creation) operator
c	: Speed of light in vacuum
ε_0	: Vacuum permittivity
ε_r	: Relative permittivity
g	: Photon–magnon coupling strength
g_e	: Landé g-factor
g_N	: Spin-number-normalized photon–magnon coupling strength
$\hbar$	: Reduced Planck's constant
$m (m^\dagger)$	: Magnon annihilation (creation) operator
μ_r	: Relative permeability
μ_0	: Vacuum permeability
μ_B	: Bohr magneton
γ	: Gyromagnetic ratio
λ	: Wavelength
χ	: Magnetic susceptibility
AC	: Alternating Current
CMOS	: Complementary Metal-Oxide-Semiconductor
DC	: Direct Current
EM	: Electromagnetic
FEA	: Finite Element Analysis
FMR	: Ferromagnetic Resonance
FSR	: Free Spectral Range
GGG	: Gadolinium Gallium Garnet
GPIB	: General Purpose Interface Bus
GTU	: Gebze Technical University
HPT	: Holstein-Primakoff Transformation
HQS	: Hybrid Quantum System

ISRR	: Inverted Split Ring Resonator
LLG	: Landau-Lifshitz-Gilbert equation
M	: Magnetization
MO	: Magneto-Optical
M-SRR	: Modified Split Ring Resonator
MW	: Microwave
N	: Number of spins
NV	: Nitrogen-Vacancy
PCB	: Printed Circuit Board
RF	: Radiofrequency
RWA	: Rotating Wave Approximation
SRR	: Split Ring Resonator
USB	: Universal Serial Bus
VNA	: Vector Network Analyzer
YIG	: Yttrium Iron Garnet

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1. INTRODUCTION

In the early 20th century, the development of quantum mechanics marked the onset of the first quantum revolution. This profound shift in our understanding of the physical world led to the development of numerous groundbreaking, such as transistors and lasers. In recent decades, we have witnessed what is often referred to as the "second quantum revolution" which refers to ongoing advancements in quantum science and technology that focus on harnessing and manipulating quantum phenomena such as superposition and entanglement for practical applications [1]. Technologies with novel functionalities like quantum computing [2,3] and quantum-secure communication [4], together with technologies that improve performance as in quantum metrology [5,6] have gathered significant attention in the last decades. Many of these technologies require operation at the microwave (MW) energy scale, most notably superconducting qubits as a leading platform for quantum information processing and also electron spins in quantum dots or nitrogen-vacancy (NV) centers.

Quantum networks, consisting of spatially separated quantum nodes and quantum channels that connect the nodes, would permit secure communication and distributed quantum computing [7,8]. Following the same road map of the modern internet, a quantum internet can be realized from the nodes to create, store, and manipulate quantum information, while channels between them transmit information and allow for entanglement between nodes [8,9]. The most favorable quantum channel is optical photons within the near-infrared communication spectrum where the low-decoherence transmission can be achieved in an optical fiber or free space with satellites [10,11]. Consequently, extensive research efforts have been directed toward developing efficient transduction schemes to bridge the gap between the microwave and optical domains [12–15].

A hybrid quantum system (HQS) that consists of interacting microwave and optical subsystems through a nonlinear medium can be used for the realization of quantum transduction. Various approaches like systems based on atomic ensembles, opto-mechanical systems, electro-optic systems, and opto-magnonic systems are actively researched [16–19]. Among them, opto-magnonic systems have several advantages over others including high bandwidth, longer coherent lifetime, and

better tunability [20,21]. A magnonic system refers to a system or device that involves the manipulation and control of magnons, which are collective excitations of spins in a magnetic material. Yttrium iron garnet (YIG) stands out as an exceptional source of magnons for quantum transduction applications since it is an insulator ferromagnet that can interact with electromagnetic waves at both microwave and optical ranges [22–25]. Other crucial advantages include the high spin density and low damping constant, which contribute to high conversion efficiency. YIG also benefits from a well-established manufacturing process for growing a thin film on gadolinium gallium garnet (GGG) substrates through epitaxial growth. Importantly, both YIG and GGG garnets are transparent to infrared light in optical telecommunication bands and have been extensively studied both theoretically and experimentally [26,27].

In the past decade, early studies of magnonic transducers have been done using YIG spheres inside 3D microwave (volume) resonators [28–30]. However, researchers have increasingly redirected their attention towards planar magnonic HQSs. Planar architecture offers several advantages, including a more compact form factor, higher coupling efficiency per spin, and compatibility with CMOS technology, which is the standard manufacturing technology for the integrated circuits and the production of planar superconducting electronics used in quantum chips [24,31,32].

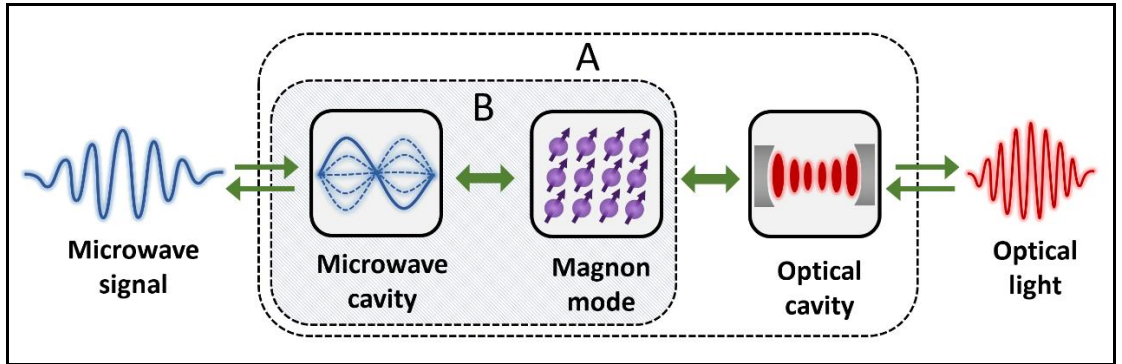


Figure 1.1: Interaction diagram of magnonic MW-optical conversion. Region A, the outer dash-lined box, covers the MW-optical transducer system, and region B, the inner shaded box, indicates the MW regime subsystem.

Figure 1.1 provides an overview of the systems involved in the magnon-based conversion of microwave signal to optical light and vice versa. The magnon mode in the middle of the diagram is coupled with the microwave cavity and the optical

cavity symbolized by green double-headed arrows. The overall conversion efficiency of a quantum transducer system relies on the strength of these couplings. Recent studies that implement planar geometry have used different structures to improve microwave/optical photon-magnon coupling. In these works that demonstrated microwave-optical conversion and belong to the region “A” in Figure 1.1, optical microcavity [33] and waveguide cavity [34] are employed to enhance optical photon-magnon coupling, and split ring resonator (SRR) is used for strong microwave photon-magnon coupling [35]. Also, there have been shown that in the microwave subsystem (region “B” in Figure 1.1) higher bandwidth by utilizing an array of resonators [36] and stronger microwave photon-magnon coupling through modifying the shape of the microwave resonator [37] can be achieved.

This thesis mainly focuses on region B from Figure 1.1, which represents a subsystem within the overall transducer system. In the following chapter, theoretical discussions encompassing both classical and quantum descriptions of the physical effect related to photon-magnon coupling are presented. In Chapter 3 a proposed setup for microwave-optical transduction and the involved systems are discussed. Chapter 4 is dedicated to the numerical analysis of optical and microwave systems including the examination of microwave photon-magnon coupling in various planar structures. The experimental studies and the obtained results are discussed in Chapter 5. Finally, a summary of the results and an outlook for the future directions are given in Chapter 6.

2. THEORETICAL BACKGROUND

2.1. Spin Waves (Magnons)

The concept of a magnon was initially introduced by Felix Bloch in 1930 [38] as an explanation for the way magnetizations in ferromagnetic materials vary with temperature. In spin lattices, where spins can couple through exchange and dipolar interactions, the local disturbance of spin dynamics can lead to the transmission of spin dynamics disruptions in wave-like forms. These waves manifest as collective excitations of the precessions of individual spins within a ferromagnetic medium. The quanta associated with these spin waves are known as magnons and can be considered quasi-particles with distinct energy levels, following the characteristics of bosons. Due to the magnetic coupling of individual spins, collective disturbances of magnetizations give rise to specific spin-wave modes with distinct frequencies and wavelengths. These modes can be observed in a one-dimensional array of magnetic moments, as depicted in Figure 2.1. Generally, spin-wave modes can be classified into two types based on their interaction energy. In the case of short wavelengths, the neighboring spins exhibit significant angle variations, resulting in the dominance of exchange interaction. These exchange-dominated modes are referred to simply as *spin-wave modes*. In contrast, in the case of long wavelengths, the tilting angle

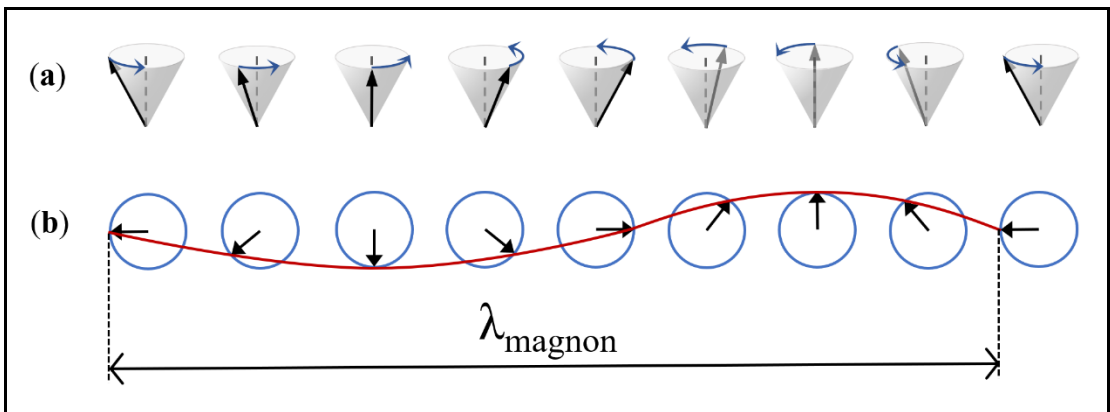


Figure 2.1: An excited spin wave on a one-dimensional spin chain when the magnetization is non-uniformly precessing. (a) Spins precession in perspective. (b) Spins viewed from above, showing one wavelength revolution.

between neighboring spins is minimal, and the long-range dipolar interaction becomes the primary influence on spin-wave characteristics. These types of dipole-dominated spin waves are referred to as *magnetostatic modes*. In an intermediate-wavelength range, both dipolar and exchange interactions play significant roles in spin-wave excitations, forming the dipolar-exchange spin-wave mode. The frequency of a specific spin-wave mode is determined by factors such as the sample's geometry and dimensions, externally applied magnetic field, material parameters, and the microwave frequency range [26,39,40].

2.1.1. Microscopic Description

For a quantitative understanding of the excitation of magnons in ferromagnetic materials, we employ Heisenberg Hamiltonian considering coupling only between the nearest-neighbor spins plus the Zeeman energy term resulting from an external static magnetic field for a one-dimensional chain of spin 1/2 particles:

$$\mathcal{H} = -\frac{1}{2}J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - g_e \mu_B \sum_i \mathbf{H}_0 \cdot \mathbf{S}_i, \quad (2.1)$$

where J is the exchange constant, $\mathbf{S}_{i(j)}$ is the spin operators for the lattice sites with index i (j), the sum over i, j considers only the nearest neighbors ($j = i \pm 1$), g_e is the Landé g-factor and μ_B is Bohr magneton, and $\mathbf{H}_0$ is the external magnetic field in the z -direction. To proceed, it is convenient to rewrite the spin operators as raising and lowering operators, for the j th site we can define,

$$S_j^+ = S_j^x + iS_j^y, \quad (2.2)$$

$$S_j^- = S_j^x - iS_j^y. \quad (2.3)$$

We can now rewrite Equation 2.1 to

$$\mathcal{H} = -\frac{1}{2}J \sum_{\langle i,j \rangle} S_i^z S_j^z - g_e \mu_B H \sum_i S_i^z - \frac{1}{4}J \sum_{\langle i,j \rangle} (S_i^+ S_j^- + S_i^- S_j^+). \quad (2.4)$$

Dealing with the spin operators can be inconvenient. However, the Holstein-Primakoff Transformation (HPT) [41] offers a method to map the spin operators into bosonic creation and annihilation operators, denoted as m and $m^\dagger$, respectively. This transformation allows us to describe spin waves using the occupation number representation, also known as second quantization. The procedure for transforming the spin operators is as follows:

$$S_+ = \hbar\sqrt{2s} \sqrt{1 - \frac{m^\dagger m}{2s}} m, \quad (2.5)$$

$$S_- = \hbar\sqrt{2s} m^\dagger \sqrt{1 - \frac{m^\dagger m}{2s}}, \quad (2.6)$$

$$S_z = \hbar(s - m^\dagger m), \quad (2.7)$$

where s is the total spin number for spin waves at a particular site. At low temperatures, the total number of spins is high compared with the number of excitations (total number of flipped spins). Within this spin-wave approximation:

$$S_+ \approx \hbar\sqrt{2s} m \quad (2.8)$$

$$S_- \approx \hbar\sqrt{2s} m^\dagger. \quad (2.9)$$

Here the raising and lowering operators are correlated with the annihilation and creation operators respectively. Along with the Fourier transformation of the bosonic ladder operators

$$m_k^\dagger = \frac{1}{\sqrt{N}} \sum_j e^{ik \cdot r_j} m_j^\dagger, \quad (2.10)$$

$$m_k = \frac{1}{\sqrt{N}} \sum_j e^{-ik \cdot r_j} m_j. \quad (2.11)$$

Equation 2.4 reduces to:

$$\mathcal{H} = \sum_k \hbar\omega_k m_k^\dagger m_k. \quad (2.12)$$

This is the Hamiltonian in the harmonic oscillator language with resonance frequency ω_k , which follows from the above approximation. For small wavevector, $\mathbf{k}$ (or in the long magnon wavelength limit compared to nearest-neighbor distance, a_0), a quadratic dispersion relation with respect to $\mathbf{k}$ can be obtained [42] as:

$$\hbar\omega = 2sJa_0^2k^2 + g_e\mu_B B_z. \quad (2.14)$$

Here the so-called Kittel mode becomes a special case when $k = 0$, where all spins precess in phase, which is the only mode considered within this thesis.

2.1.2. Macroscopic Description

Magnons can also be described classically. In practice, instead of dealing with a single isolated atom, magnetic systems usually involve numerous atoms, with a large number of electrons interacting through exchange coupling. Consequently, from the individual states with magnetic moment $\mathbf{m}$, a quasi-continuous treatment in a macroscopic description with magnetization $\mathbf{M} = n\mathbf{m}$ can emerge. Here n is the number of microscopic magnetic moments per unit volume. In this way, the magnetization within a given volume can be effectively analyzed using a macrospin description. Inside a ferromagnetic solid, the collective magnetic moments experience a combined magnetic field that includes not only the external Zeeman field ($\mathbf{H}_0$) but also local exchange, local anisotropy, and dipolar fields. To account

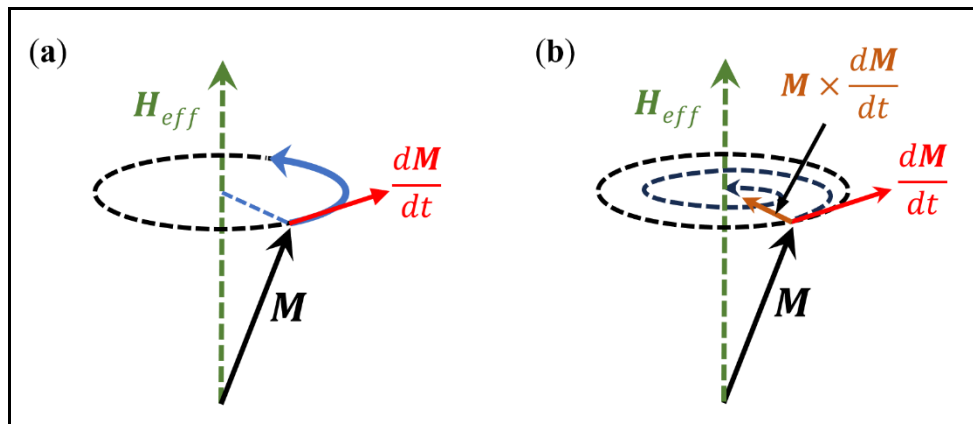


Figure 2.2: Sketch of the magnetization precession around an effective magnetic field (a) without damping and (b) with Gilbert damping.

for these various contributions, an effective field ($\mathbf{H}_{eff}$) is introduced. When the equilibrium state is disturbed, the magnetization tilts by an angle relative to the magnetic field of $\mathbf{H}_{eff}$. Through energy minimization, magnetization tends to align parallel to the field. However, since a magnetic moment inherently possesses total angular momentum, it exerts a torque on the magnetization. This torque represents a change in the rate of angular momentum, causing the magnetization to undergo precession around the static $\mathbf{H}_{eff}$ field, as illustrated in Figure 2.2(a).

In the absence of damping, the classical equation of motion for magnetization is

$$\frac{d\mathbf{M}}{dt} = -\gamma\mu_0\mathbf{M} \times \mathbf{H}_{eff}. \quad (2.14)$$

which is also known as the lossless form of *Landau-Lifshits* equation [43]. Here $\gamma = \mu_0 g_e |q|/2m_e$, is the gyromagnetic ratio of each ferromagnetic spin, where q and m_e are the charge and mass of the spin moment. According to Equation 2.14, the magnetic moment precesses around the static field at a fixed cone angle without reaching the equilibrium position. However, this contradicts what is observed experimentally, where the magnetic moment eventually reaches an equilibrium state after a finite time. In 1955, Gilbert [44] resolved this problem by introducing the effects of magnetic damping within the material in the equation which is referred to as the Landau-Lifshitz-Gilbert (LLG) equation [27],

$$\frac{d\mathbf{M}}{dt} = -\gamma\mu_0\mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S} \left(\mathbf{M} \times \frac{d\mathbf{M}}{dt} \right), \quad (2.15)$$

where α is the Gilbert phenomenological and dimensionless damping parameter which describes how fast the motion of the magnetization will stop by following a helical trajectory as shown in Figure 2.2(b).

2.2. Ferromagnetic Resonance (FMR)

The LLG equation states that in the absence of a continuous driving torque, the amplitude of magnetization precession will decrease due to damping and the magnetization will eventually align along the direction of the effective applied

magnetic field. To sustain the magnetization precession, a continuous driving torque is required which can be obtained by applying a microwave magnetic field ($\mathbf{h}e^{-i\omega t}$) that oscillates at a frequency ω . The magnitude of this field is usually much smaller compared to the magnitude of the applied external magnetic field. In this case, the magnetization $\mathbf{M}$ can be written as $\mathbf{M} = M_0\mathbf{k} + \mathbf{m}e^{-i\omega t}$ where $\mathbf{m}e^{-i\omega t}$ is the oscillating component of the magnetization caused by the microwave magnetic field and is much smaller than M_0 . This resonant absorption of energy in the microwave frequency range by the magnetic moment of a ferromagnet is commonly referred to as (FMR) [45].

To obtain a general equation for the dispersion of the Kittel mode, which represents the uniform precession mode with a wavevector of zero, it is necessary to account for the demagnetizing fields. These fields, characterized by the demagnetization tensor $\mathbf{H}_d = -\vec{\mathbf{N}}\mathbf{M}$, decrease the influence of an external field on the spins. The contribution strongly relies on the shape of the magnetic sample under test. The inclusion of a shape dependence was first introduced by Kittel in 1948 [46]. When an external magnetic field is applied along the z-axis with sufficient strength to saturate the sample (i.e., M_0 equals the saturation magnetization, M_s), resulting in the alignment of the magnetization vector parallel to the external field, the dispersion relation for ferromagnetic resonance can be derived for a rotational ellipsoid as follows [46]:

$$\omega_{\text{FMR}} = \gamma\mu_0\sqrt{(H_z + (N_x - N_z)M_s)(H_z + (N_y - N_z)M_s)}, \quad (2.16)$$

where N_x , N_y , and N_z are the demagnetization factors along the x-, y-, and z-axes for any shape of an ellipsoid. For a thin film magnetized in the film plane ($N_x=1$, $N_y=N_z=0$ in SI unit), this formula reduces to [47]

$$\omega_{\text{FMR}} = \gamma\mu_0\sqrt{H_z(H_z + M_s)}, \quad (2.17)$$

and for magnetizations oriented in the axis normal to the film plane ($N_x=N_y=0$, $N_z=1$), it becomes

$$\omega_{\text{FMR}} = \gamma\mu_0(H_z - M_s). \quad (2.18)$$

These modes can be resonantly excited if the frequency of microwave magnetic fields equals the mode resonance frequency, $\omega_{FMR}/2\pi$.

2.3. Magnetocrystalline Anisotropy

Magnetocrystalline anisotropy refers to the tendency of magnetic materials to exhibit different magnetization in different crystallographic directions. This anisotropy arises from the way the magnetic moments of individual atoms or ions within the material interact with the crystal lattice structure. The primary source of anisotropy is spin-orbit interaction where for an electron with orbital that is not spherically symmetric, the energy of the state depends on the orientation of the orbital to surrounding ions in the crystal [48,49]. Additionally, for crystals with non-cubic lattice, a secondary source of orientation-dependent energy would be the mutual interaction of the magnetic dipoles of crystal (dipole-dipole interaction) [50].

The underlying crystal structure of YIG has cubic symmetry, and magnetic moments come from the Fe^{3+} ions with the spherical $^6S_{5/2}$ ground state. Therefore, it is expected that since the ground state orbitals contain no angular momentum, magnetocrystalline anisotropy will be absent due to lack of spin-orbit coupling. However, there is in fact, a small anisotropy effect which is attributed to the $3d$ shell deformation of Fe^{3+} by the surrounding ions of crystal lattice resulting in a small spin-orbit interaction [51,52].

The magnetocrystalline anisotropy energy (E_K) for the crystal structure with cubic symmetry, magnetized in an arbitrary direction, can be conveniently expressed in terms of its *direction cosines* to the cube edges; α_1 , α_2 , and α_3 . The anisotropy energy must satisfy the cubic symmetry conditions; first, the anisotropy energy density ($U_K = E_K/V$) must be invariant under the reversal of the net magnetization $\mathbf{M}$, and second, the anisotropy energy density must be constant under the interchange of any two axes. It can be shown that the function that satisfies these conditions is [53]

$$U_K = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 + \dots \quad (2.19)$$

The parameter K_i has units of energy density and depends on composition and temperature. Here, the direction cosines, α_1 , α_2 , and α_3 , are related to the magnetization by,

$$\alpha_1 = \frac{M_1}{M_s}, \alpha_2 = \frac{M_2}{M_s}, \alpha_3 = \frac{M_3}{M_s}, \quad (2.20)$$

where M_i is the component of $\mathbf{M}$ along the i th axis.

In thin films, a stress-induced *uniaxial* anisotropy can be observed. A bulk anisotropy with the dominating uniaxial term also occurs naturally in hexagonal or tetragonal crystals. The uniaxial anisotropy term is characterized by a single high-symmetry axis that corresponds to either the highest or lowest energy. The axis is called the *hard axis* or *easy axis* if it corresponds to the highest or lowest energy, respectively [45].

2.4. Photon-Magnon Coupling Model

In general, models describing the interaction between photons and magnons can be classified into two categories: classical and quantum. In the classical approach, one must solve the coupled equations of motion, the LLG equation, and Maxwell's equations. On the other hand, in the quantum approach, one begins by defining a Hamiltonian and then proceeds to determine the eigenfrequencies and transmission properties. Despite these different approaches, the ultimate equation used for the theoretical modelling of photon-magnon coupling remains unchanged.

2.4.1. Classical model

In this model, there are two oscillators with unit mass each, corresponding to the microwave cavity photon and the magnon modes and possess resonance frequencies denoted as ω_c and ω_m , respectively. These two oscillators are coupled via a coupling constant κ . The damping factors associated with the cavity and

magnon modes are β and α respectively. These damping constants are utilized to

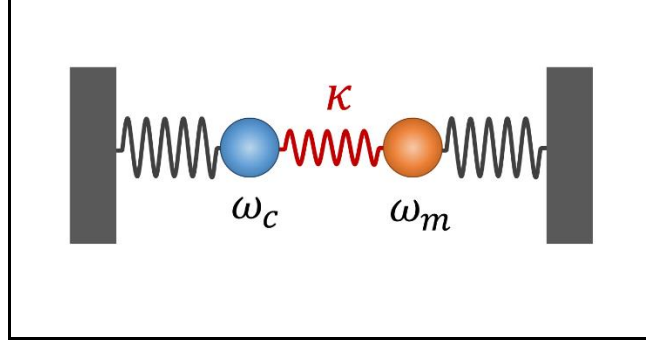


Figure 2.3: Schematic illustration of coupled oscillators.

model the inherent losses in the cavity and the Gilbert damping in the magnon mode.

The equations governing the motion of the system can be expressed in a matrix format of size 2×2 :

$$\begin{pmatrix} \omega^2 - \omega_c^2 + i\omega\omega_c\beta & -\kappa\omega_c^2 \\ -\kappa\omega_c^2 & \omega^2 - \omega_m^2 + i\omega\omega_c\alpha \end{pmatrix} \begin{pmatrix} A_c \\ A_m \end{pmatrix} = \begin{pmatrix} -f \\ 0 \end{pmatrix}, \quad (2.21)$$

where A_c and A_m represent the maximum amplitudes of oscillation for the cavity and magnon, respectively. The parameter f represents the driving force acting on the oscillator that represents the cavity photon mode. The diagonal elements of the matrix equation correspond to the resonance frequencies of the harmonic oscillators that model the cavity and magnon modes, while the off-diagonal terms describe the coupling between them. By examining this matrix equation, it becomes evident that if there is no coupling term ($\kappa = 0$), only the resonance of the cavity mode oscillator will be observed, resulting in $A_m = 0$. By solving the equation through the determinant of the matrix,

$$\det(\Omega) = (\omega^2 - \omega_c^2 + i\omega\omega_c\beta)(\omega^2 - \omega_m^2 + i\omega\omega_c\alpha) - \kappa^2\omega_c^4, \quad (2.22)$$

two roots can be obtained for the ω . The resonance frequency dispersion of the two oscillators is determined by the real part of the roots, while the evolution of the linewidth for both modes can be understood from the imaginary part of the roots [54]. These findings are useful for interpreting experimental data, particularly in

experiments that demonstrate the generation of the Rabi gap and the changes in linewidth for the cavity photon and magnon modes.

In the case of strong coupling when $\alpha, \beta \ll 1$, the damping effects are negligible, and the determinant can be simplified as

$$\det(\Omega) = (\omega^2 - \omega_c^2)(\omega^2 - \omega_m^2) - \kappa^2 \omega_c^4, \quad (2.23)$$

from which the roots can be calculated near the coupling point $\omega \approx \omega_c \approx \omega_m$ to be,

$$\omega_{\pm} = \frac{(\omega_c + \omega_m \pm \sqrt{(\omega_c - \omega_m)^2 + \kappa^2 \omega_c^2})}{2}. \quad (2.24)$$

From the above equation, it is evident that the coupling between the two oscillators results in the emergence of two hybridized modes, characterized by resonance frequencies ω_+ and ω_- , where $\omega_+ > \omega_-$. When the resonance frequencies of both oscillators are equal, the real part of the eigenfrequencies of this system can be simplified as follows.

$$\omega_{\pm} = \omega_c \pm \frac{\kappa \omega_c}{2}. \quad (2.25)$$

Thus, the resonance frequency difference between the two hybridized modes is given by $\omega_{gap} = \omega_+ - \omega_- = \kappa \omega_c$. Therefore, if the cavity resonance frequency is known, the coupling strength between the two resonators can be determined experimentally from the *Rabi gap* as $g = \frac{\kappa \omega_c}{2}$. Using Equation 2.24, the dispersion of resonance frequency of the two modes can be plotted as a function of the detuning $\Delta = \omega_m - \omega_c$ in Figure 2.4.

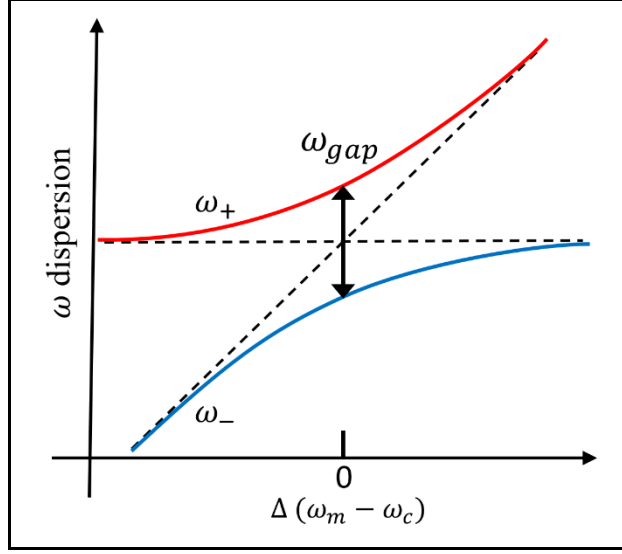


Figure 2.4: Dispersion of resonance frequency modes obtained from the classical harmonic oscillator model plotted as a function of the detuning Δ .

2.4.2. Quantum Model

The most basic Hamiltonian representing the interaction between the spins of YIG, and the microwave cavity photons consists of three components: the Hamiltonians for the cavity photons ($\mathcal{H}_p$) the spin system ($\mathcal{H}_s$), and the interaction between these two systems ($\mathcal{H}_I$). Thus, it can be expressed as $\mathcal{H} = \mathcal{H}_p + \mathcal{H}_s + \mathcal{H}_I$ and can be treated by the Jaynes-Cummings model, which is a fundamental mathematical framework in quantum optics [55]. By assuming a large number of spins ($N \gg 1$), the HPT can be applied, treating the excitations of the spin system (magnons) as bosonic particles [56]. Furthermore, other assumptions can be the single resonant cavity mode at ω_c , and only considering the lowest spin excitation mode (Kittle mode) at ω_m . Therefore,

$$\mathcal{H}_p = \hbar\omega_c a^\dagger a, \quad (2.26)$$

$$\mathcal{H}_s = \hbar\omega_m m^\dagger m, \quad (2.27)$$

$$\mathcal{H}_I = \hbar g(a + a^\dagger)(m + m^\dagger), \quad (2.28)$$

here the creation (annihilation) operators for the photon and magnon are denoted as $a^\dagger(a)$ and $m^\dagger(m)$ respectively, with a coupling strength of g . The terms

of the $\mathcal{H}_I$ can be expressed as $am \sim e^{-i(\omega_c+\omega_m)t}$ and $am^\dagger \sim e^{-i(\omega_c-\omega_m)t}$, along with their Hermitian conjugates. With approximation of $\omega_c \sim \omega_m$, the $e^{-i(\omega_c+\omega_m)t}$ term rapidly oscillates and has can be neglected due to its time-averaging effect. Therefore, the terms $\hbar g(am + a^\dagger m^\dagger)$ can be disregarded that constitutes the essence of so-called rotating wave approximation (RWA). Thus, the Hamiltonian for this system becomes:

$$\mathcal{H} = \hbar\omega_c a^\dagger a + \hbar\omega_m m^\dagger m + \hbar g(am^\dagger + a^\dagger m). \quad (2.29)$$

This Hamiltonian describes the basic physics of the coupling between magnons and photons. However, a more comprehensive approach would be quantizing the magnetic field of the MW photon and working its coupling to the Heisenberg ferromagnet through Zeeman interaction [54]. After applying HPT, spin-wave approximation, and using Fourier transformation, the coupling strength g turns out to be proportional to the square root of the spin density (N). Hence, materials with a high spin density, such as YIG, are desirable to achieve strong photon-magnon coupling. The eigenvalues of the Hamiltonian described in Equation 2.29 are:

$$\omega_\pm = \frac{(\omega_c + \omega_m \pm \sqrt{(\omega_c - \omega_m)^2 + 4g^2})}{2}. \quad (2.30)$$

These eigenvalues lead to the characteristic anti-crossing dispersion of resonance frequencies. Similar to what is discussed in the harmonic oscillator model the coupling strength ($g = \omega_{gap}/2$), can be determined by extracting the splitting gap (Rabi gap) of the anti-crossing dispersion spectrum of the coupled modes from experimental or numerical results [56].

2.5. Yttrium Iron Garnet (YIG)

One of the most commonly used magnetic materials in magnonics is a single-crystal yttrium iron garnet (YIG, chemical formula: $Y_3Fe_5O_{12}$). Researchers have consistently favored YIG due to its remarkable set of advantageous properties. Since

its initial discovery, this material has found significant utilization in various microwave technology applications, including high-frequency filters [57]. YIG, being a ferrimagnetic insulator, possesses a high Curie temperature of 559 K.

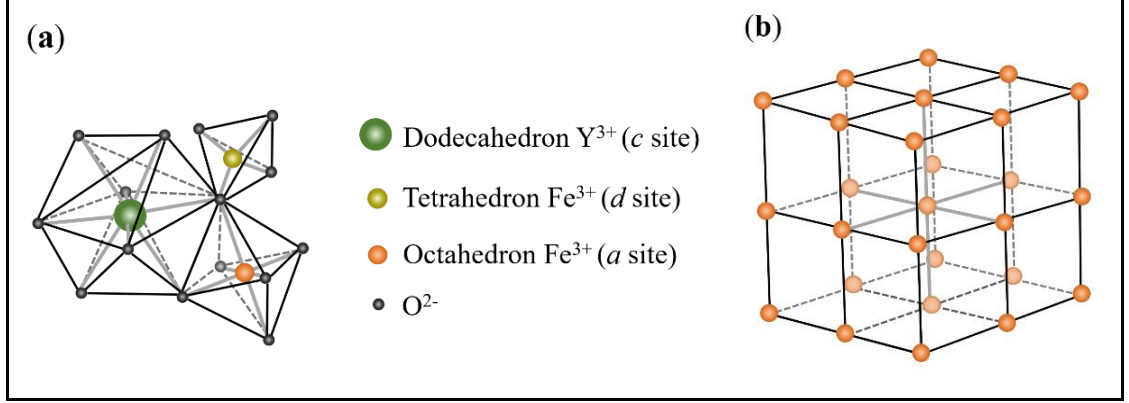


Figure 2.5: (a) Schematic diagram of the crystal structure of YIG. (b) The unit cell of YIG is depicted by the locations of the Fe^{3+} of the “ a site” which is divided into eight subunits.

Since the magnetic ions in YIG (Fe^{3+}) have negligibly small orbital moment, their interaction with lattice deformations and phonons is weak. As a result, YIG benefits from small magnetic damping of spin waves which is characterized by very narrow FMR linewidth [39]. The crystal structure of YIG shown in Figure 2.5 [58] demonstrates that the oxygen ions (O^{2-}) form three distinct polyhedrons: the dodecahedron, the octahedron, and the tetrahedron [29]. Within this structure, the yttrium ions (Y^{3+}) occupy the dodecahedral site, while the iron ions (Fe^{3+}) occupy both the tetrahedral and octahedral sites. The Fe^{3+} ions in these sites possess different spins, which are ordered ferrimagnetically. The magnetocrystalline anisotropy constants of YIG are $K_1 = -610 \text{ J/m}^3$ and $K_2 = -26.0 \text{ J/m}^3$ at room temperature [26]. The easy axis of magnetocrystalline anisotropy of YIG is along the (111) direction. A (111) YIG film has an out-of-plane (perpendicular) anisotropy field of about 85 Oe and a threefold in-plane anisotropy field of less than 85 Oe.[59].

The magnon resonances in YIG spheres exhibit high-quality factors, making YIG suitable for the development of tunable microwave filters and resonators. The extremely low Gilbert damping factor of approximately 10^{-5} and a significantly high spin density of $4.22 \times 10^{27} \text{ m}^{-3}$, make it an excellent candidate for use in HQS as the magnonic material employed in experiments involving cavity photon-magnon coupling [60]. The best quality YIG films are grown using the liquid phase epitaxy

method on a gadolinium gallium garnet (GGG) substrate owing to the close matching between their lattice constant (12.383 Å for GGG and 12.376 Å for YIG). Both of these garnets are transparent to infrared light in optical telecommunication bands and have been extensively studied theoretically and experimentally [26].

2.6. Faraday Effect

The Faraday Magneto-Optical (MO) effect is a phenomenon characterized by the rotation of polarization in transmission. To understand the concept behind this effect, let us consider a magnetic field ($\mathbf{B}$) applied along the z direction and, an electromagnetic wave that is linearly polarized in the x direction, passing through the MO material along the z -axis as illustrated in Figure 2.6. Consequently, the electrons within the material, influenced by the incident wave, oscillate in the x direction with a velocity $\mathbf{v}$. As a result of the Lorentz force ($\mathbf{F} = q\mathbf{v} \times \mathbf{B}$), where q is the electron charge, a coupling between the x and y directions takes place, resulting in the oscillations of the electrons to move in an elliptical pattern. Therefore, the transmitted waves acquire an additional component in the y direction, in addition to their original component along the x -axis. This phenomenon leads to the rotation of

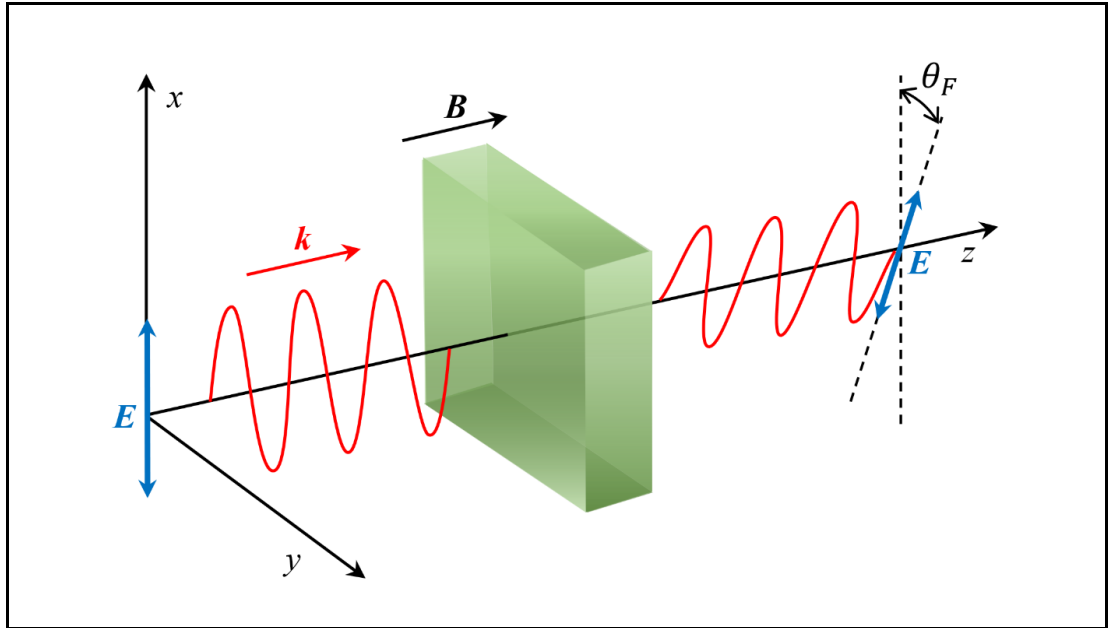


Figure 2.6: Schematic illustration of the Faraday effect.

the wave's polarization plane, known as the Faraday rotation. For further understanding of the Faraday effect, we can implement Maxwell's equations [40]. The electric field of the incident linear electromagnetic wave depicted in Figure 2.6 can be written as:

$$\mathbf{E} = \mathbf{E}_0 e^{i(kz - \omega t)}, \quad (2.31)$$

where E_0 is the amplitude of the electric field. This wave should satisfy the equation:

$$\frac{k^2}{\mu_0 \omega^2} \left[\mathbf{E} - \frac{\mathbf{k}(\mathbf{k} \cdot \mathbf{E})}{k^2} \right] = \bar{\epsilon} \cdot \mathbf{E}, \quad (2.32)$$

where, $\bar{\epsilon}$ is the permittivity tensor of the MO material.

In the absence of a magnetic field, the MO material is generally isotropic ($\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz}$). The corresponding tensor is then diagonal,

$$\begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{xx} & 0 \\ 0 & 0 & \epsilon_{xx} \end{pmatrix}, \quad (2.33)$$

where $\epsilon_{xx} = N^2$, with $N = n - i\kappa$ is the complex refractive index of the material.

In the presence of a magnetic field in the z -direction (see Figure 2.6), antisymmetric off-diagonal elements will appear in the tensor permittivity:

$$\begin{pmatrix} \epsilon_{xx} & i\epsilon_{xy} & 0 \\ -i\epsilon_{xy} & \epsilon_{xx} & 0 \\ 0 & 0 & \epsilon_{xx} \end{pmatrix}, \quad (2.34)$$

where, ϵ_{xy} is a dispersive term, and it depends on the wavelength. This expression explains the coupling between x and y components under the magnetic field resulting in the Faraday effect.

The non-reciprocal nature of the Faraday effect is a significant characteristic. The rotation of the polarization plane occurs due to the interaction between two electric field components under the influence of the Lorentz force. The direction of the rotation relies on the magnetic field and electron oscillations, but it is

independent of the direction of light propagation. As a result, when a polarized wave travels back and forth through the material, the rotation effect is doubled instead of being canceled.

3. MICROWAVE-OPTICAL TRANSDUCTION SETUP

The proposed experimental setup for the microwave-optical conversion using a YIG film is schematically shown in Figure 3.1. In this setup, a 1550 nm laser source would provide an optical pump laser beam, and a network analyzer would generate and read microwave signals through *S-parameter* measurement. The setup benefits from cavity-enhanced interaction between magnons and photons at both microwave and optical domains. YIG film is located on a planar ring microwave resonator/cavity with a through-hole and between two mirrors of an optical cavity, whose details will be discussed in the following sections.

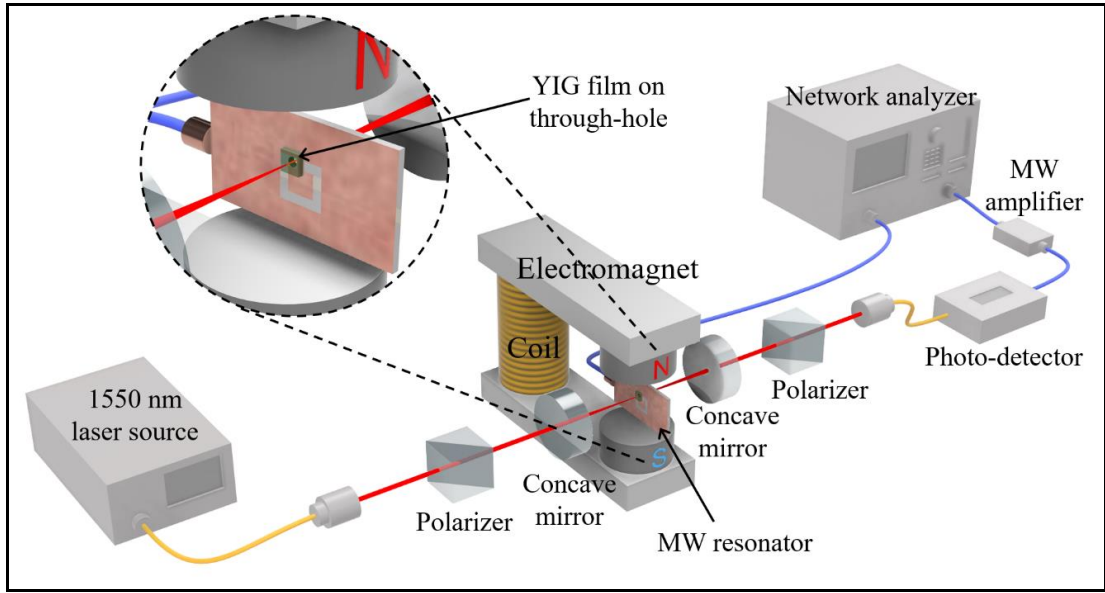


Figure 3.1: Proposed experimental setup for transduction study.

In the process of transduction, a 1550-nm laser beam (pump) with an angular frequency of ω_p and linear polarization impinges on the YIG film. Meanwhile, the itinerant microwave photons (signal) with an angular frequency of ω_m , sourced from the first port of the network analyzer coherently drive magnons via the microwave cavity. The driven magnons then scatter optical photons through the Faraday interaction. Upon passing through the YIG sample, the polarization of the pump light oscillates at the frequency of the induced magnetization oscillation caused by the

Faraday effect. This process generates the optical *sideband* at the angular frequency of $\omega_p \pm \omega_m$ due to the modulation of the pump light. The beat signal between the pump and the sideband is measured using a polarizer and a fast photodetector with a microwave amplifier connected to the second port of the network analyzer.

3.1. Through-Hole Planar Microwave Resonator

In the design process for planar microwave resonators, we have introduced a novel approach that incorporates through-hole features to accommodate various microwave cavity designs while enabling interaction with the optical cavity. By integrating microwave resonators with a through-hole, we can position a microwave-coupled YIG film on top of the hole. This configuration allows for the perpendicular passage of pumping and signal lights, facilitating the coupling between external optical cavity modes and magnon modes. As illustrated in Figure 3.2(a) the planar microwave board consists of a microstrip feeding line that couples to a nearby planar resonator (SRR) which features a circular through-hole at its center. The YIG crystal or thin film is placed on top, covering the hole. This arrangement allows a perpendicular incident pump laser beam to pass through both the YIG film and the board, as shown in the cross-section view in Figure 3.2(b). The planar resonator, with the YIG film adjacent to the through-hole, is positioned between two poles of an electromagnet that applies an in-plane external magnetic field ($\vec{H}_0$) in the y -direction to the YIG film. To form an optical cavity with the YIG film at the midpoint, two concave mirrors are situated on the left and right sides. The pump light enters and is confined between the mirrors by passing through the board via the hole and the YIG film.

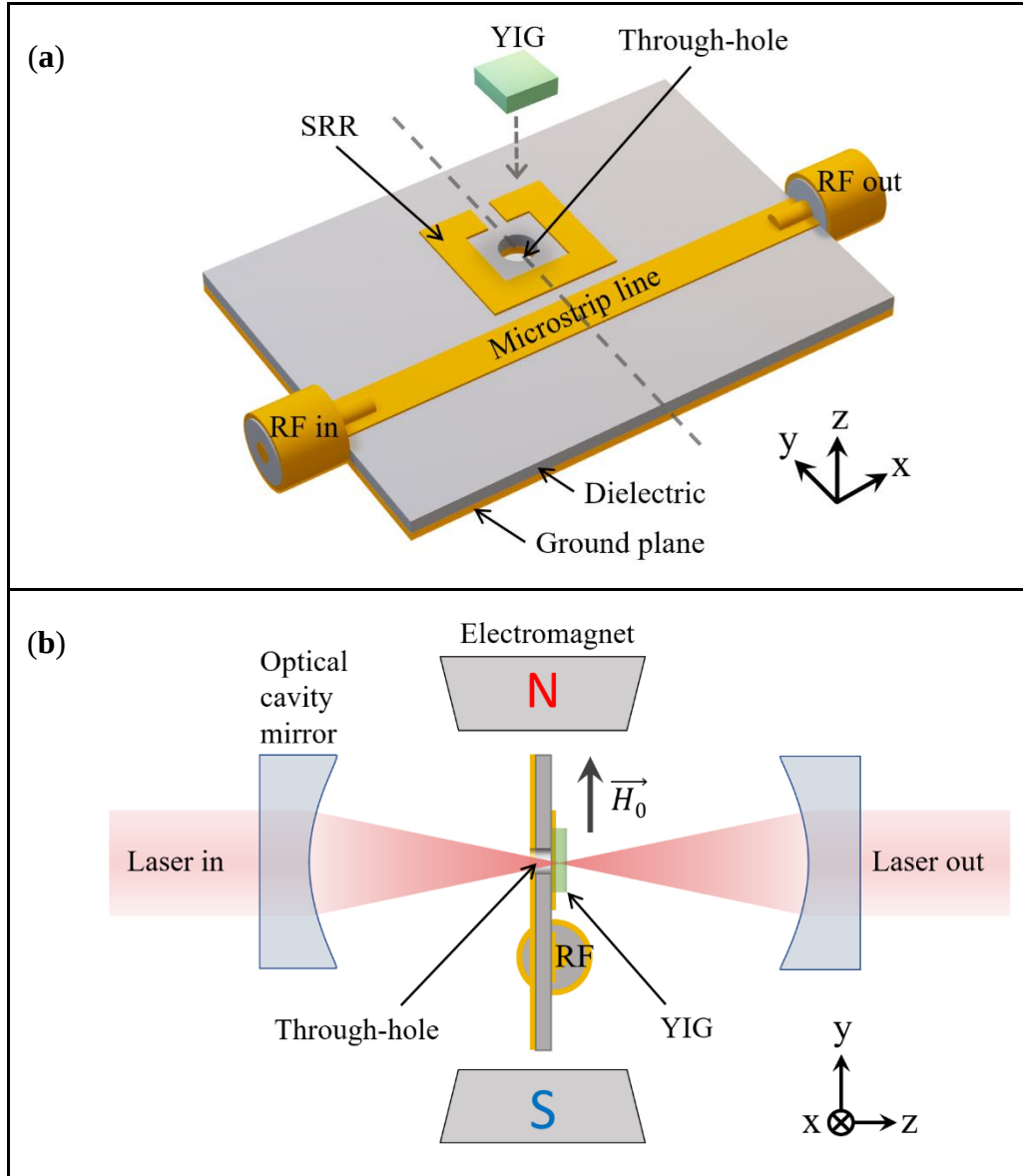


Figure 3.2: Schematic illustration for the proposed MW-optical conversion setup. (a) SRR with a through-hole at the center of the ring. (b) Cross-section view of the resonator across the dashed line in (a) between two poles of an electromagnet at top and bottom, and inside an optical cavity.

The underlying physics of the conversion process involves three harmonic oscillator modes: a microwave cavity mode, the Kittel mode, and an optical cavity mode. By adjusting the external magnetic field, the precession frequency of the Kittel mode's uniform magnetization around the y -axis can be matched with the frequency of the microwave cavity. This alignment allows the time-varying magnetic component of the microwave cavity mode along the x and z axes, $h_{x,z}(t)$, to drive the magnetization precession of the Kittel mode, resulting in strong microwave-magnon coupling. The Kittel mode can also couple to the optical cavity through the Faraday

effect, where the polarization angle of the pump light oscillates at the precession frequency. As discussed in the previous chapter the strength of this interaction is directly proportional to the magnetization strength in the direction of light propagation. Thus, to obtain high coupling strengths between magnons and both microwave and optical photons, it is crucial to position the YIG film and through-hole in a region with maximal $|h_{x,z}(t)|$ values.

3.2. Optical Cavity (Fabry-Perot)

Passive optical resonators, created through the appropriate arrangement of mirrors, are valuable tools for investigating and manipulating light, as well as for constructing lasers. A well-known example of a free-space optical resonator is the Fabry-Perot resonator, which consists of two spherical concave mirrors positioned along the optical axis. These resonators exhibit a unique characteristic wherein a light beam with a defined shape and frequency can be transmitted with high efficiency through the resonator, despite being composed of highly reflective mirrors. The geometry of a Fabry-Perot resonator consisting of concave left and right mirrors is shown in Figure 3.3. The space between these mirrors constitutes the cavity, surrounded by air both inside and outside. When a beam is incident from the left, it results in the presence of both the incident and reflected beams on the left side of the cavity. Within the cavity, there are both right-propagating and left-propagating beams. However, on the right side of the cavity, only the transmitted beam is observed. When two mirrors with radii ρ_1 and ρ_2 are separated by a distance L , they can form a stable optical resonator if they meet the stability criterion of $0 < g_1 g_2 < 1$, where $g_{1,2} = 1 - L/\rho_{1,2}$ represent the stability parameters of the two mirrors. A stable optical resonator defines a set of spatial modes, each with its distinctive mode shape [61]. In order to excite a particular spatial mode in the resonator, we must also consider that the distance between the two mirrors establishes a resonance condition that must be satisfied for that specific spatial mode.

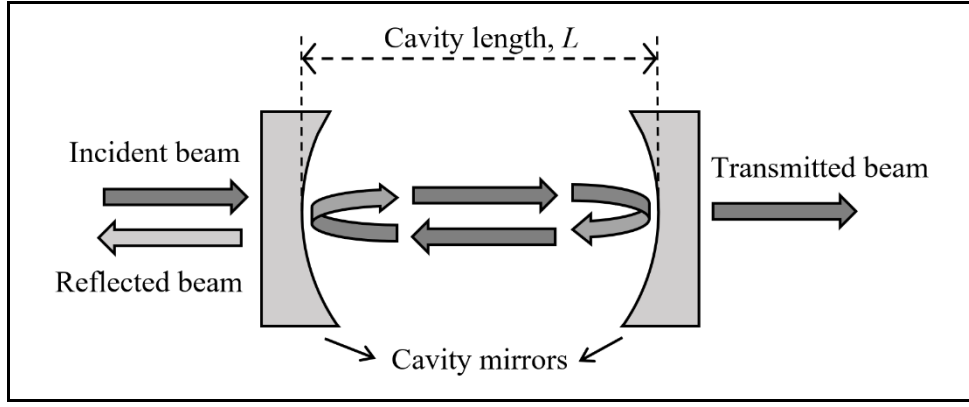


Figure 3.3: Geometry of Fabry-Perot optical cavity.

While high transmission can be achieved at resonance, the resonator exhibits high reflectivity for off-resonance frequencies. The frequency distance between two consecutive modes is called the *free spectral range*, $\Delta\nu_{FSR}$, and is given by [62]

$$\Delta\nu_{FSR} = \frac{c}{2L}, \quad (3.1)$$

where c is the velocity of light.

In the design process of the Fabry-Perot cavity for microwave-optical conversion, it is important to match $\Delta\nu_{FSR}$ (or an integer multiple of it) to the microwave resonator frequency, ω_m . In this way, both the input pump frequency, ω_p , and the output sideband frequency, $\omega_p \pm \omega_m$, coincide with that of an optical mode. This will result in more efficient microwave-optical conversion by allowing the so-called *triple-resonance* condition to be met in which the microwave signal, pump, and optical signal are all resonant with electromagnetic modes [12,34].

The *finesse*, F , is a measure of how narrow the resonance peaks are with respect to their frequency distance. A higher finesse value indicates a more well-defined and narrower resonance peak, which implies that the cavity is better at selectively transmitting light at specific wavelengths or frequencies. Finesse can be calculated by

$$F = \frac{\pi(R_1 R_2)^{\frac{1}{4}}}{1 - \sqrt{R_1 R_2}}, \quad (3.2)$$

where R_1 and R_2 are the corresponding mirror reflectance.

Having the free spectral range and finesse, the bandwidth of the resonance is defined as

$$\delta\nu = \frac{\Delta\nu_{FSR}}{F}. \quad (3.3)$$

The resonator can decompose any input field into its spatial modes, making it function as both a spatial and frequency filter. The fundamental mode of the resonator can be characterized by its *waist*, denoted as (w_0),

$$w_0 = \sqrt{\frac{L\lambda}{\pi}} \left(\frac{g_1 g_2 (1 - g_1 g_2)}{(g_1 + g_2 - 2g_1 g_2)^2} \right)^{\frac{1}{4}}, \quad (3.4)$$

where λ is the wavelength. When radii of curvature for the mirrors are equal, $\rho_1 = \rho_2$, the waist location is at the center of the resonator.

3.3. S-Parameter Measurement

In this thesis, the cavity photon-magnon coupling is experimentally studied by measuring the microwave transmission through microwave network analysis. A microwave network refers to the utilization of one or multiple interconnected microwave devices to transmit microwave signals [57]. In many applications, reflection, transmission, and power characteristics hold significant importance. In such cases, the entire system is considered a microwave network, where the relative amplitudes establish the connection between output voltages, currents, and powers with those at the input [63].

The S-parameter matrix characterizes networks with any number of ports and determines a relationship between the incident wave and the reflected and transmitted waves at each port across a spectrum of frequencies. The S-parameter matrix for a two-port network is widely employed and serves as the basic building block for constructing more complex matrices needed for larger networks. It is given by

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}, \quad (3.5)$$

which can be expanded into

$$b_1 = S_{11}a_1 + S_{12}a_2, \quad (3.6)$$

and

$$b_2 = S_{21}a_1 + S_{22}a_2. \quad (3.7)$$

These equations give the relationship between the outgoing and incident waves at each of the network ports, in terms of the S-parameters. As shown in Figure 3.4(a), S_{11} and S_{22} are reflections at port 1 and port 2 while S_{21} and S_{12} represent the forward (from port 1 to port 2) and reverse transmission parameters respectively.

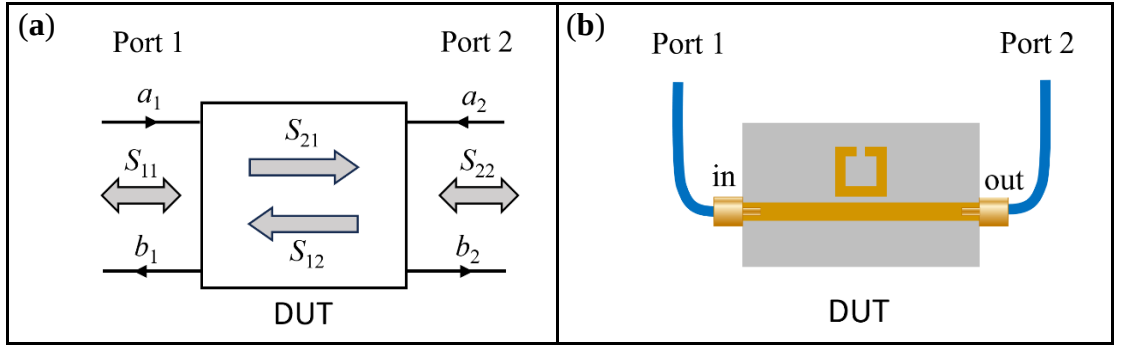


Figure 3.4: (a) Schematic of the scattering matrix S_{ij} for a two-port network (b) SRR fed by a microstrip line representing the DUT with two ports connected via cables.

To obtain the S-parameters, a_1 and a_2 can be defined as the incident voltage waves with b_1 and b_2 being outgoing/reflected voltage waves. If we assume that port 2 is terminated in the reference impedance, Z_0 , then b_2 will be fully absorbed making $a_2 = 0$, thus we have

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = \text{port 1 voltage reflection coefficient}, \quad (3.8)$$

and

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} = \text{forward voltage gain}, \quad (3.9)$$

Similarly, if port 1 is terminated in Z_0 , then $a_1 = 0$, giving,

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} = \text{reverse voltage gain}, \quad (3.10)$$

and

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} = \text{port 2 voltage reflection coefficient}. \quad (3.11)$$

Typically, the device under test (DUT) is not directly connected to the signal source but is separated by a distance, for instance, from connecting microwave cables. It is shown in Figure 3.4(b) for an SRR for transmission measurements. To be able to obtain information on the S-matrix directly at the DUT input and output, the reference plane for the phase needs to be shifted accordingly which can be accomplished through the calibration process of a network analyzer system.

Since the S-parameters are a measure of the ratio between input and output voltage waves at a specific port, these parameters are usually expressed in decibel (dB) units. The conversion equation is:

$$|S_{ij}|(\text{dB}) = 20 \log_{10} |S_{ij}|(\text{linear magnitude}). \quad (3.12)$$

The S_{21} parameter holds interest in FMR studies, since this parameter measures transmission, the voltage at port 2 resulting from port 1 will drop when the resonance condition is met. This decrease signifies that some power hasn't been transmitted rather it has been absorbed by the sample in a resonant energy transfer, eventually dissipating as heat. In both simulation and experimental studies of this thesis, the FMR and microwave photon-magnon coupling dispersion spectra are obtained with the help of the S_{21} parameter.

4. NUMERICAL SIMULATIONS

4.1. Finite Element Analysis Software

For numerical studies, two commercially available finite element analysis software were utilized. The RF package from COMSOL Multiphysics is used to study microwave photon-magnon coupling while its optical packages are utilized to study the Faraday effect and also modelling and calculation of Fabry-Perrot optical cavity characteristics. CST Studio Suite software package, being a powerful tool for microwave studies was used to design various planar microwave resonators with desired characteristics and to numerical calculations of the microwave photon-magnon coupling.

Electromagnetic field simulation software can model magneto-optical effects at microwave frequencies with an effective permeability. In this thesis, the simulation of the so-called gyromagnetic dispersion behavior of YIG is accomplished by defining YIG as a magnetic gyrotropic material. The evaluation of gyromagnetic dispersion is possible for ferrite materials that are magnetized up to saturation by a homogeneous static magnetic field. With this approach, it is possible to observe the Kittel mode, and also higher magnetostatic spin-wave modes of excitation that depend on the geometry of the YIG sample [37,64]. At optical frequency, however, it is difficult to give magnetization, hence to the magnetic susceptibility, a clear physical interpretation [26]. Therefore, at optical frequency, an effective permittivity is more suitable to describe the electromagnetic fields which is the case for the Faraday effect study.

4.2. COMSOL Analyses

4.2.1. Gyrotropic Permeability Definition

To compute microwave photon-magnon interaction in COMSOL, the lossy ferrite material model can be assigned to the YIG sample. Within the “Electromagnetic Wave, Frequency Domain” physics of the RF module, the following equation applies to the electric field vector $\mathbf{E}$ inside the model (Figure 4.1):

$$\nabla \times (\bar{\mu}_r^{-1} \nabla \times \mathbf{E}) - k_0^2 \left(\bar{\epsilon}_r - \frac{j\bar{\sigma}}{\omega\epsilon_0} \right) \mathbf{E} = 0, \quad (4.1)$$

where $\bar{\mu}_r$ denotes the relative permeability tensor, $\bar{\sigma}$ is the conductivity tensor, ϵ_0 is the permittivity of vacuum, $\bar{\epsilon}_r$ is the relative permittivity tensor, and k_0 is the free space wave number. Losses in the ferrite are introduced as complex-valued permittivity and permeability tensors.

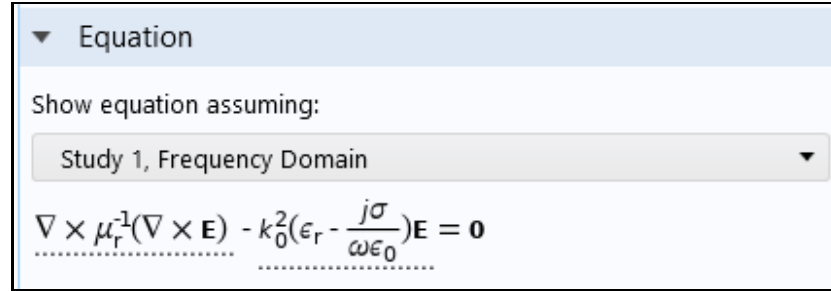


Figure 4.1: Wave equations utilized by Electromagnetic Waves, Frequency Domain (*emw*) solver of COMSOL RF module.

The model assumes that the static magnetic bias field, H_0 , is much stronger than the alternating magnetic field of microwaves. Under this assumption, and including losses, the anisotropic permeability of a ferrite magnetized in the positive z direction is given by:

$$\bar{\mu} = \begin{pmatrix} \mu & i\kappa & 0 \\ -i\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{pmatrix}, \quad (4.2)$$

where

$$\kappa = -i\mu_0\chi_{xy}, \quad (4.3)$$

$$\mu = \mu_0(1 + \chi_{xx}), \quad (4.4)$$

and the elements of the magnetic susceptibility tensor χ are given by [57]:

$$\begin{aligned} \chi_{xx} = & \frac{\omega_0\omega_m(\omega_0^2 - \omega^2) + \omega_0\omega_m\omega^2\alpha^2}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2} \\ & - i \frac{\alpha\omega\omega_m(\omega_0^2 + \omega^2(1 + \alpha^2))}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2}, \end{aligned} \quad (4.5)$$

$$\begin{aligned} \chi_{xy} = & \frac{2\omega_0\omega_m\omega^2\alpha}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2} \\ & + i \frac{\omega\omega_m(\omega_0^2 - \omega^2(1 + \alpha^2))}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2}, \end{aligned} \quad (4.6)$$

where

$$\omega_0 = \mu_0\gamma H_0, \quad (4.7)$$

$$\omega_m = \mu_0\gamma M_s, \quad (4.8)$$

$$\alpha = \frac{\mu_0\gamma\Delta H}{2\omega}. \quad (4.9)$$

To obtain an anti-crossing dispersion spectrum as described in Chapter 2 a YIG film with dimensions of $2 \times 2 \text{ mm}^2$ and $20 \text{ }\mu\text{m}$ thickness on an inverted pattern of SRR modeled as shown in Figure 4.2(a). A comprehensive description of the resonator will be provided in the CST Studio simulation results, as our primary focus here is solely on the computation of the microwave photon-magnon coupling effect. The dispersion spectrum of the transmission coefficient S_{21} parameter as a function

of the sweep frequency and applied H_0 on YIG is shown in Figure 4.2(b). The anti-crossing signatures imply the coupling of not only the Kittel mode but also a magnetostatic mode just above it (indicated by two arrows in Figure 4.2(b)). The splitting gap distance, as discussed in Chapter 2, can be used to calculate the coupling strength, g .

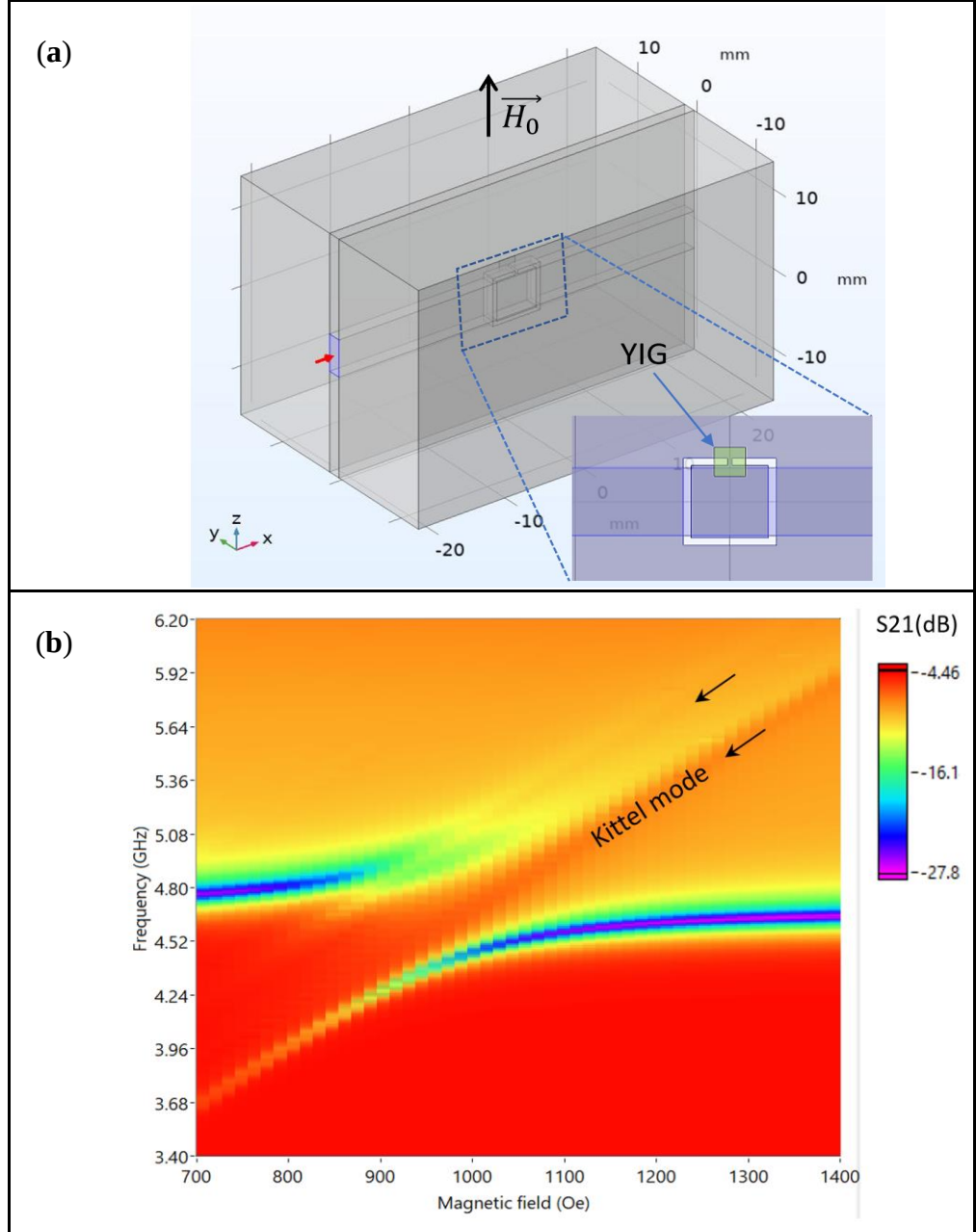


Figure 4.2: (a) The geometry of the YIG on the microwave resonator model. (b) S_{21} parameter spectrum on the plane of frequency and H_0 magnetic field.

4.2.2. Faraday Rotation (Magneto-Optic Effect)

In order to model the Faraday rotation in COMSOL, the “Electromagnetic Waves, Frequency Domain” solver from the Wave Optics module has been chosen. Modelling at the optical frequency range would require defining the permittivity tensor. As discussed in Chapter 2, for the magnetic field applied in the z -direction, antisymmetric off-diagonal elements will appear in the permittivity tensor:

$$\bar{\epsilon} = \begin{pmatrix} \epsilon_{xx} & i\epsilon_{xy} & 0 \\ -i\epsilon_{xy} & \epsilon_{xx} & 0 \\ 0 & 0 & \epsilon_{zz} \end{pmatrix}. \quad (4.10)$$

This expression illustrates the coupling between x and y components under the influence of the magnetic field resulting in the Faraday effect. The simulation results

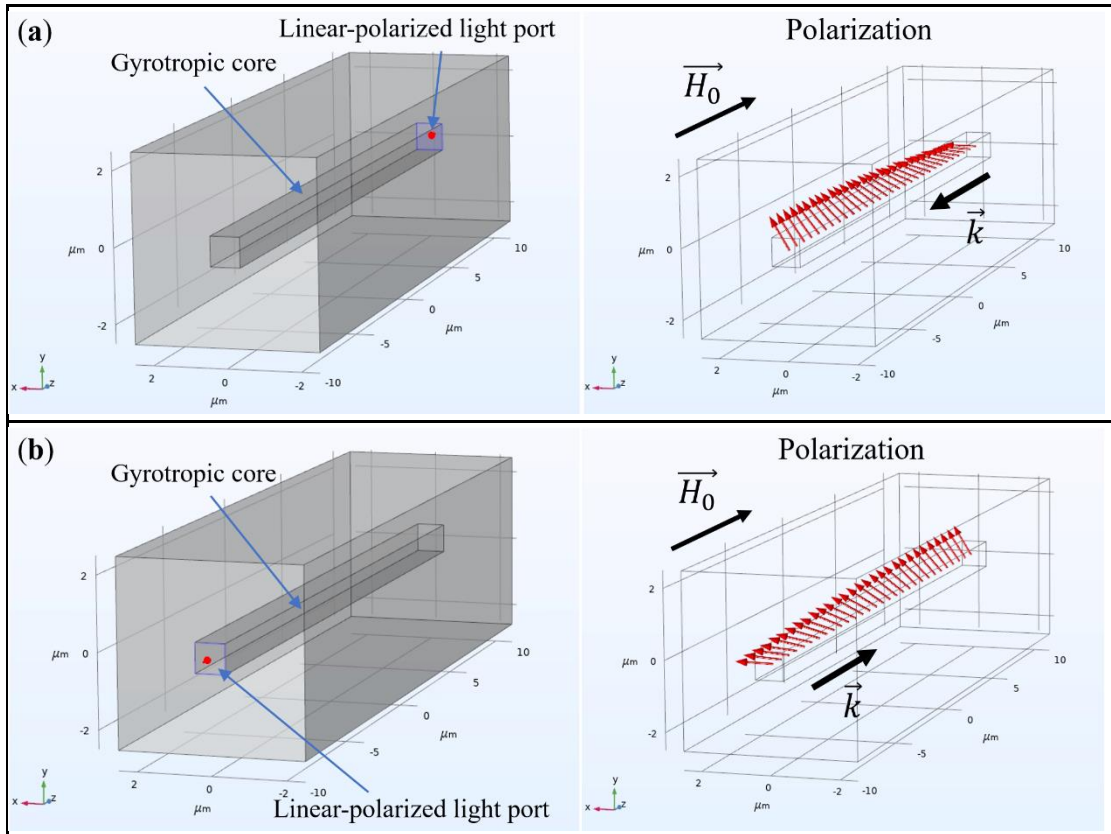


Figure 4.3: Waveguide model and simulation results showing the non-reciprocal property of the Faraday effect. (a) Polarization rotation when the wave propagation vector and the magnetic field direction are opposite and (b) when they are in the same direction.

show the non-reciprocal nature of the Faraday effect which means that the polarization rotation direction only depends on the direction of the applied external magnetic field and not the propagation vector ($\mathbf{k}$) as shown in Figure 4.3.

4.2.3. Fabry-Perot Cavity

Using the geometry definition of Fabry-Perot cavity and equations discussed in the previous chapter the parameters were set and calculated within the Wave Optics module of COMSOL. During the design process of the cavity, we considered the available equipment at the laboratory and future microwave-optical transduction studies. Therefore, the wavelength and the radius of mirror curvature are set accordingly which are given in Table 4.1.

Table 4.1: Simulation parameter values of Fabry-Perot cavity.

Parameter	Value
Wavelength, λ	1550 nm
Cavity length, L	19.7 mm
Radius of mirror curvature, $\rho_{1,2}$	38 mm
Stability parameters, $g_{1,2}$	0.48
Free spectral range, $\Delta\nu_{FSR}$	7.60 GHz
Finesse, F	116.2
Resonance bandwidth, $\delta\nu$	65 MHz
Beam waist radius, w_0	90 μm

Figure 4.4 shows the simulation result for the magnetic field component of the confined beam at its resonance modes around 193.41643 THz. The solver of the Wave Optics physics module used was the “Electromagnetic Waves, Beam Envelopes” which is very suitable for optical cavity simulations with long geometries. However, it should be noted that because of the way this solver works the pattern of the plotted maxima and minima of the electromagnetic field are highly dependent on meshing choices and do not represent the actual pattern.

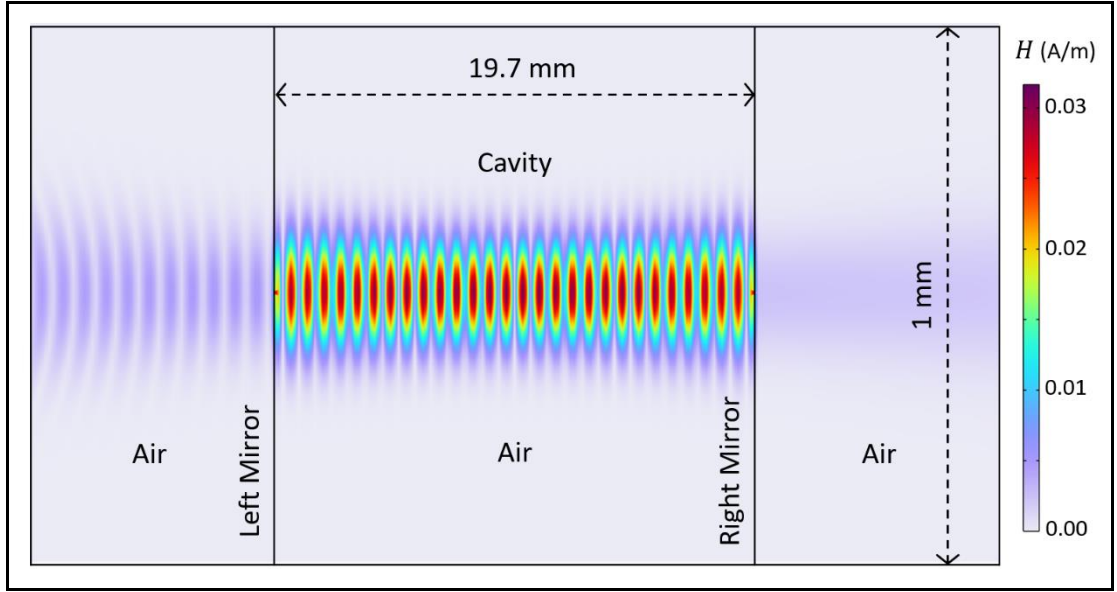


Figure 4.4. The geometry of the Fabry–Perot cavity (not to scale) and the magnetic field component of the incident beam at a resonance frequency (~ 193.41643 THz).

To benefit from the triple-resonance condition, as discussed before, we adjusted the cavity length, L , to get a free spectral range in frequency of 7.60 GHz (Figure 4.5). This value is based on the fabricated microwave resonator used for experimental evaluations which will be discussed in the next chapter.

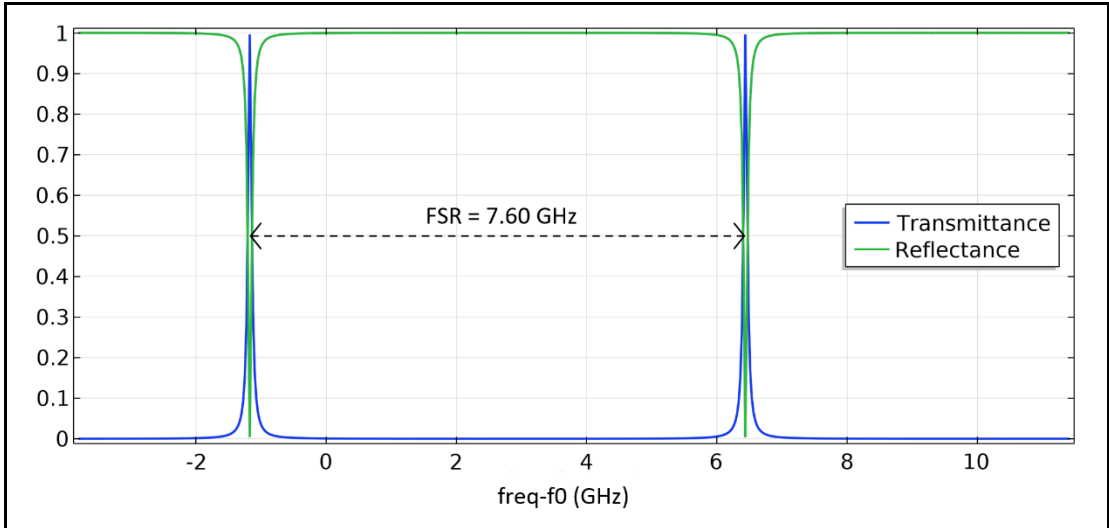


Figure 4.5: Transmittance and reflectance over two FSR frequency sweeps.

4.3. CST Studio Simulations

For the computational study of microwave photon-magnon coupling in CST Studio, it is possible to define YIG as a gyrotropic material using the built-in option in the software. This allows for a convenient design and analysis process as the software offers much more ready tools for RF studies. The magnetic dispersion section of the “Material Properties” window as shown in Figure 4.6 contains the required parameters to define YIG as ferrite material. The first required material parameter is the “Mu infinity” value, representing the high-frequency limit of the relative permeability which is chosen to be the same as the vacuum. Table 4.2 includes the defined parameters for the Mu infinity, Landé g-factor, saturation magnetization, the resonance line width representing the damping effects, and finally the external applied magnetic field vector (x,y,z). Since the solver internally is running in the SI unit, it is required to select parameter conversion for the Gauss units system.

Table 4.2: Parameters of gyrotropic material for YIG in CST Studio (Gauss units).

Mu infinity	Landé g-factor	Saturation magnetization, M_s (Gauss)	Resonance line width (Oe)
1.0	2	1750	12

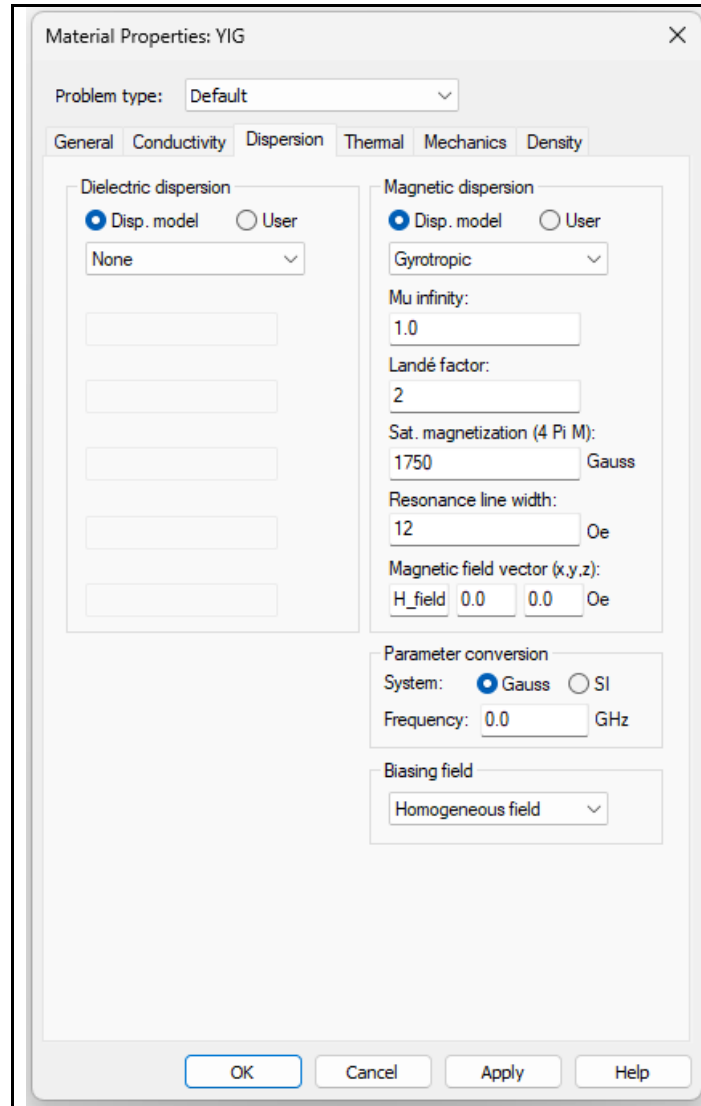


Figure 4.6: Material option window for defining YIG as a gyrotropic material in CST Studio.

4.3.1. Common Parameters for MW Resonator Designs

For three different types of microwave resonators, calculation studies have been done using CST Studio. The microwave board has a relative permittivity (ϵ_r) of 2.6, a thickness of dielectric material of 0.76 mm, and an 18 μm thick copper layer. The feeding microstrip line width (w) is calculated to be equal to 2.05 mm for matching 50 Ohm impedance. The YIG film of $2 \times 2 \text{ mm}^2 \times 20 \mu\text{m}$ represented by a transparent green square in the figures, is positioned on top of the through-hole. In the preliminary step of calculating the resonators' characteristics, the resonance frequencies were adjusted to be around 7.6 GHz.

Table 4.3: Common parameters used in MW resonator designs.

PCB size, height $\times$ length (mm)	Laminate relative permittivity, ϵ_r	Laminate thickness (mm)	Copper cladding thickness (μm)	microstrip line width, w (mm)
25×30	2.6	0.76	18	2.05

4.3.2. Split Ring Resonator (SRR)

The geometry for the modeled split ring resonator is shown in Figure 4.7. The values of the indicated parameters are listed in Table 4.4.

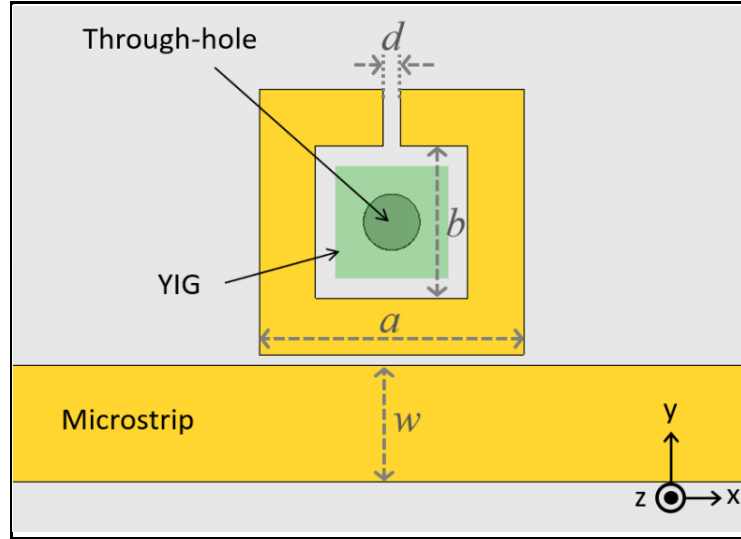


Figure 4.7: Geometry of the resonators with YIG on top of the through-hole for SRR.

From the S-parameter curve trough near the resonance frequency of both numerical simulations and experiments, the quality factor (Q factor) can be calculated by

$$Q = \frac{f_0}{f_H - f_L} = \frac{f_0}{\Delta f}, \quad (4.11)$$

where Δf is the bandwidth at -3 dB cut-off frequencies (f_H and f_L) when the center frequency is the resonance frequency, f_0 .

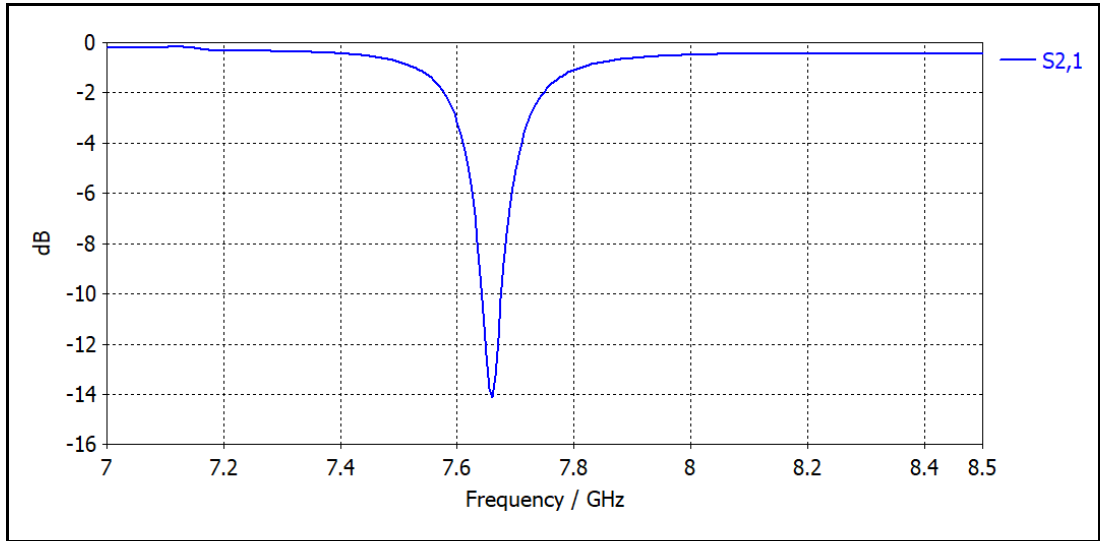


Figure 4.8: S_{21} parameter for SRR.

Figure 4.8 shows the computed S_{21} parameter curve from which the quality factor can be calculated which is included in Table 4.4.

Table 4.4: Parameters used in SRR modelling and the obtained Q factor.

Resonance Frequency, f_0 (GHz)	Outer Square Size, a (mm)	Inner Square Size, b (mm)	Gap Distance, d (mm)	Q factor
7.66	4.4	2.4	0.3	288

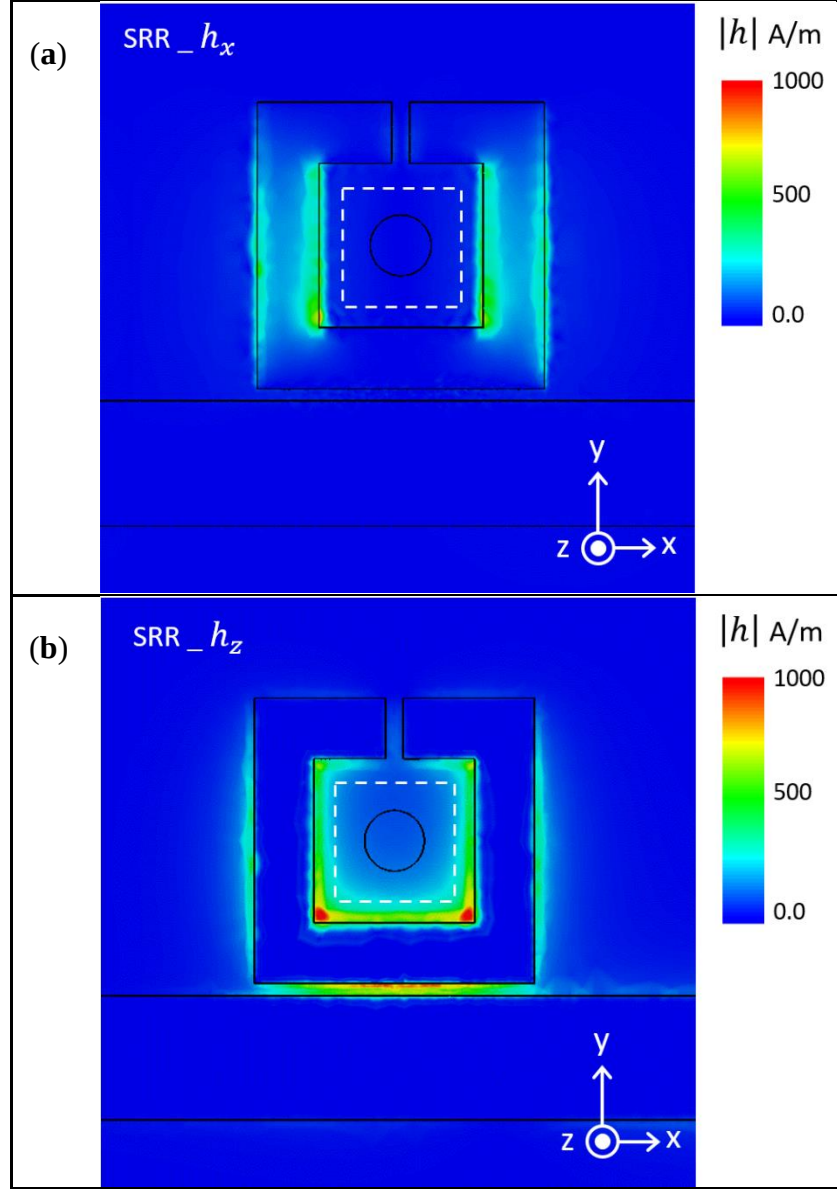


Figure 4.9: SRR spatial distribution of the maximum value of the magnetic component intensity of the EM field in (a) $\hat{x}$ and (b) $\hat{z}$ direction on the surface of the corresponding resonators.

Figure 4.9 illustrates the spatial distribution of the MW field's magnetic component in the x - and z -directions (h_x , h_z) on the resonators' surface at the resonance frequency. It is important to note that the applied static magnetic field ($\vec{H}_0$) is aligned with the y -axis. As a result, the YIG magnetization has a static (longitudinal) component along the y -axis, while the dynamic (oscillating) components (m_x and m_z) are oriented along the x - and z -axes.

In the case of the SRR, the YIG film covers only a sparse region of the h_x and h_z components, indicated by a white dashed square, located at the center of the SRR pattern. It is evident that placing the YIG film in the center does not optimize the

coupling between the YIG and the resonator. However, shifting the rectangular YIG sample to increase the coupling is challenging because the area above the conducting parts of the SRR is not suitable for optical access through a through-hole. Moreover, altering the shape of the YIG sample to match the area with the highest magnetic field seems impractical for real-world implementation.

Figure 4.10 displays the dispersion spectra of the transmission coefficient ($|S_{21}|$ parameter) of the SRR as a function of the sweep frequency and the applied external magnetic field (H_0) on YIG. The dashed curved lines within the spectra highlight the anti-crossing patterns. As discussed in Chapter 2, from the splitting distance of these curved lines, the coupling strengths, g can be extracted (these values are discussed in the last section).

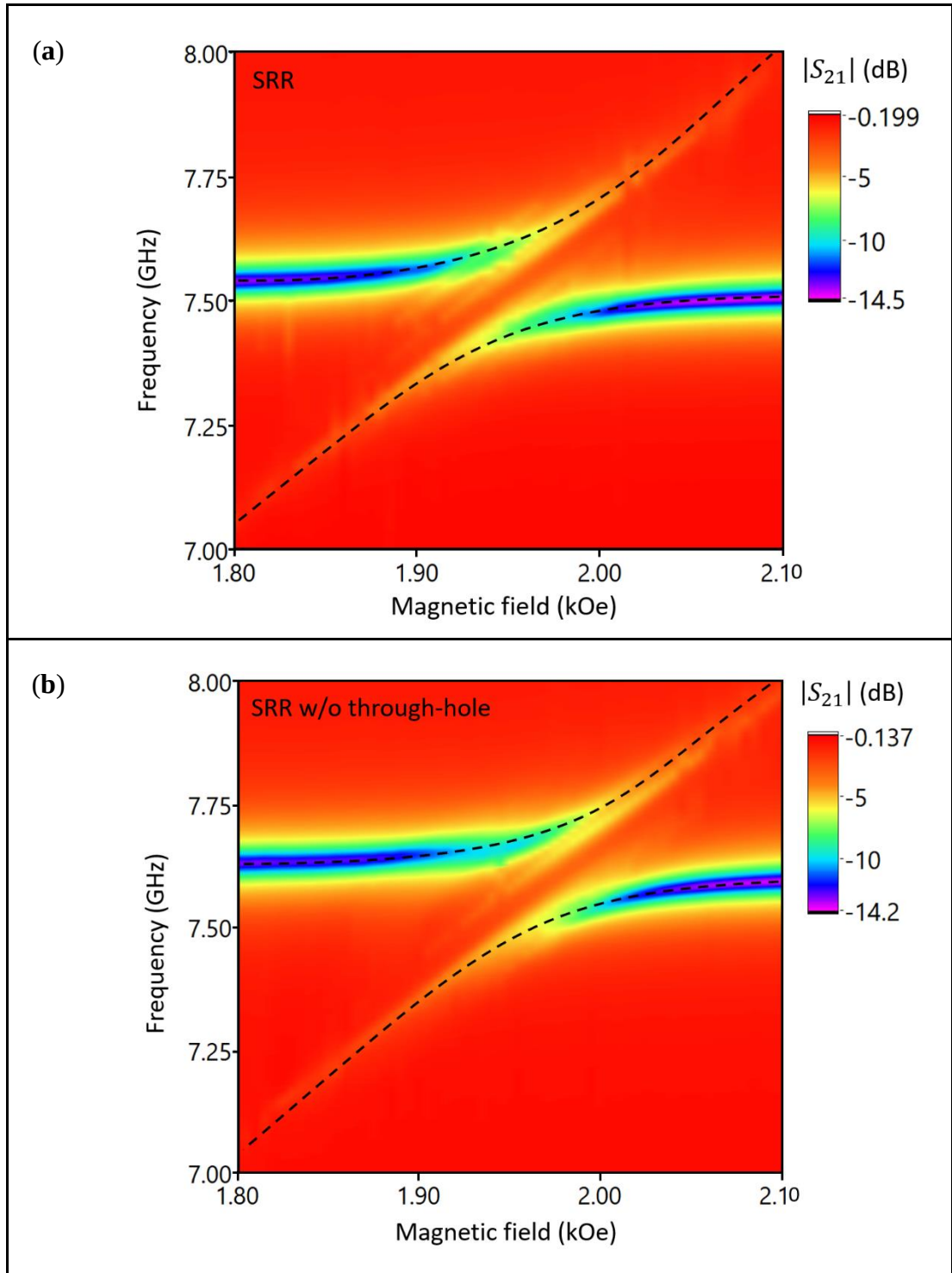


Figure 4.10: $|S_{21}|$ transmission coefficient spectra on the plane of microwave frequency and H_0 magnetic field from simulation results for SRR (a) with through-hole and (b) without through-hole.

4.3.3. Modified SRR (M-SRR)

The Modified SRR (M-SRR), adapted from a recent work [37] is a circular ring with a wedge-shaped split and a through-hole at the center as shown in Figure 4.11.

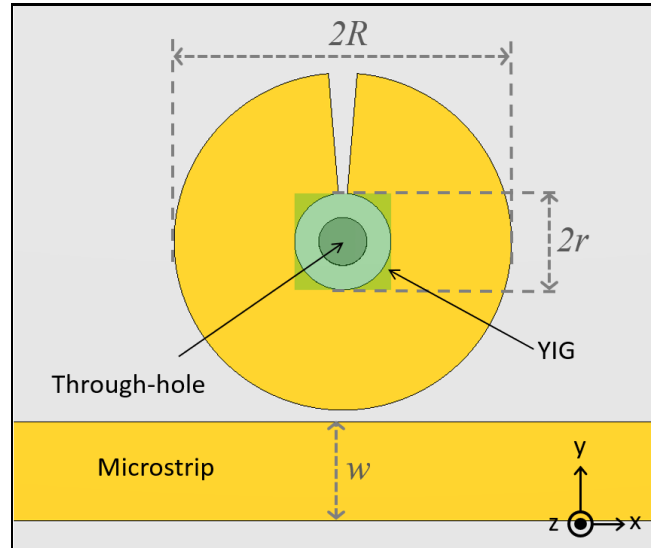


Figure 4.11: Geometry of the resonators with YIG on top of the through-hole for M-SRR.

The values of the geometry parameters are presented in Table 4.5.

Table 4.5: Parameters used in M-SRR modelling and the obtained Q factor.

Resonance Frequency, f_0 (GHz)	Outer circle radius, R (mm)	Inner circle radius r (mm)	Radial cut angle (degree)	Q factor
7.64	3.5	1	10°	245

The S_{21} parameter curve of M-SRR over the frequency range of 7 - 8.5 GHz is shown in Figure 4.12 and from this curve, the Q factor in Table 4.5 is derived.

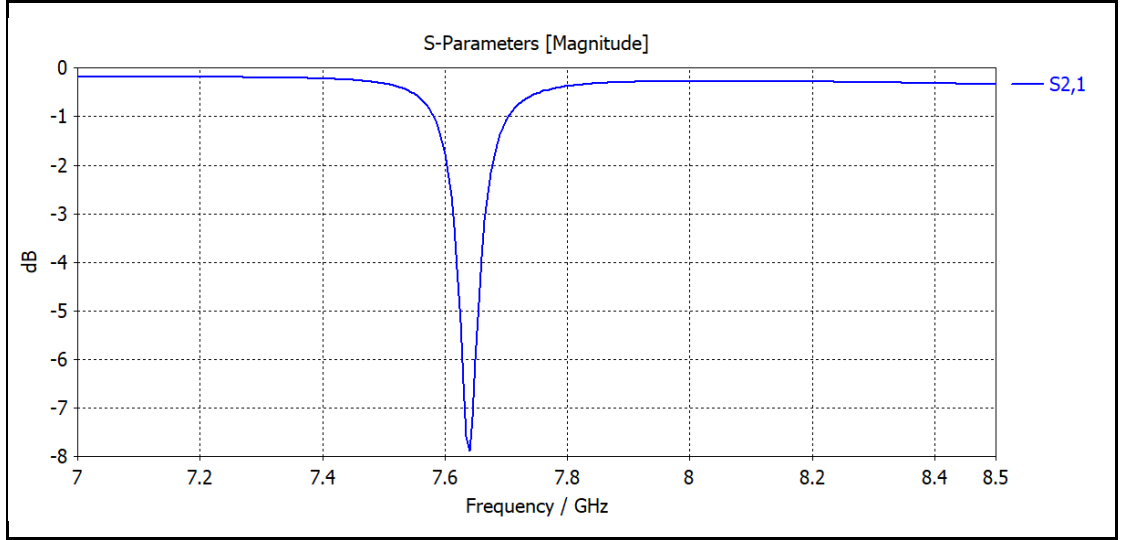


Figure 4.12: S_{21} parameter for M-SRR.

As shown in Figure 4.13 in the M-SRR case, the h_x component of the magnetic field exhibits a concentrated region around the YIG, which then disperses towards the outer edge of the ring. This distribution is suboptimal for exciting the uniform (Kittel) mode because the h_x component has opposite directions on the left and right parts of the ring. Consequently, when integrating the product of h_x and m_x (magnetization along the x -axis) over these areas in the YIG film, the contributions will cancel each other out. However, the h_z component displays excellent coverage, which explains its relatively high coupling strength, as will be further discussed in this section.

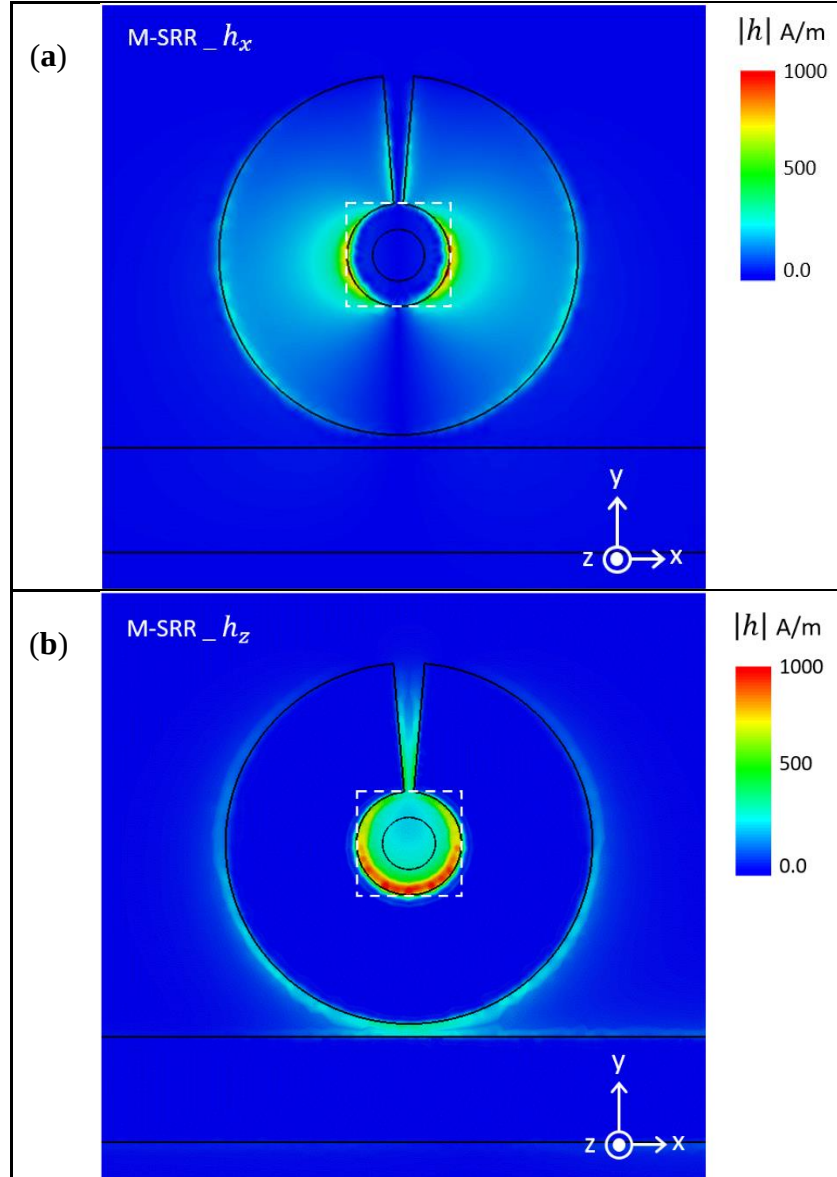


Figure 4.13: M-SRR spatial distribution of the maximum value of the magnetic component intensity of the EM field in $\hat{x}$ and $\hat{z}$ direction on the surface of the corresponding resonators.

Figure 4.14 shows the dispersion spectra of the transmission coefficient ($|S_{21}|$ parameter) of the M-SRR, whose anti-crossing characteristic is indicated by dashed curve lines from which coupling strengths can be extracted.

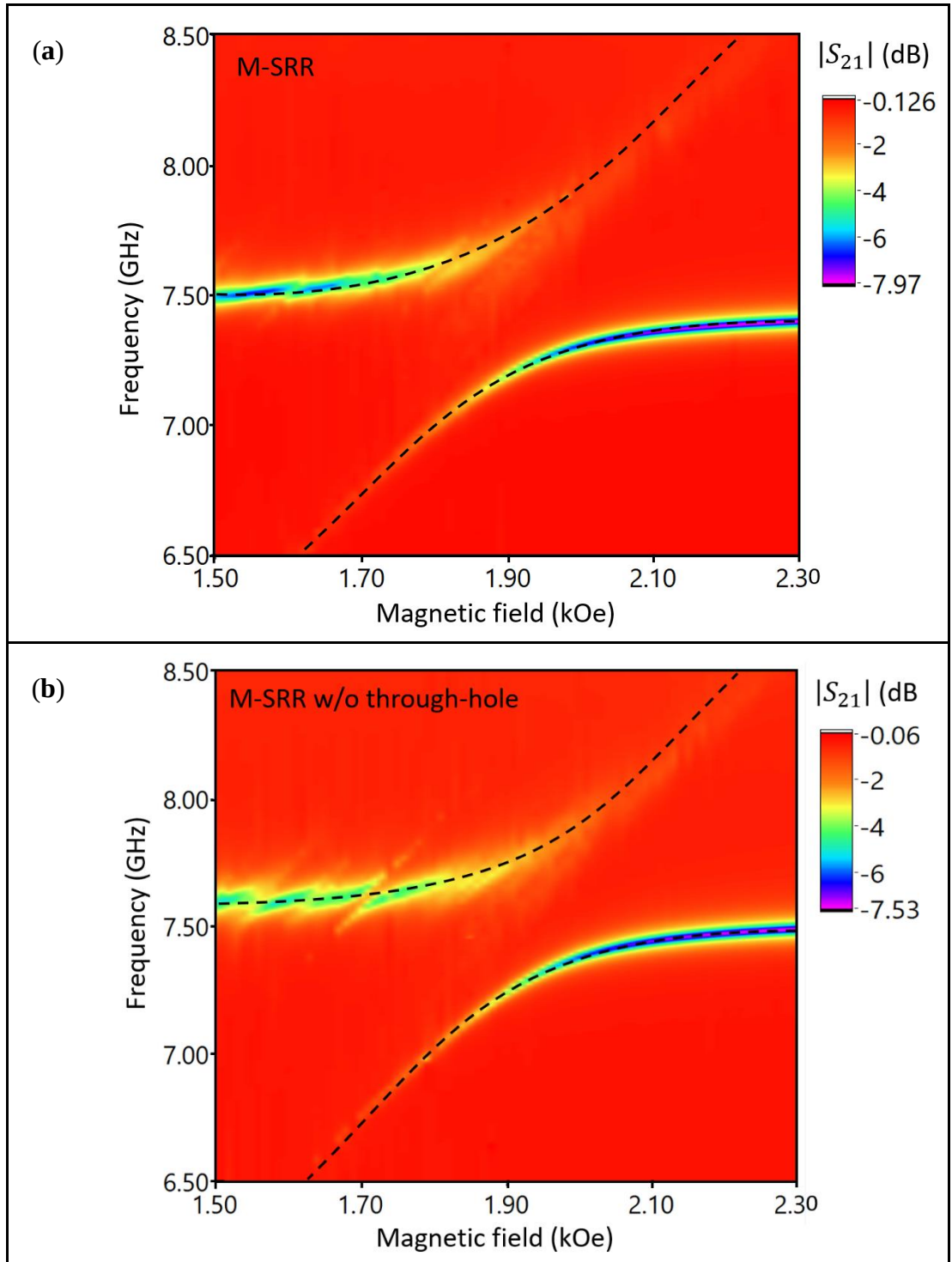


Figure 4.14: $|S_{21}|$ transmission coefficient spectra on the plane of microwave frequency and H_0 magnetic field from simulation results for SRR (a) with through-hole (b) without through-hole.

4.3.4. Inverse Split Ring Resonator (ISRR)

The Inverted pattern of SRR (ISRR) configuration, as described in reference [65], involves a negative square split ring patterned on the conducting ground plane beneath the microstrip line. In this design, the hole is positioned inside the split ring, adjacent to the conducting gap, and only penetrates through the dielectric layer. The geometry parameters of the model are shown in Figure 4.15.

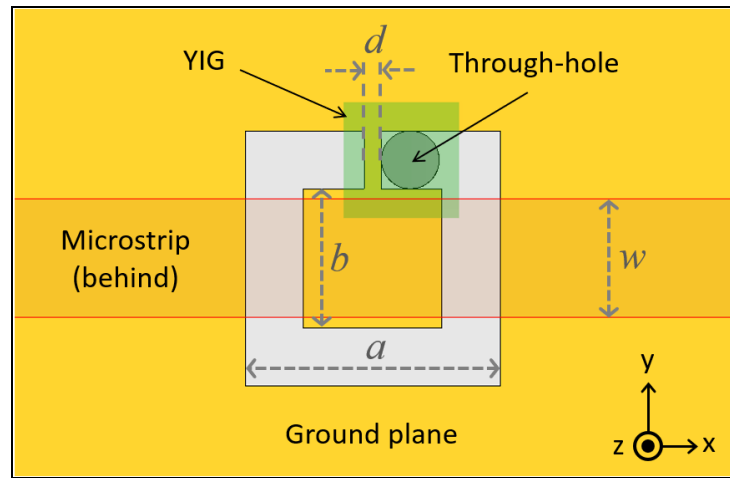


Figure 4.15: Geometry of the resonators with YIG on top of the through-hole for ISRR (the feeding microstrip line is on the backside of the board).

Table 4.6 contains the values for the parameters used in the geometry of ISRR during the design process.

Table 4.6: Parameters used in ISRR modelling and the obtained Q factor.

Resonance Frequency, f_0 (GHz)	Outer Square Size, a (mm)	Inner Square Size, b (mm)	Gap Distance, d (mm)	Q factor
7.71	4.4	2.4	0.3	83

The S_{21} parameter plot for ISRR is shown in Figure 4.16 from which the Q factor is calculated.

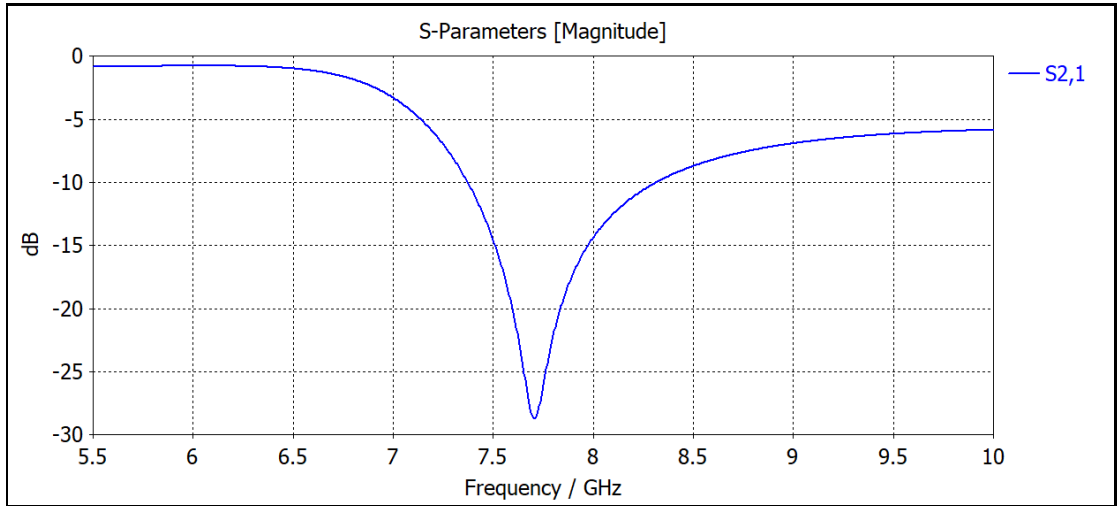


Figure 4.16: S_{21} parameter for ISRR.

In the ISRR configuration, almost all of the excited magnetic field components are localized around the conducting split gap. Figure 4.17(a) clearly demonstrates that the h_x component of the MW field is highly concentrated and exhibits a rather uniform distribution precisely on top of the split gap. This localization of the magnetic field leads to strong coupling with the overlapping region of the YIG thin film, resulting in a high value of the integral of $h_x m_x$. Moreover, this distribution is advantageous for exciting the uniform or nearly uniform mode of magnetic resonance. Although the h_z component covers more area at the hole side of the conducting gap, it has an opposite direction on the counter side, leading to a canceling effect in the integral of $h_z m_z$. Additionally, in the case of thin film samples, the coupling between h_x and m_x is stronger compared to h_z and m_z . This inconsistency in coupling strengths arises from the contribution of the demagnetization field in the direction normal to the YIG thin film (z-axis) as discussed in the second chapter.

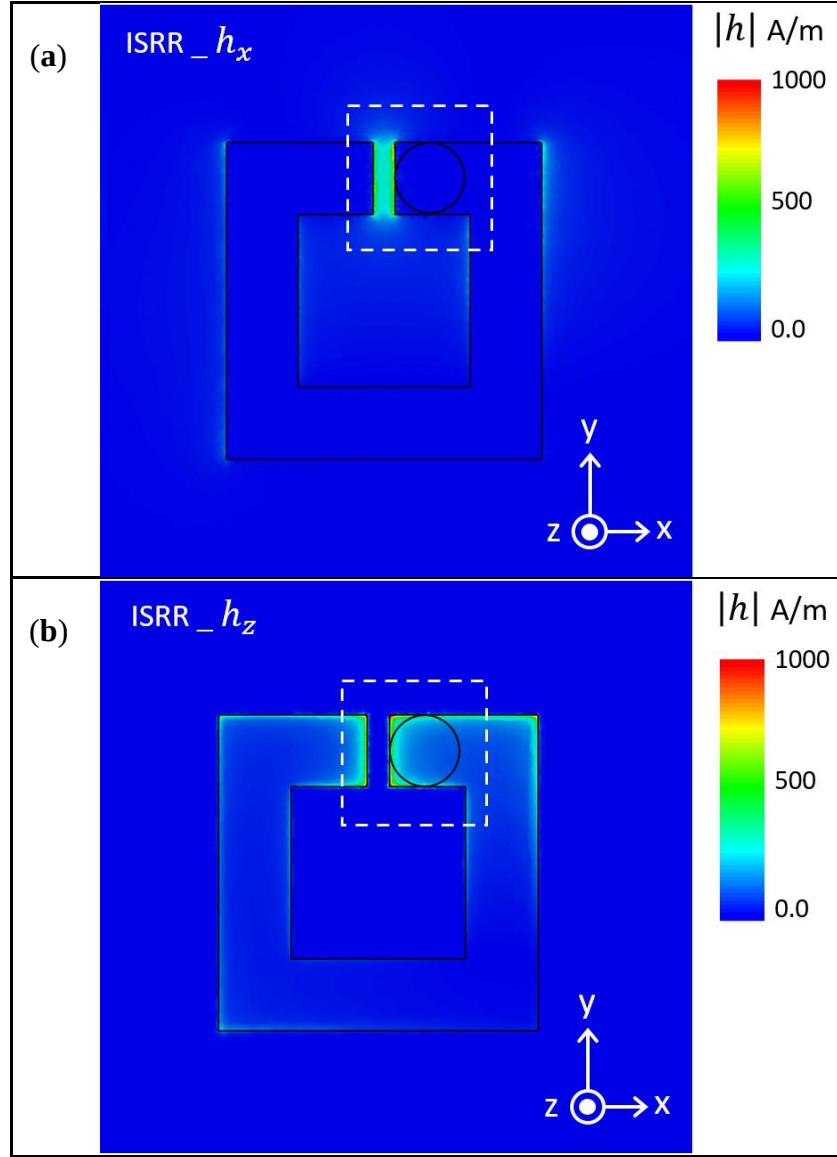


Figure 4.17: ISRR spatial distribution of the maximum value of the magnetic component intensity of the EM field in (a) $\hat{x}$ and (b) $\hat{z}$ direction on the surface of the corresponding resonators.

Figure 4.18 displays the dispersion spectra of the transmission coefficient ($|S_{21}|$ parameter) of the ISRR, from which coupling strengths are extracted and presented at the end of this chapter.

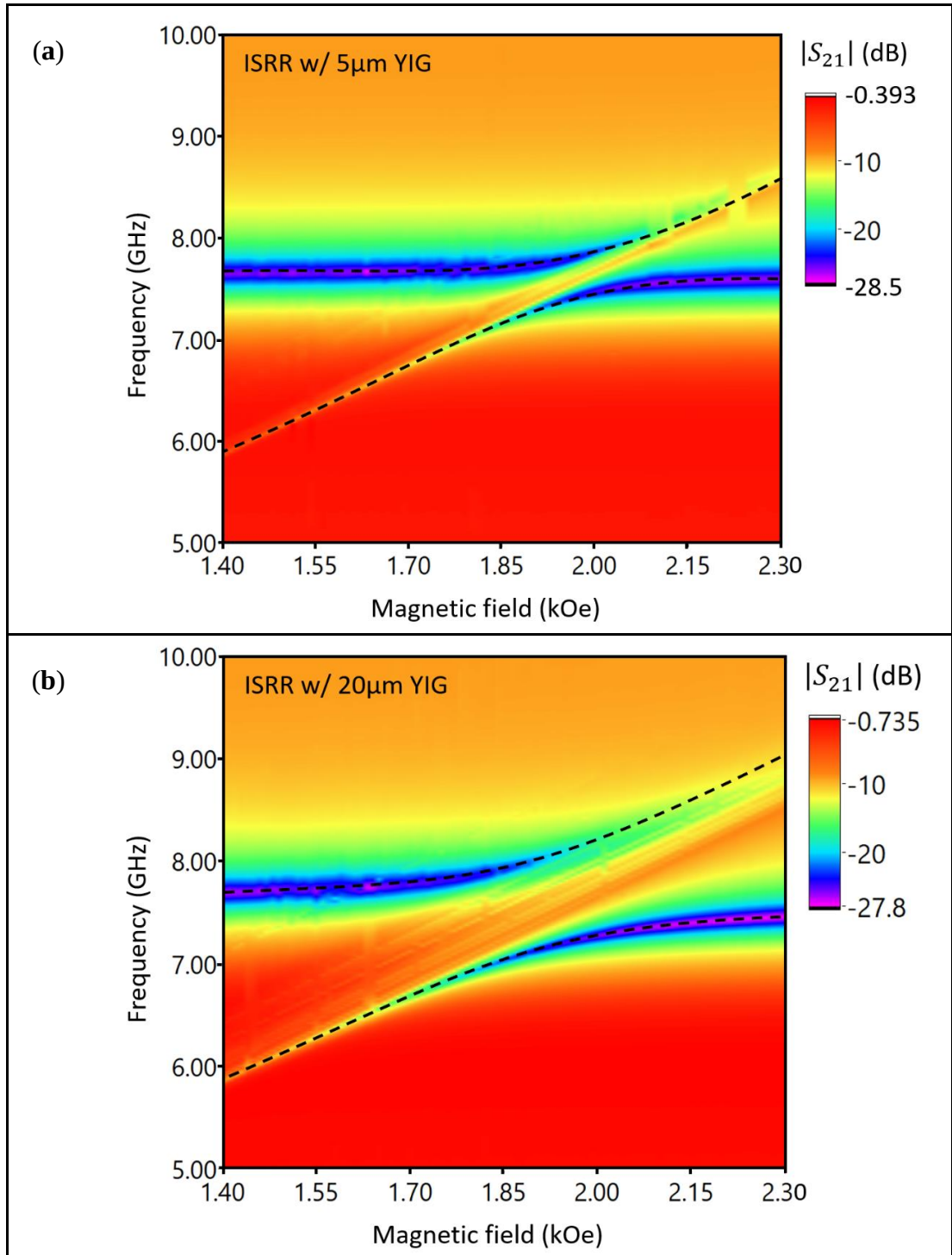


Figure 4.18: $|S_{21}|$ transmission coefficient spectra on the plane of microwave frequency and H_0 magnetic field from simulation results for ISRR with (a) 5 μm (b) 20 μm YIG thicknesses.

4.3.5. Comparison Between the Designs

For both the SRR and M-SRR configurations, the hole located at the center of the ring also penetrates the conducting ground plane. Consequently, simulations were conducted to analyze the resonator characteristics both with and without the hole. Comparing the SRR and M-SRR with and without the hole, it is observed that, aside from a slight shift in the resonance frequency, the presence of the hole does not affect the coupling strength. The ISRR has the highest coupling strength of the three geometries. However, the ISRR configuration offers a more compact and less disruptive design. Additionally, the simulation of the transmission spectrum for the ISRR demonstrates the highest coupling strength when compared to the SRR and M-SRR configurations (as indicated in Table 4.7). It is worth noting that the square shape of the ISRR resonator is better suited for the rectangular YIG thin film. Moreover, as mentioned previously, the RF field profile in the ISRR promotes the uniform precession of magnetization, which is advantageous for the desired coupling. Considering these factors, the ISRR design was selected for experimental evaluation due to its superior coupling strength and suitability for future optical experiments.

To compare with other studies, the normalized coupling strength based on the spin number can be calculated as $g_N = g / \sqrt{N}$. By taking into account a YIG spin density of $4.22 \times 10^{27} \text{ m}^{-3}$ from the previous chapter, the estimated net spin number of the YIG samples was $N_5 = 8.44 \times 10^{16}$ for 5 μm thickness and $N_{20} = 3.38 \times 10^{17}$ for 20 μm thickness. In Table 3, the coupling strengths of four simulated resonators are extracted from the transmission spectra of different resonators. The SRR system exhibits the lowest coupling strength, as anticipated due to insufficient YIG coverage of the excited magnetic field. Likewise, the significant coupling strengths observed in the M-SRR and ISRR systems can be attributed to the high concentration of excited magnetic field components within the YIG material, as discussed earlier in this chapter.

In the case of the ISRR, the discrepancy in spin-number-normalized coupling strengths (g_N) of YIG films with different thicknesses (5 μm and 20 μm) can be attributed to the higher filling factor of the thicker YIG sample with respect of the region of intense AC magnetic field near the conducting gap of the ISRR.

Table 4.7: Coupling strengths extracted from the simulated coupling dispersion spectra of resonator models with YIG film positioned over through-hole.

Coupling strength	SRR	M-SRR	ISRR (5 μm YIG)	ISRR (20 μm YIG)
$g / 2\pi$ (MHz)	85	271	189	443
$g_N / 2\pi$ (Hz)	0.146	0.466	0.650	0.762

5. EXPERIMENTS AND RESULTS

5.1. Experimental Setup

5.1.1. Instrumentation

To carry out experimental investigations concerning the interaction between microwave photons and magnons within YIG samples at room temperature, a dedicated experimental setup has been established at the Optomagnonics Lab. Figure 5.1 illustrates the schematic layout of the setup as follows. A planar microwave resonator connected to two ports of a vector network analyzer with a YIG film on it is placed between two poles of an electromagnet. To adjust the external static magnetic field a power supply varies the current in the coil of the electromagnet while the strength of the external magnetic field is probed by a gaussmeter. For data logging and control automation, VNA, electromagnet, and gaussmeter are all connected to a PC with a measurement control interface.

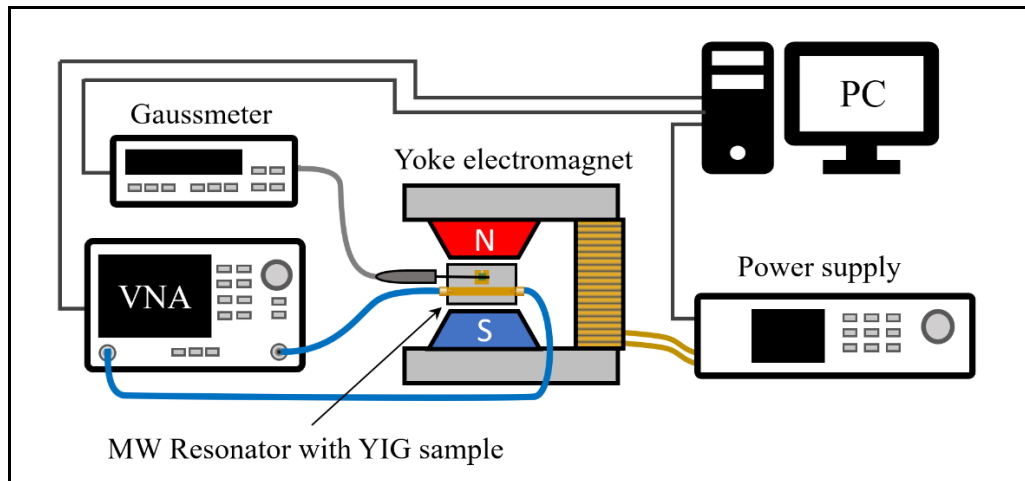


Figure 5.1: Schematic diagram of the experimental setup for measuring microwave photon-magnon coupling strength.

The installed setup is shown in Figure 5.2. For the measurement of S-parameters, an Agilent PNA E8364B model VNA is utilized which is connected to the microwave resonator via flexible cables (*Sucoflex*) placed in the center of a

custom-made yoke electromagnet system. The power supply employed in this configuration is a Kepco BOP 50-20MG current source model that offers a bipolar output ranging from 0 to 50 DC volts with a current range of 0 to 20 amperes. The magnetic field strength is monitored using a Lake Shore Model 475 DSP gaussmeter which uses Hall probes for this purpose.

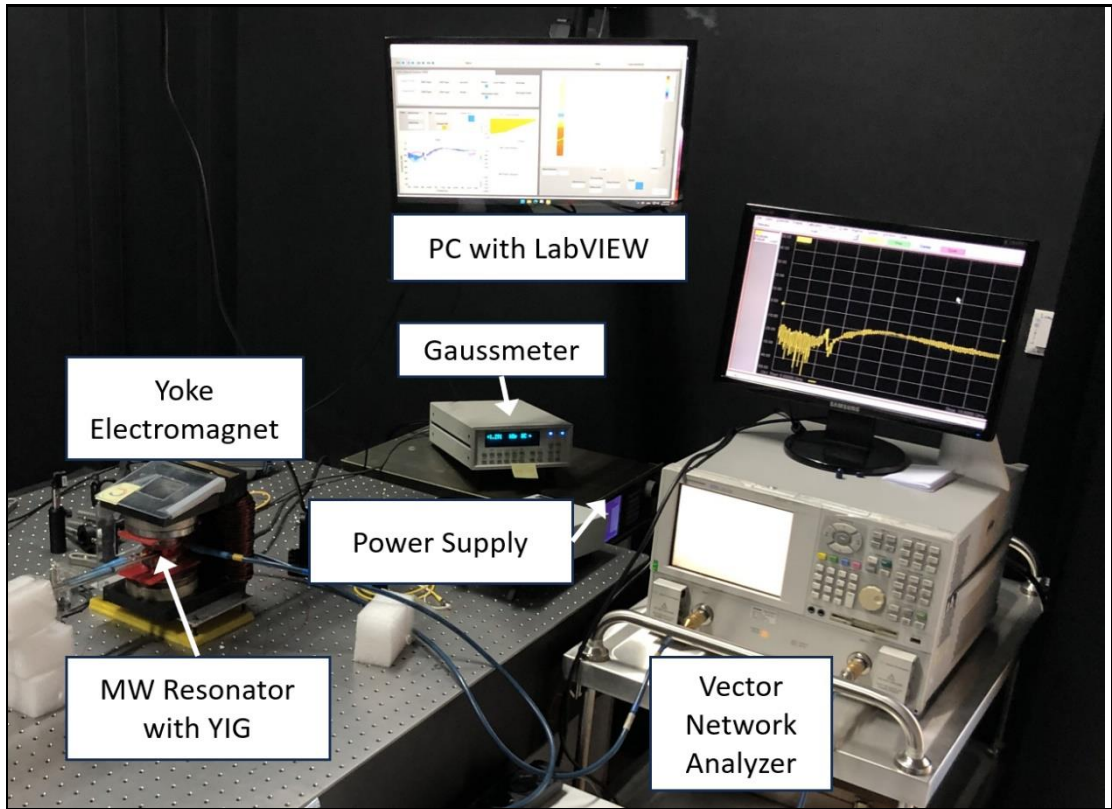


Figure 5.2: Experimental setup for measuring MW photon-magnon coupling strength in the Optomagnonics Lab.

5.1.2. Probe Station

The probe station, including the electromagnet and sample fixture, is mounted on a height-adjustable stage on the optical table of the laboratory (see Figure 5.2). The close-up view of the probe station is shown in Figure 5.3. To provide the external static bias magnetic field (H_0) a yoke-type electromagnet was assembled by winding a coil on an already available C-shaped permanent magnet from a previous project. The C-shaped magnet is made of a pair of disc-shaped neodymium (NdFeB) permanent magnets that are placed at the ends of a pure iron frame producing ~ 2000 Oe uniform static magnetic field. By powering the coil with the above-mentioned

power supply, we were able to vary its field around 1000 Oe at the center point between two poles. Furthermore, to cover an even greater range of adjustable magnetic fields, a 3D-printed plastic fixture that supports Helmholtz coils around the microwave resonator was designed and fabricated (the red structure in Figure 5.3).

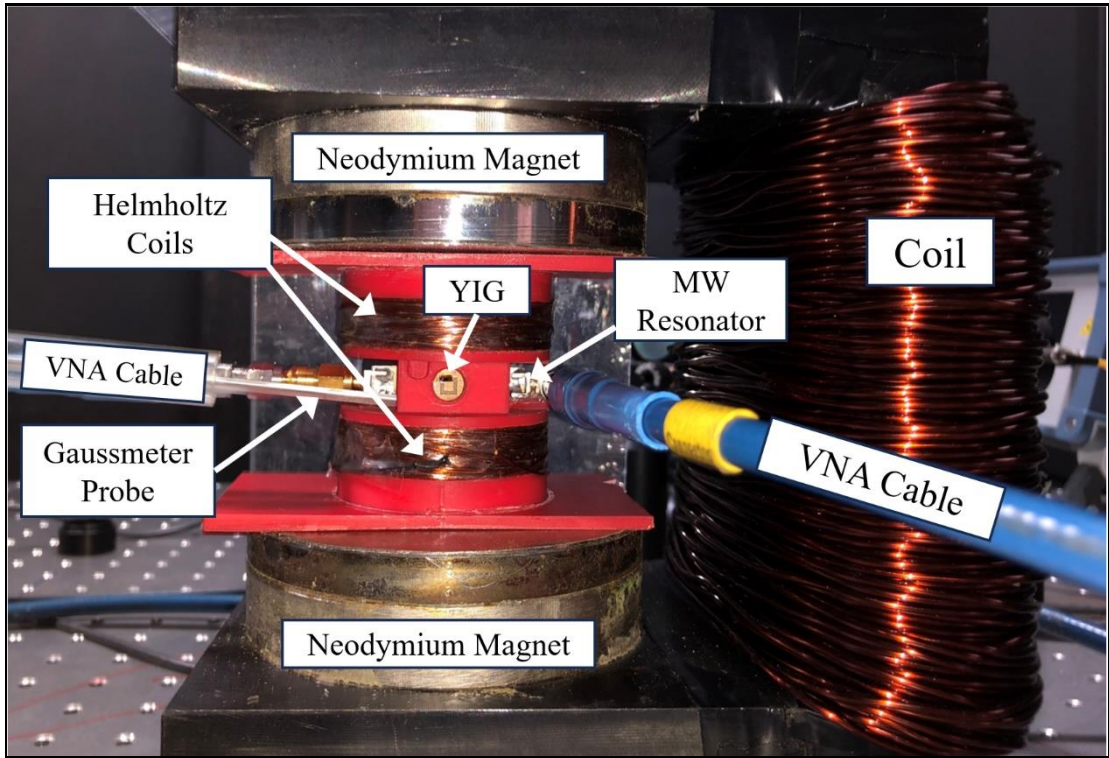


Figure 5.3: Close-up view from sample holder between two poles of yoke electromagnet during a measurement.

In the design process of the 3D-printed fixture in addition to the Helmholtz coils, a circular aperture for a laser beam, and housing structures for a pair of concave mirrors of the Fabry-Perot optical cavity were also considered as depicted in Figure 5.4. The simulation results discussed earlier were used to determine the distance between two mirrors.

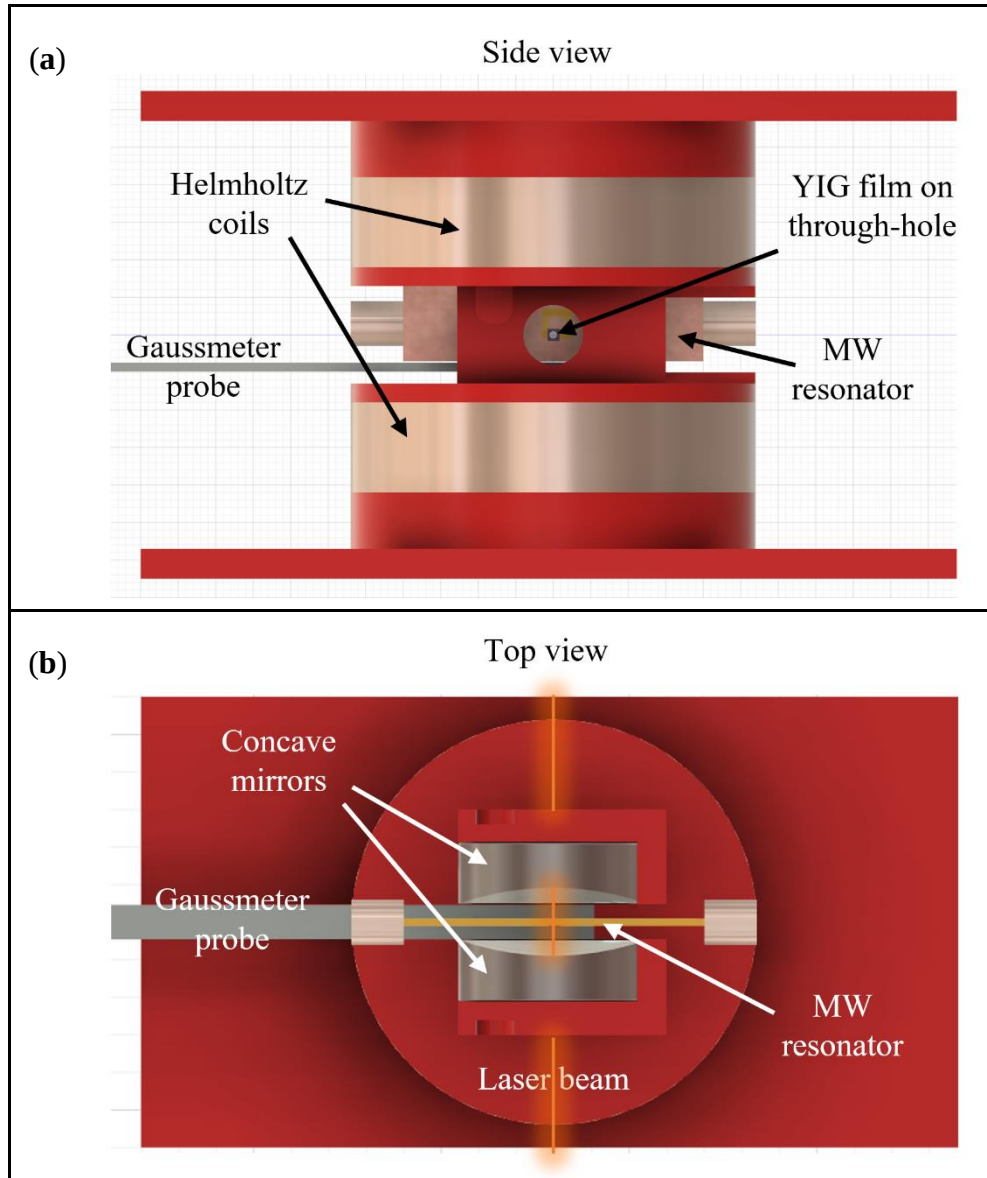


Figure 5.4: Side (a) and Top (b) view of the 3D-printed fixture design that holds an MW resonator at its center with an aperture for a laser beam. The design allows for the accommodation of the Helmholtz coils, mirrors of the optical cavity, and the gaussmeter probe.

5.1.3. YIG Samples

For the experiments, commercially obtained YIG films are epitaxially grown on 500 μm thick GGG substrates with crystallographic orientation of (111). According to the provider company, the films are fabricated by liquid phase epitaxy technique (LPE) from high-temperature single crystal growth techniques and hold ~ 2 Oe of FMR linewidth. The experimented YIG films, which are represented by a transparent green square positioned on top of the through-hole in the figures of the

previous chapter, have thicknesses of 5 μm or 20 μm . Figure 5.5 shows the three irregular pieces of 5 μm YIG film which were later cut into rectangular pieces.



Figure 5.5: Epitaxially grown 5 μm YIG thin films on GGG substrate.

5.2. MW Resonator Fabrication

The numerical investigations reveal that the ISRR model exhibits the most favorable geometry for achieving a robust coupling between microwave photons and magnons. In the experimental assessment of this model, the fabrication process involved the use of a *Rogers AD 225C* RF board, which possesses a relative permittivity (ϵ_r) of 2.6. It consists of a laminate with a thickness of 0.76 mm and has 18 μm thick copper layers on both sides. To obtain a 50 Ohm impedance match at two ports, the width of the feeding microstrip line (w) is calculated to be 2.05 mm. The whole process of milling and drilling of the resonator was carried out using an RF application-compatible circuit board plotter machine (LPKF ProtoMat S103) which is located within the premises of the Electronics Engineering faculty. Later, two SMA connectors soldered to the PCB as shown in Figure 5.6.

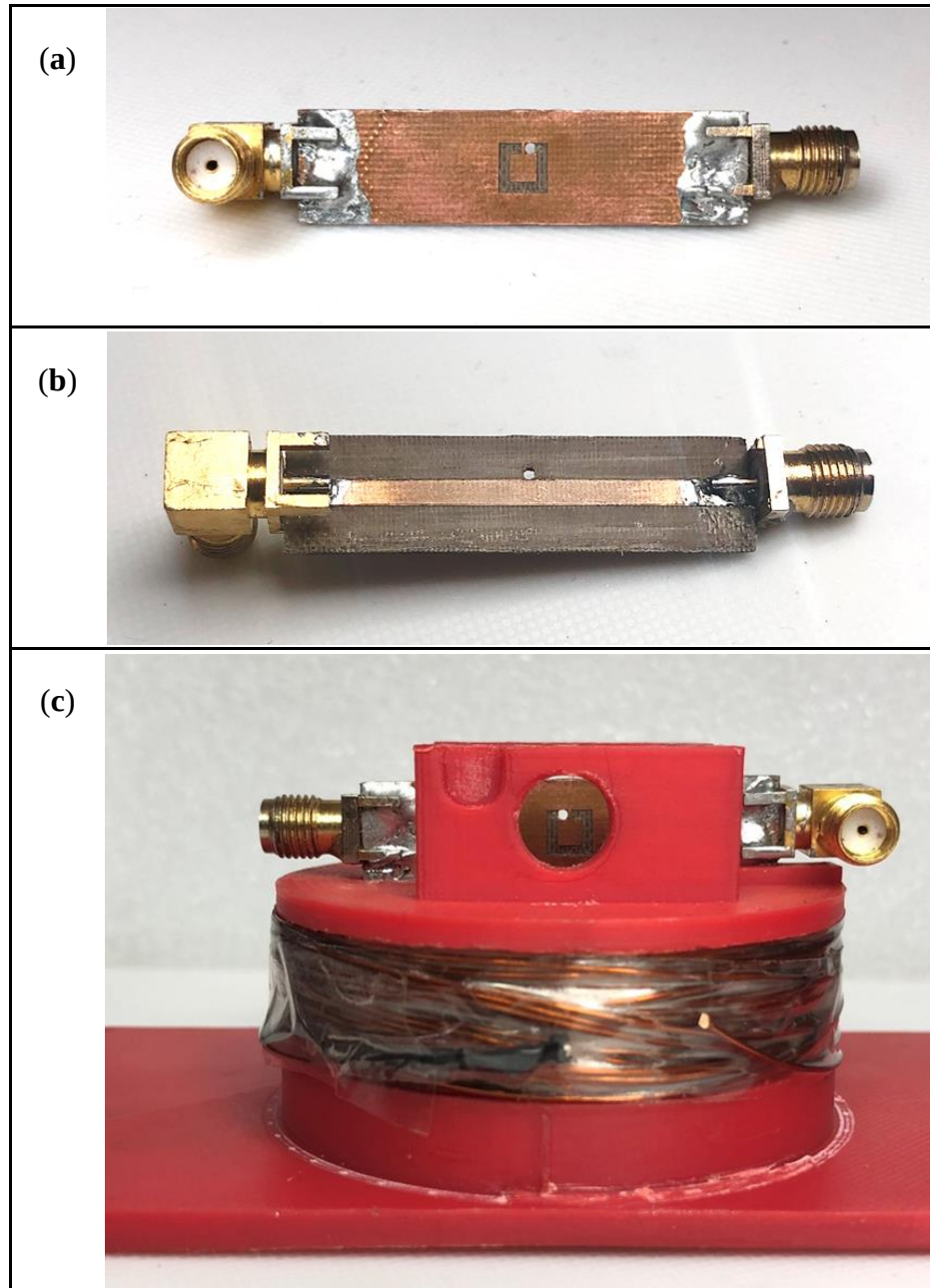


Figure 5.6: Fabricated ISRR with a through-hole: (a) backside, (b) frontside, and (c) inside the bottom half side of the 3D-printed fixture that has a circular aperture for a laser beam and holds one pair of the Helmholtz coils.

After testing the resonator via VNA, a quality factor of ~ 116 was obtained from its S_{21} plot shown in Figure 5.7.

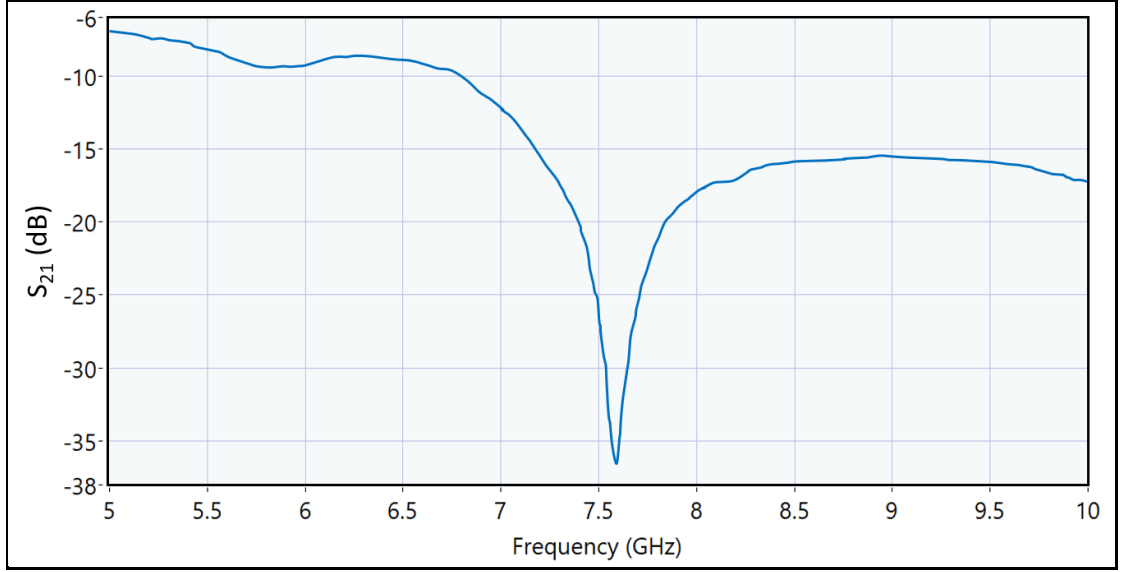


Figure 5.7: S_{21} parameter plot of the fabricated ISRR.

5.3. Data Acquisition and Automation Software

For data acquisition and automation of instrument control, LabVIEW graphical programming language was chosen for its well-known advantages in the field of testing and automation. The developed program has the capability to read and control multiple devices and offers real-time plotting of the dispersion spectrum. It can communicate with the instruments introduced before, i.e., VNA, gaussmeter (abbreviated as GM in the program), and power supply (PS) using general purpose interface bus IEEE-488 (GPIB). Additionally, a photodetector (PD) also can be connected to the program using a universal serial bus (USB) for future application purposes. Figure 5.8 displays the front panel, showcasing the dedicated control functionalities for the above-mentioned instruments and the real-time plotting of the S-parameter as well as the scanned S-parameter spectrum through the H-field. The design pattern used for the development of the program code (block diagram) is given in Appendix B.

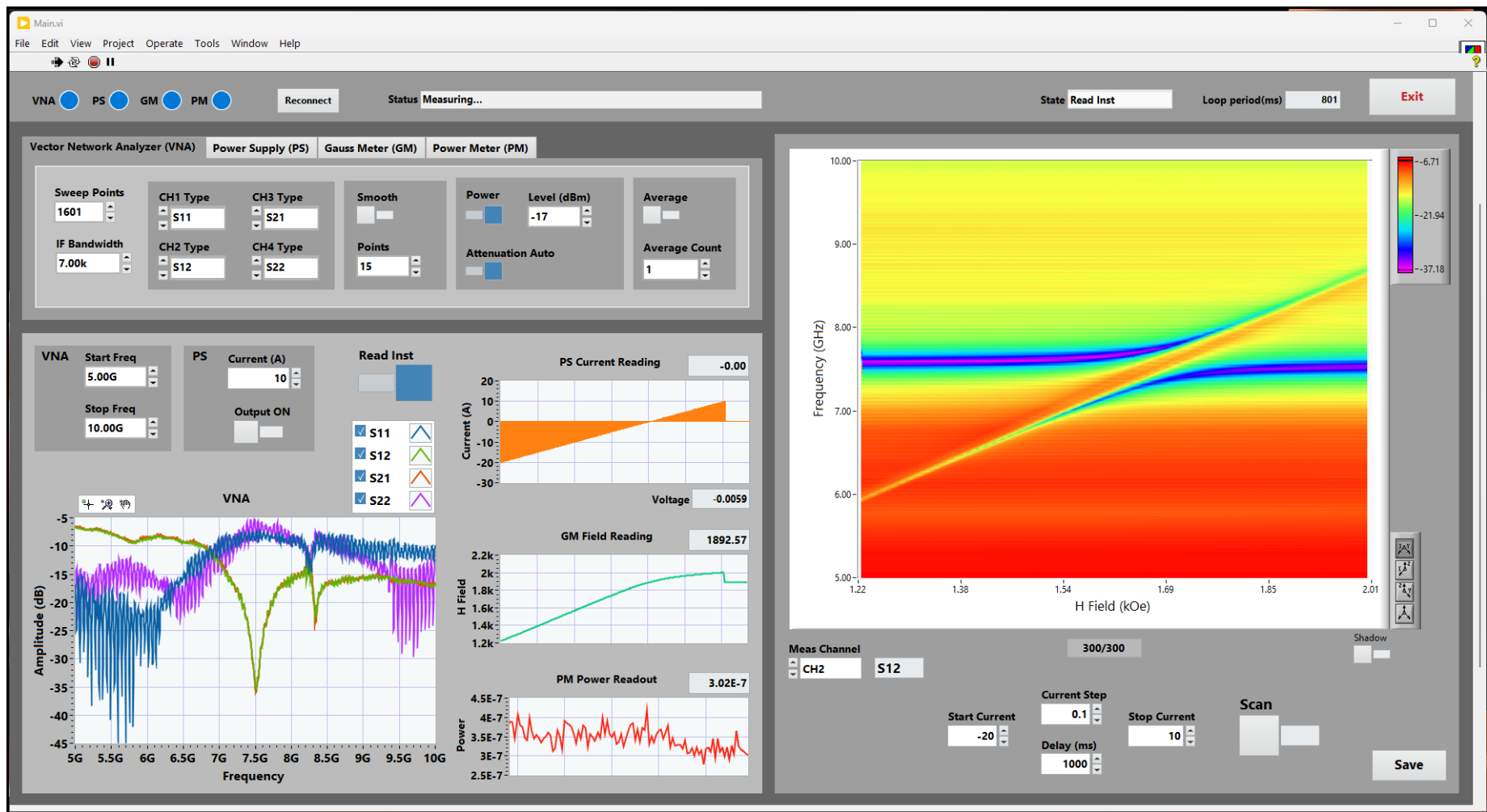


Figure 5.8: Front panel view of the developed LabVIEW program.

5.4. Photon-Magnon Coupling Spectra

The dispersion spectra for YIG films on ISRR with thicknesses of 5 and 20 μm were effectively obtained using the described experimental setup. Figure 5.9 displays the measured spectra acquired during the experiment, demonstrating a close resemblance to the simulation results presented in Figure 4.18. The coupling strengths are summarized in Table 5.1 and can be compared with the simulation data presented in Table 4.7. These findings provide clear evidence that significant coupling values can indeed be achieved at room temperature by carefully positioning the YIG film within the uniform and high-intensity magnetic field region of the ISRR while covering its through-hole. Furthermore, it is reasonable to anticipate that an ultra-strong coupling regime can be attained at cryogenic temperatures [66]. Additionally, the successful electromagnetic FEA simulations, which involve the definition of gyrotropic properties for YIG while magnetized up to its saturation point, demonstrate the feasibility of precise numerical calculations without the need for resorting to micromagnetic simulation software.

Table 5.1: Coupling strengths extracted from the experimental results for YIG films on ISRR.

Coupling strength	5 μm thick YIG	20 μm thick YIG
$g / 2\pi$ (MHz)	196	448
$g_N / 2\pi$ (Hz)	0.675	0.771

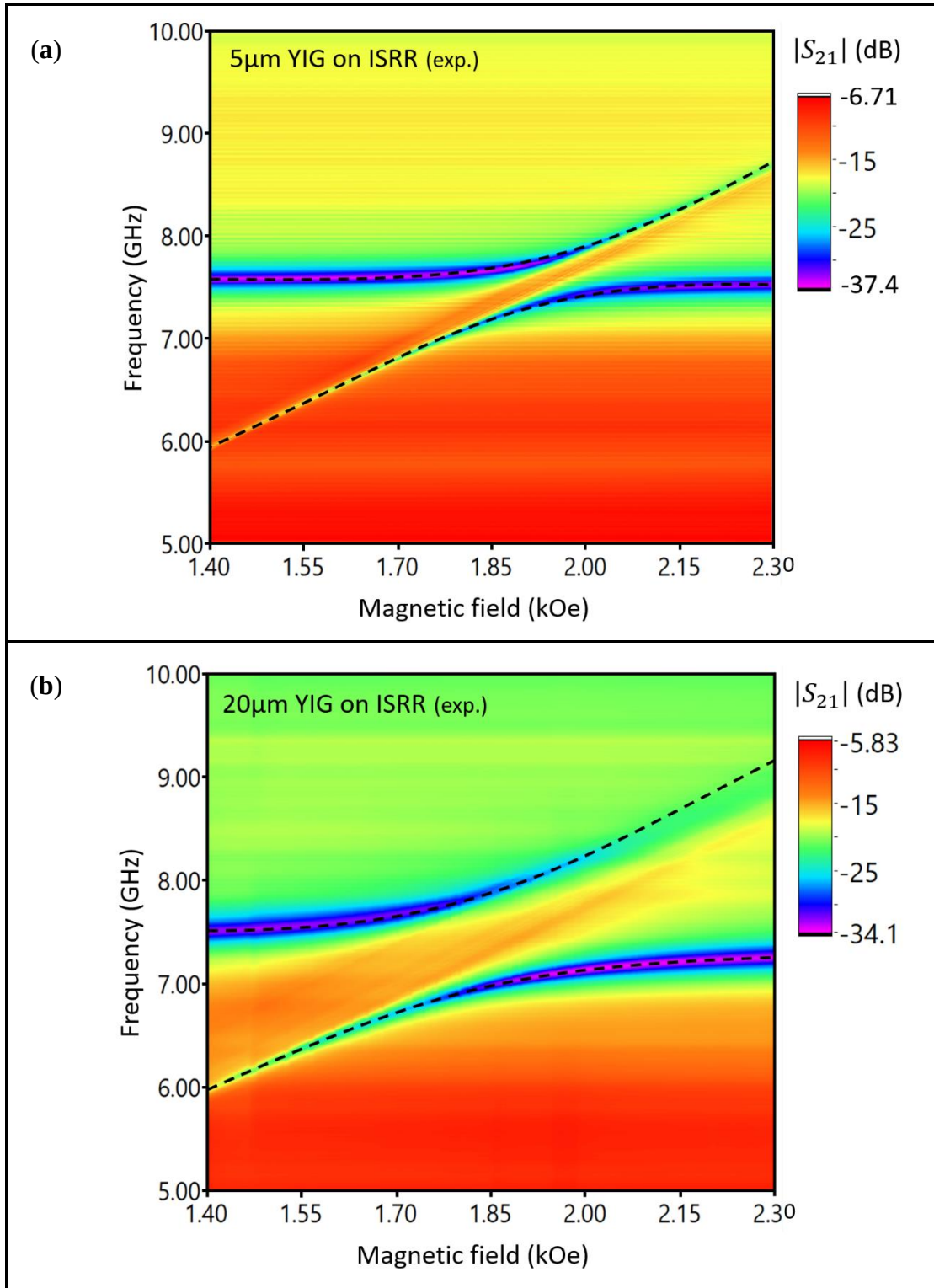


Figure 5.9: $|S_{21}|$ dispersion spectra from the experiment results for YIG film with a thickness of (a) 5 μ m (b) 20 μ m on ISRR.

6. CONCLUSION AND OUTLOOK

This thesis has explored the microwave magnon-photon coupling phenomenon and its application for quantum transduction, which is the process of quantum information conversion between microwave and optical domains. The advantages of microwave magnon-photon coupling in planar structures have been discussed, along with recent works in this area. The primary focus of this research has been the investigation of various planar microwave structures, employing YIG as a magnon source. In the pursuit of developing a planar structured quantum microwave-optical converter, enhanced by the integration of microwave and optical cavities, an innovative transduction setup was introduced. This setup incorporates an optical Fabry-Perot cavity in conjunction with a planar microwave resonator featuring a through-hole design to facilitate the passage of a laser beam.

Numerical analysis using FEA software played a crucial role in this thesis. COMSOL Multiphysics was employed for the numerical simulation of the microwave photon-magnon coupling, the Faraday effect, and the modelling of the Fabry-Perot cavity. Within the context of this research, three distinct designs of planar microwave resonators were put forth, and their couplings to magnons were numerically analyzed with CST Studio Suite. The findings demonstrated that the ISRR design exhibited the most robust coupling strength among these models.

In the experimental phase of this study, the fabrication of the ISRR resonator was accomplished using a PCB prototyping machine, followed by their characterization via VNA measurements. A dedicated experimental setup was established within the Optomagnonics Lab. This setup involved the assembly of a custom-made yoke electromagnet on an optical table, providing the capability to apply and manipulate the external magnetic field as needed for the experiments. For the probe station of the setup, a fixture around the microwave resonator positioned at its center was designed and produced through 3D printing. This fixture was specifically designed to provide housing for Helmholtz coils for fine-tuning the external magnetic field and a pair of mirrors with a precise distance for the optical cavity. To streamline the data acquisition process, a comprehensive LabVIEW program was developed, automating various aspects of the measurements. During experimental testing on the fabricated ISRR resonator, the presence of strong

microwave photon-magnon coupling was confirmed, aligning with the initial numerical simulations. Using the parameters of the model, a coupling strength of 448 MHz at room temperature was measured by placing a 20 μm YIG film on the ISRR. The remarkable agreement between the simulated and experimental data, confirms the applicability of FEA for simulating micro-scaled systems containing highly gyrotropic materials, particularly when these materials are magnetized up to their saturation point. It is important to note that it is possible to enter an ultra-strong coupling regime at cryogenic temperatures with superconducting cavities.

The successful experimental verification of strong microwave photon-magnon coupling provides a solid foundation for future experiments aiming to achieve full conversion using the studied resonator. To gain a more comprehensive understanding of transduction efficiency, more extensive numerical analyses in the optical domain may be pursued. The combination of theoretical analysis, numerical simulations, and experimental investigations can provide valuable insights and lay the groundwork for future research in this exciting and promising field. Given that ferromagnetic magnons can be coherently coupled to superconducting qubits, pursuing the development of magnonic microwave-optical transducers holds promise for the realization of a scalable quantum network.

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BIOGRAPHY

Morteza VAFADAR YENGEJEH graduated from the Physics Department at the Science and Research Branch of Islamic Azad University in the year 2009. He started postgraduate education at Nano Science in 2013, with a concentration in Nanofabrication from the Electric and Electronic Institute, Atatürk University, and completed his master's degree with the thesis titled "*Threshold Switching Phenomenon in Vanadium Oxide and Its Potential Application as a Memory Select Device*" in 2015. A year later, he started his doctorate study at the Department of Physics, Institute of Natural and Applied Sciences, Gebze Technical University under the supervision of Prof. Dr. Bulat RAMI.

APPENDICES

Appendix A: Publications in the Scope of the Thesis

Vafadar Yengejeh M., Yıldız F., Yorulmaz S. Ç., Rameev B., (2022), “Hybrid High-bandwidth Microwave-magnon Systems for Quantum Communications and Sensing”. In: “2022 Photonics & Electromagnetics Research Symposium (PIERS)”.

Vafadar Yengejeh M., Rameev B., (2023), “Through-Hole Microwave Resonators for Magnonic Quantum Transducer”, Applied Magnetic Resonance, 54 (4), 581–589.

Appendix B: LabVIEW Program Code

The design pattern chosen for the development of the LabVIEW project is a customized implantation of a so-called “event-driven state machine”. The block diagram of the main “VI” file is shown in Figure B1.1. There are two *while loops* that can continuously run in parallel: the main while loop at the top and the status while loop at the bottom. The first prioritized structure inside the main while loop is the user *event structure*. This enables the main while loop to start its every iteration first by checking input events from the user. If no event is triggered by the user, the *event structure* reaches its “Timeout” event and executes the code inside it. This approach allows prioritizing the user command before running the rest of the code. Inside the timeout event resides the state’s *case structure* of the “state machine” design.

Figure B1.2. shows the state’s *case structure* inside the “Timeout” event. At every iteration, the case of the state is *dequeued* from the state’s *queue* wire. The first state to be called by the *Dequeue Element* function is the “INSTRUCTION” state in which “Routine” and “Subroutine” *case structures* determine the list of states to be added to the state’s *queue* wire by the *Enqueue Element* function. When the state’s *queue* runs out of elements (the *Dequeue Element* function hits the timeout) the “INSTRUCTION” state gets selected and the next state elements are enqueued inside it. The state’s *case structure* in the “Initialize” state and the drop-down window listing all other states are shown in Figure B1.3.

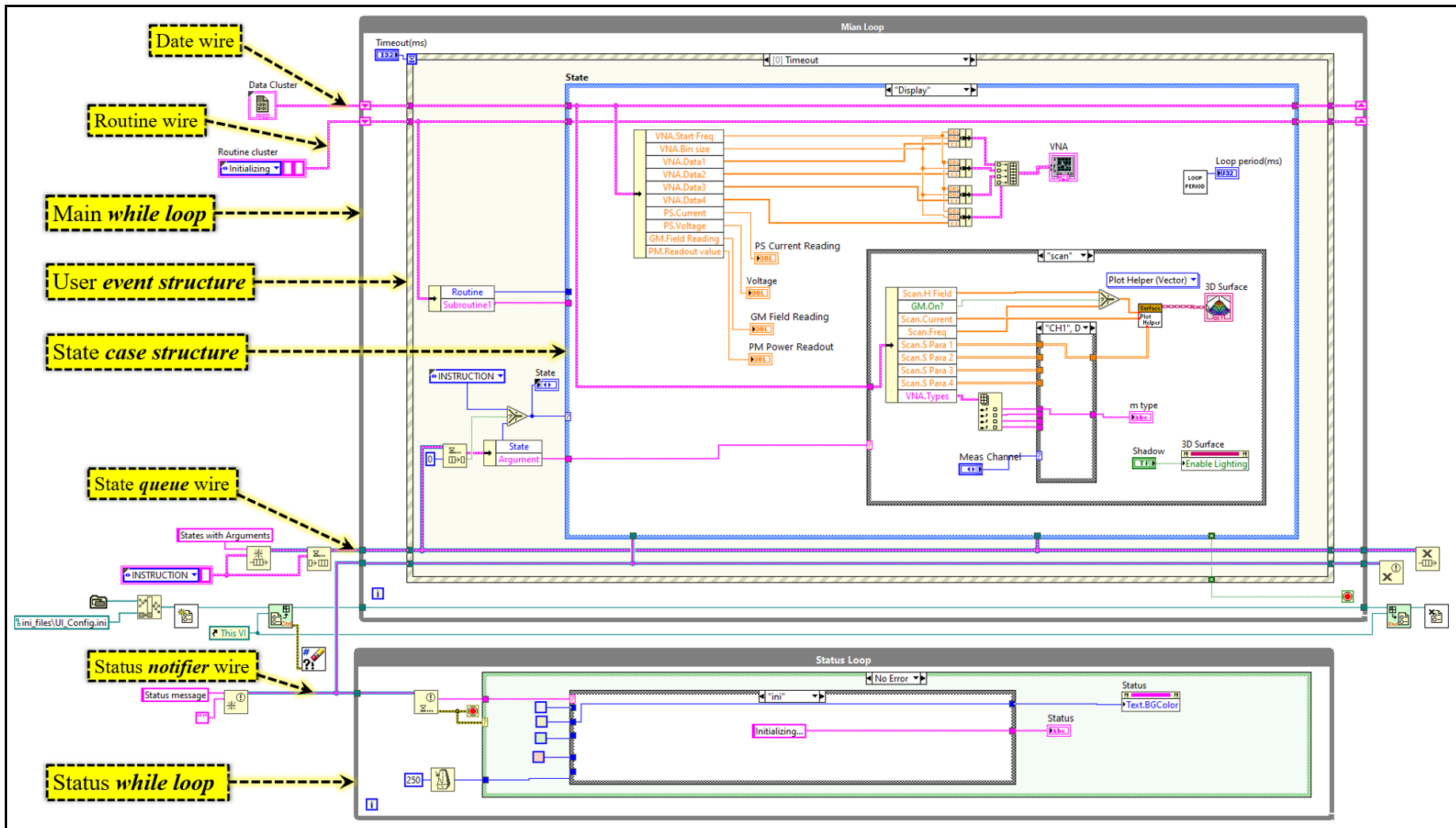


Figure B1.1: Block diagram view of the main VI file.

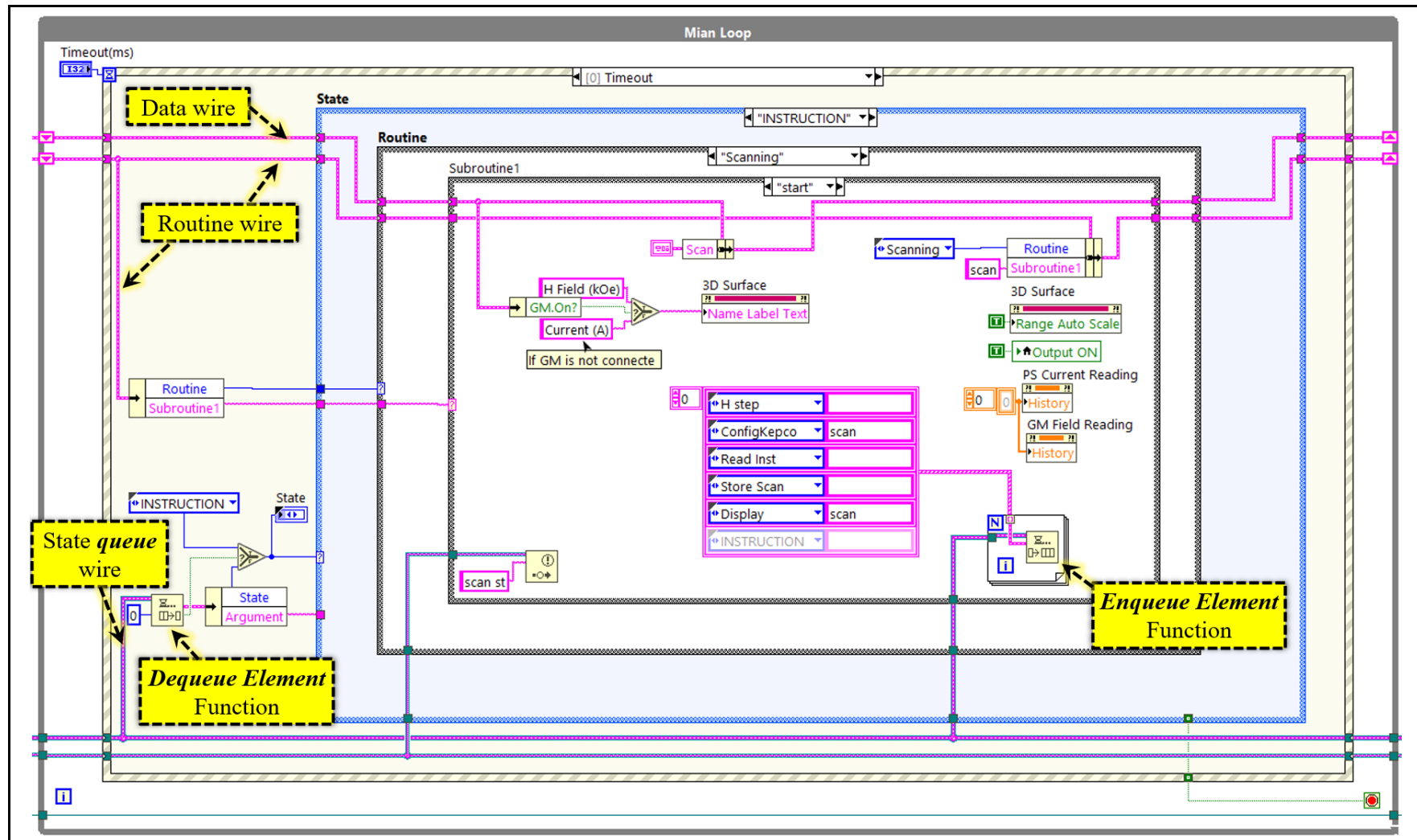


Figure B1.2: Routine and subroutine case structures inside the “INSTRUCTION” state within “Timeout” event in the Main while loop.

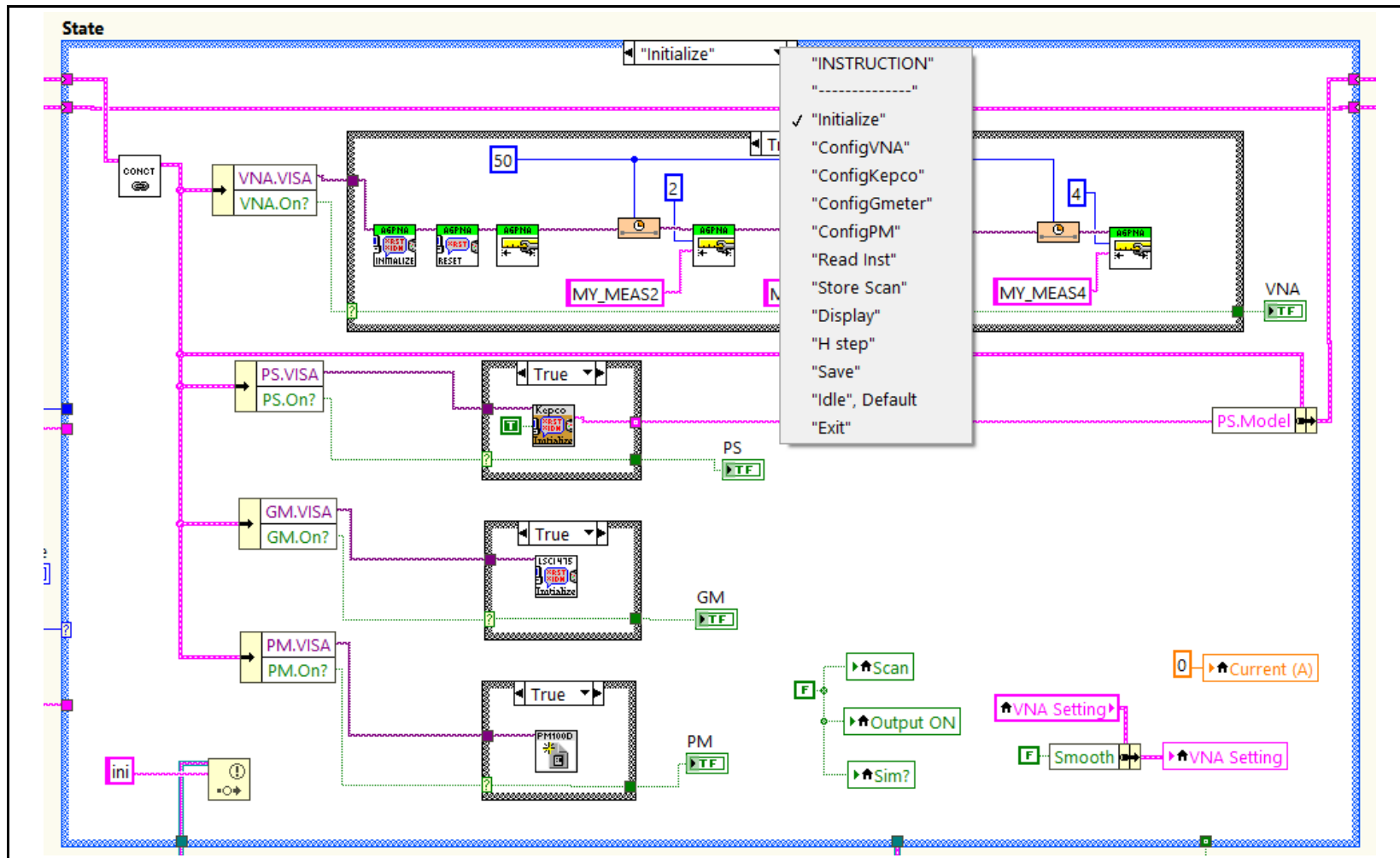


Figure B1.3: State's case structure in the "Initialize" state and the drop-down window listing all other states.