Design Simulation and Analysis of X Band Microstrip Circulator

Major Project Report

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology

in

Electronics & Communication Engineering

(Communication Engineering)

By

Vishwa Kelaiya

(14MECC07)

INSTITUTE OF TECHNOLOGY

NAAC ACCREDITED 'A' GRADE

Electronics & Communication Engineering

Department of Electrical Engineering

Institute of Technology

Nirma University

Ahmedabad-382 481

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Declaration

This is to certify that

i) The thesis comprises my original work towards the degree of Master of Technology in Communication Engineering at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgement has been made in the text to all other material used.

Vishwa Kelaiya

Certificate

This is to certify that the Major Project entitled **"Design Simulation and Analysis of X Band Microstrip Circulator"** submitted by **Vishwa Kelaiya (14MECC07)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Communication Engineering at Nirma University, Ahmedabad is the record of work carried out by her under our supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of our knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Abstract

Microwave circulator is an important microwave ferrite device which is widely used in wireless transceivers. Many approaches are found for the designing of stripline and waveguide circulators which includes analysis of stripline circulator in terms of scattering matrix, broad banding of above resonance circulator, phenomenological description in terms of rotating modes, different topologies regarding waveguide circulator configuration and many more. No universal equations or approach exist for designing of microstrip circulator.

This thesis presents design, simulation and analysis of X-band microstrip junction circulator. Major application of microstrip junction circulator presented here is as duplexer in RADAR. Other application includes providing isolation to source or load, multiplexing, phase shifting and many more. The circulator designed here is centered at 9.6 GHz with 800 MHz bandwidth. According to the specification, isolation of more than 20 dB and insertion loss less than 0.4 dB is required which is at par with industrial standards. Yttrium iron garnet (YIG) is used as ferrite material. Here, the design equations given by Fay and Comstock are followed and many prototypes are simulated using CST Microwave Studio.

As an important aspect of this thesis, first ferrite is selected from available choices based on the comparative study of its properties. Ferrite radius is determined theoretically and practically. Two types of electrical designs are prepared from which one prototype is designed with two types of magnetic circuits. Obtained S parameters are compared, which are better than the main objective.

Contents

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Abbreviations

CST	Computer Simulation Technology
YIG	Yttrium Iron Garnet
RADAR	Radio Detection And Ranging
VSWR	Voltage Standing Wave Ratio
FMR	Ferro Magnetic Resonance
AR	Above Resonance
BR	Below Resonance
CAD	Computer Aided Design
MIC	Microwave Integrated Component
PNA	Power Network Analyzer
ECAL	Electronic Calibrater

Chapter 1

Introduction

In many modern RF subsystems passive devices like circulators and isolators are used. Circulators are mainly used in RADARs for duplexing purpose. It can be used as shunt component in microwave communication, directional coupler in measurement equipment, duplexer in radar system, and it also can increase gain bandwidth of parametric amplifier [10]. Microwave ferrite devices permit the control of microwave propagation by a static or switchable dc magnetic field [4]. Circulator is defined as a device with ports arranged in such a way that energy entering a port is coupled to adjacent port but not coupled to other ports. A circulator can have any number of ports, but only circulators with three ports involve the nonreciprocal behavior of ferrites. Ferrite is the most important part of the junction circulator. Unlike a magnetic material, a ferrite is a magnetic dielectric which allows an electromagnetic wave to penetrate the ferrite, thereby permitting an interaction between the wave and magnetization within the ferrite [12].

1.1 Objective

The objective of this project is to design a microstrip junction circulator. A ferrite microstrip junction circulator is to be developed in X-band at 9.6 GHz ± 400 MHz frequency band with 0.4 dB insertion loss and 20 dB isolation. The main objectives are as follows.

- Study of microwave ferrites, microstrip junction circulator configurations and magnet design.
- Design and simulation of ferrite microstrip junction circulator.
- Analysis of ferrite microstrip junction circulator with magnetic circuit.

1.2 Motivation

The motivation for this thesis includes indigenous development of ferrite circulator which is predominantly used in wide range of RF subsystems, RADAR as well as communication payloads. Here major application of microstrip circulator is to be used as duplexer in RADAR. It can be used as isolator or direction coupler in measurement equipment.

1.3 Methodology

Thorough understanding of ferrite material, its properties and of permanent magnets are required. Following steps are carried out for the development of junction circulator.

- Literature survey of basic concepts related to junction circulator.
- Literature survey for understanding the properties of ferrite materials and ferrite selection.
- Theoretical design of various configurations and their comparison to select the most optimum configuration.
- Computer aided design using CST Microwave Studio(using both Frequency Domain and Magneto static Solver).

- Fabrication and Testing

1.4 Thesis Organization

The rest of the thesis is organized as follows.

Chapter 2, *Literature Survey*, includes literature survey of ferrites, different configuration of microstrip circulators, stripline circulator,and new approaches related to self biased circulator.

Chapter 3, *Circulator Concept*, describes circulator basics, Related terminologies and its applications.

Chapter 4, *Magnetic Propertis of Ferrites*, describes different magnetic properties of ferrite, importance of permeability tensor and its derivation in detail.

Chapter 5, *Operation and Design of Circulator*, describes circulation action, design flow, selection of ferrite and design theory of microstrip circulator.

Chapter 6, *Introduction to CST Studio Suite* describes basic introduction to CST Studio Suite and different solver overviews.

Chapter 7, *Design and Simulation*, describes designing method and simulation of elecritcal design of circulator.

Chapter 8, *Magntic Circuit Design and Magnetic Simulation*, describes about permanent magnets, selection of magnet, magnet circuit design and simulation and simulation of prototype 2 with actual magnet.

Chapter 9, *Fabrication and Testing*, describes about fabrication, assembly, testing and discussion of experimental results.

Chapter 10, *Conclusion and Future work*, includes final conclusion of the thesis and future work.

Chapter 2

Literature Survey

In the paper [4], the development and current situation of microwave ferrite technology is reviewed. A brief introduction of the fundamentals of important ferrite materials and the development of ferrimagnetic spinel and garnet (YIG) materials is given. In microwave ferrite devices, the propagation of microwave can be controlled by a static or switchable dc magnetic field. The ferrite devices can be linear or nonlinear, reciprocal or nonreciprocal. The development of these devices requires knowledge of microwave circuit theory, magnetic material and electromagnetic theory.

The various terms used in explaining the effect of ferrite materials like Faraday Rotation, Ferromagnetic Resonance , Field Displacement, Nonlinear effects, Spin Waves

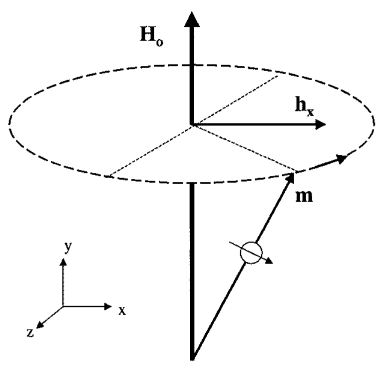


Figure 2.1: Magnetic dipole moment m precessing around a static magnetic field H_{dc}

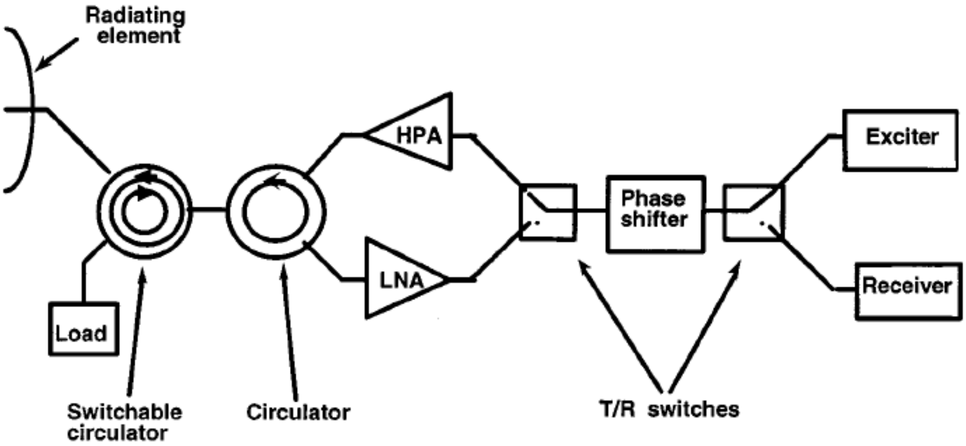


Figure 2.2: Application of circulator[1]

are discussed. The brief introduction about permeability tensor is given. The permeability tensor is derived from the tensor susceptibility , which is derived in turn from the equation of motion of a magnetic dipole due to electron spin in the presence of both a transverse RF magnetic field h_x and a static magnetic field H_0. This is shown in Fig.2.1. Purpose and function of circulator is briefly discussed here. In microwave systems which use a single antenna for both sending and receiving purpose, the function of circulator is to provide duplexing as shown in Fig.2.2.

The operation of Y junction strip-line circulator is described in terms of counter rotating modes in paper [1]. Basic structure of strip-line junction circulator consists of center conducting disk embedded by two ferrite cylinders and two conducting ground plates. Three conducting strips are attached to the center disk at 120° apart from each other. At the resonant frequency, the Y junction strip-line circulator is under coupled and standing wave existed in the structure. The maximum isolation exists at the frequency at which insertion loss is minimum. The resonance of a center disk is an essential feature for the operation of circulator. When the disk is unmagnetized, the standing wave pattern will appear as shown in the Fig.2.3. where input voltage at port 1 results in 180° out of phase voltages at port 2 and port 3 with respect to input

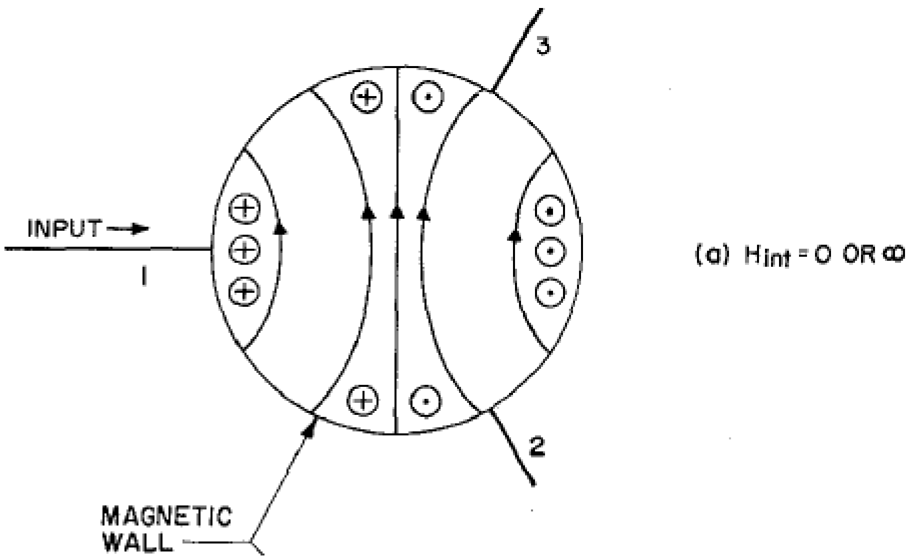


Figure 2.3: Standing wave pattern for Unmagnetized disk

voltage and it will be half in the magnitude compared to input voltage. So, basically in unmagnetized case circulator behaves as coupler. When the disk is magnetized properly by applying external bias field, the standing wave pattern will appear as shown in Fig.2.4.

Here it can be seen that given input voltage at port 1, the same voltage with phase and magnitude appears at port 2 and port 3 is isolated. The standing wave pattern as shown in Fig.2.4 is generated by two counter rotating field patterns of the same configuration.

If a magnetic biasing field is provided in the direction of the axis of the disk, two rotating modes will not resonate at the same frequency. The pattern which rotates in the similar manner of electron spins of ferrite cylinder tend to precess under the influence of biasing field and will have scalar permeability μ_+ and that which rotates in opposite direction will have scalar permeability μ_-. These split modes are denoted as + (plus) and - (minus) depending on the rotation compared to electron spins of ferrite cylinder. If the system is excited at a frequency intermediate of split modes then, + mode which has higher resonant frequency will have inductive reactance and

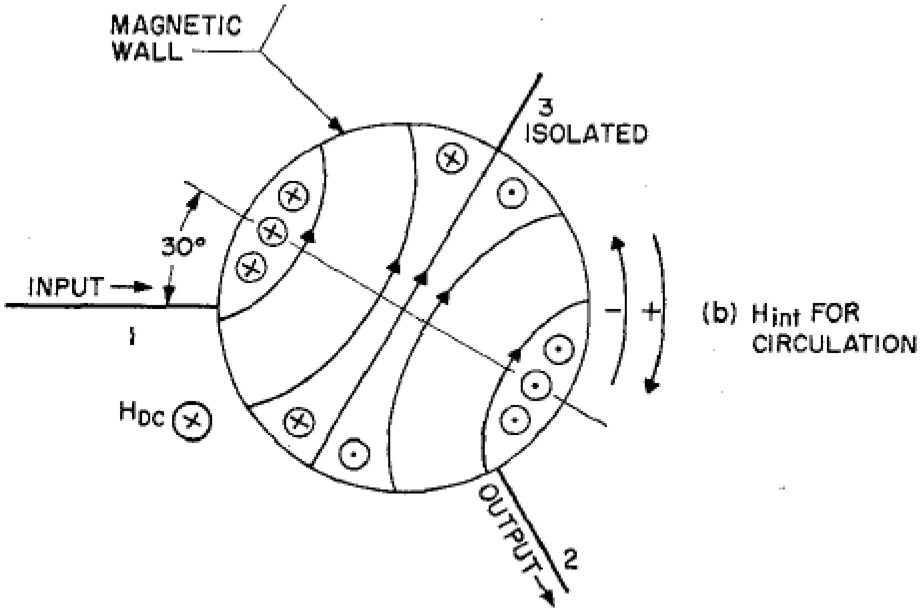


Figure 2.4: Magnetized disk

mode which has lower resonant frequency will have capacitive reactance. At a certain frequency and phase angle, both inductive and capacitive impedances will be equal and opposite to each other so resultant impedance will be real. If the degree of splitting is chosen such that the phase angles of the impedances of the two modes are each 30° then, the standing wave pattern will get rotated by 30°. The rotation is in the direction of the + mode and this 30 rotation brings the E field null to port 3 so this port is isolated and power entering at port 1 is coupled to port 2. Thus, the direction of circulator action is in the direction of the mode for $H_{dc} < H_{res}$ and opposite for $H_{dc} > H_{res}$.

The properties of nonreciprocal ferrite device depend strongly on the properties of ferrite used [3]. For the three different groups of nonreciprocal devices, the dependence of different device specifications, such as power capability, insertion loss etc. on line width, critical field, dielectric loss tangent etc. is similar and the dependence of bandwidth and insertion loss on polarization field and ferrite magnetization is specific for a special group.Passive nonreciprocal microwave ferrite devices belong to one of

Device Specifications	**Material Properties**
Isolation	$4\pi M_s$
Phaseshift	H_{dc}
Insertion loss	ΔH
Bandwidth	$\varepsilon_r, t_g, \delta_\varepsilon$
High-power capability	h_{crit}
Latching characteristics	H_{coerc}, B_{rem}

Table I: Relation between device specification and material properties

three groups. One group makes use of Faraday rotation in circular waveguides, the second group is based on nonreciprocal field effects in rectangular waveguides and the last one is the group of junction circulators. Junction circulators are popular due to their compact and simple design. The relation between device specifications and the ferrite properties is related in this paper which is given below.

In the paper of [9] simple symmetric junction circulators with three ports is briefly discussed. A three-port symmetric junction circulator has threefold rotation symmetry. The introduction of a general model for junction circulators based on the following four assumptions is also discussed.

1 All symmetric junction circulators consist of a number of identical resonators.

2 The number of identical resonators is equal to the no of ports.

3 Each resonator is coupled to one port, and conversely.

4 The resonators are mutually coupled. And this model is given in Fig.2.5.

In the paper [5] the development of broadband circulators which operated below resonance and cover octave bandwidths in frequency regions 0.6-0.8 GHz is discussed. Without imposing symmetry, the interrelationship of VSWR and isolation between various ports is established. The isolation of any port is dependent on the impedance

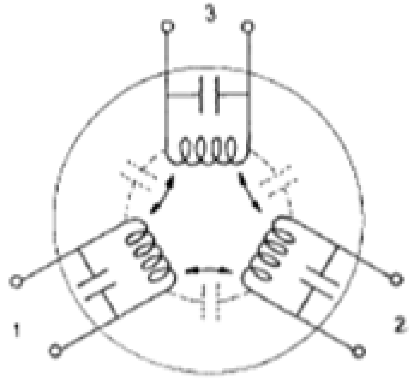


Figure 2.5: Junction circulator model

match at preceding port. For a circulator operating in the low loss mode port 1 $\rightarrow$ port 2 $\rightarrow$ port 3 $\rightarrow$ port 1 means when the power entered port 1, the isolation between port 1 and port 3 could be expressed by expression:

$$Isolation(1 \rightarrow 3) = 10log(1/\|Gamma_2|^2) \quad (2.1)$$

where Γ = Reflection coefficient of port 2

The useful curves are presented which gives optimum ranges of $4\pi M_s$ and ferrite disk diameter to frequency. The magnetic biasing field should be approximately equal to $4\pi M_s$ of the material previously chosen, but it can be adjusted in the test for the best result. If low insertion loss is to be maintained; the ferrite material should have a very low dielectric tangent. The line width of the material must be narrow (approximately 50 to 100 Oe) to avoid the resonance losses.

Conventional circulators need permanent magnet for strong biasing field. As a result the size, cost and weight is increased which is unfavorable as per the recent trend of miniaturization. New circulator design is developed with self-biased strontium M-type barium ferrite operating at 13.6 GHz which is the first self-biased circulator below 20 GHz [7]. New design is proposed with dielectric substrate resting on hexaferrite slab. This makes fabrication simpler as compared to conventional circulator in which

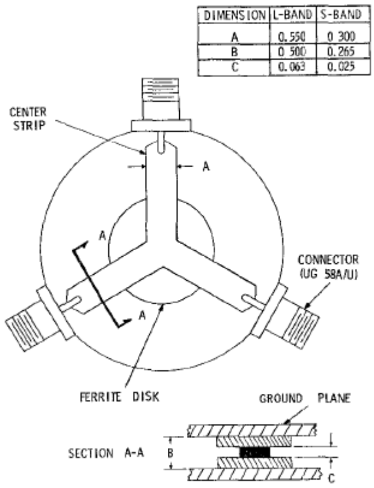


Figure 2.6: Strip-transmission-housing and ferrite configuration for L-band And S-band region

ferrite puck is created in dielectric material. The M-type hexaferrite possesses high density, high remanence and high saturation magnetization which make it suitable for self-biasing.

Circulator Design: The microstriplines are patterned as shown in Fig.2.7. It is fabricated on dielectric substrate duroid which is placed on the disk of strontium barium ferrite. This makes fabrication steps easy and less time consuming than conventional circulator. The quarter wave microstrip line is used for matching ports. k/μ is between 0.1 to 0.5 which is very small so coupling angle is insensitive to circulation condition.

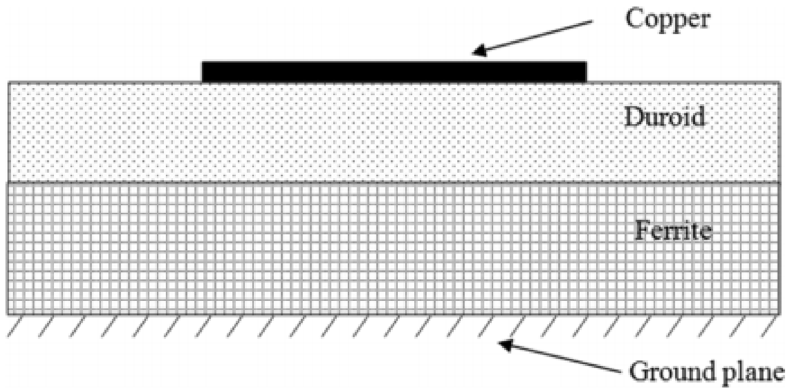


Figure 2.7: Cross section of junction resonator and quarter-wave microstrip line

Magnetic properties of hexaferrite are measured with vibrating sample magnetometer and shorted waveguide ferromagnetic resonance technique. The hexaferrite parameters are as follow: M_r =302.4 kA/m, H_A =1.4MA/m, δH =79.6 kA/m, $\varepsilon_{r,f}$ =19, $\varepsilon_{r,d}$ =2.2
Where $\varepsilon_{r,f}$ is the permittivity of hexaferrite and $\varepsilon_{r,d}$ is the permittivity of duroid substrate. The results achieved by this circulator design are as follow:
Isolation = 21dB, Insertion loss = 1.52 dB and 15 dB isolation bandwidth = 220 MHz.

Chapter 3

Circulator Concept

3.1 Definition

Circulator is defined as a device with ports arranged in such a way that energy entering a port is coupled to adjacent port but not coupled to other ports [10]. The basic three port circulator is shown in Fig.3.1. It can be seen that energy entering at port 1 is transferred to port 2, decoupling port 3. Similarly energy entering at port 2 is transferred to port 3, decoupling port 1. And energy entering port 3 enters port 1, port 2 being decoupled.

An isolator is also one kind of passive nonreciprocal device. It is a two port device in which the energy is transferred in one direction only and not in other direction. Here energy entering port 1 goes to port 2. But energy coming from port 2 cannot travel to port 1. Isolators can also be made with the circulators by connecting a matched load to port 3.

3.2 Basic Terminologies

There are many electrical properties of circulator that are defined as follows:

- **Insertion loss:** Insertion loss (I.L) is defined as the loss of signal power or

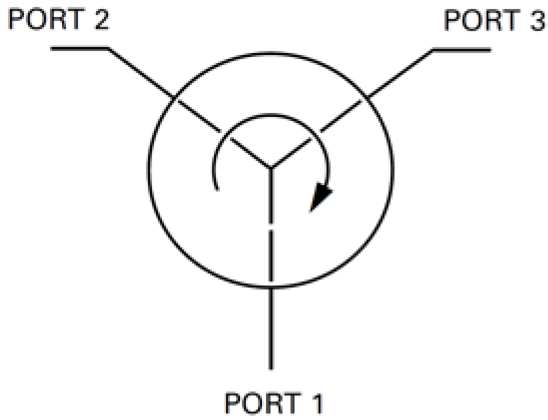


Figure 3.1: Three port circulator

energy when signal travels from one port to another. It can also be defined as the ratio of output power to the input power expressed in dB. Normally it ranges from 0.1 dB to 0.4 dB. The higher the insertion loss it will cost more to use that circulator or isolator in system. Insertion loss basically power dissipated in heat when signal travels from one port to another.

$$I.L(dB) = 10log_{10}\frac{P_{out}}{P_{in}} \tag{3.1}$$

- **Isolation:**Isolation is important specification of any circulator/isolator. Isolation basically refers to how well decoupling of energy is achieved to adjacent ports of the device. It is measured in dB. The isolation of an isolator is directly related to VSWR of port 3 when port 1 is stimulated and port 3 is isolated. It is given as,

$$Isolation(dB) = 10log_{10}\frac{P_3}{P_1} \tag{3.2}$$

- **Return loss(R.L):**Return loss (R.L) is defined as the ratio of reflected power to the incident power or input power. It is related to reflection coefficient (Γ).

$$R.L = \frac{P_{ref}}{P_{in}} \tag{3.3}$$

$$R.L(dB) = -20log|\Gamma| \tag{3.4}$$

- **VSWR:** The reflective property of the ports of circulator or isolator is given by reflection coefficient magnitude ρ.

$$|\rho| = \sqrt{\frac{P_{ref}}{P_{in}}} \tag{3.5}$$

VSWR can be given in form of $|\rho|$ as follows

$$VSWR = \frac{1 + |\rho|}{1 - |\rho|} \tag{3.6}$$

- **Temperature Range:** The temperature range over which the ferrite and magnet material of circulator or isolator retains its properties is called the operating temperature range.

3.3 Application

Circulators find their application in various fields which are mentioned below.

- For decoupling of generator and load of amplifier stages.
- For reducing intermodulation caused by other transmitters load return loss and VSWR.
- For combining transmitters and receivers on the same antenna.
- For combining amplifier stages in solid state transmitters.
- For operating one port amplifiers.
- For locking and priming of oscillators.
- In broadcast and TV transmitters.

- In radar systems.
- In radio links and navigation.
- In military equipment.

Chapter 4

Magnetic Propertis of Ferrites

4.1 Introduction

Ferrite being anisotropic medium in presence of alternating magnetic field, magnetized ferrite perturbs the alternating RF field giving rise to many useful applications. The behavior of all microwave ferrite devices is explained by J. Douglas Adam [4].

- **Faraday Rotation-** If circularly polarized wave propagates through ferrite which is subjected to axial magnetic field B, then plane of polarization gets rotated by some amount of degree this is called faraday rotation.

- **Ferromagnetic resonance** If the applied RF magnetic field is equal to the frequency of the precessional frequency, the direction of electron spin magnetic moment will greatly differ from direction of dc field. This is called ferromagnetic resonance (fmr).

- **Field Displacement-** The displacement of the field distribution perpendicular to the direction of propagation results in more or lesser field inside the ferrite which is called field displacement.

- **Nonlinear Effects-** Subsidiary losses can occur at higher power level amplification and frequency doubling which are called nonlinear effects.

This section explains change in ferrite characteristic when it is magnetized and how wave propagation through ferrite is affected by this change. The property of magnetized ferrite is that while it is having scalar permittivity, it is having tensor permeability i.e. permeability of ferrite is not same in all three dimension. This tensor permeability is basic cause of circulation inside ferrite. In the material, electrons are spinning around their axis. This spin of electron gives rise to magnetic dipole moment. In most solids electron spins occur in pairs with opposite signs so the overall magnetic moment is negligible. In magnetic material, however, a large fraction of the electron spins are unpaired (more left hand spins than right hand spins, and vice versa). Due to random orientation of this dipole net magnetic moment would be zero. However when external magnetic field is applied on such material magnetic dipoles would get aligned with external magnetic field giving large overall magnetic moment. When such magnetic material is placed in external magnetic field it gets magnetized and the magnetization vector will start precession around axis of externally applied magnetic field. This is shown in the Fig.4.1. Here in this section some results of derivation are directly mentioned. They are important for understanding circulation in ferrites.

4.2 Derivation of Equation of Tensor Permeability

Material with elementary permeability of μ is placed in external magnetic field of $\bar{H}_0$, now under equilibrium conditions, the dipole moment vector $\bar{\mu}_0$ lies in the direction of $\bar{H}_0$ which is assumed to be in z direction. Θ is angle of magnetization vector with z-axis. Now torque exerted on $\bar{\mu}_0$ is

$$\bar{T} = \bar{\mu} \times \bar{H}_0 \tag{4.1}$$

Angular momentum associated with magnetic dipole moment is $\bar{J}$.

$$\bar{\mu} = -\gamma \bar{J} \tag{4.2}$$

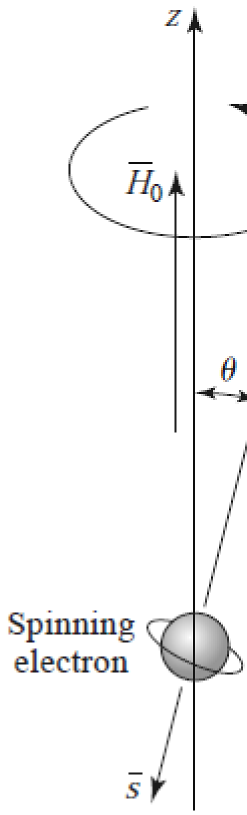


Figure 4.1: Spinning dipole moment and angular moment vectors for a spinning electron

where γ is gyromagnetic ratio given by 2.21$\times$ 10^{-5} (rad/sec)/(A/m). Now torque is time rate change of angular momentum

$$\bar{T} = -\frac{1}{\gamma}\frac{d\bar{\mu}}{dt} \tag{4.3}$$

From 4.1 and 4.3

$$\frac{d\bar{\mu_0}}{dt} = -\gamma(\bar{\mu_0} \times \bar{H_0}) \tag{4.4}$$

Thus the total magnetic moment per unit volume is given by

$$M_0 = N\mu \tag{4.5}$$

Where N is number of unbalanced pairs per unit volume. Now equation becomes

$$\frac{d\bar{M_0}}{dt} = -\gamma(\bar{M_0} \times \bar{H_0}) \tag{4.6}$$

This equation is termed as equation of motion of magnetization.

4.3 Permeability Tensor of Ferrite

The differential equation of the motion of magnetization vector of magnetic ferrite is given in (4.6). Now such externally magnetized ferrite is incident with RF magnetic field $\bar{h}$. Thus total magnetic field in ferrite is consists of dc magnetic field $\bar{H_0}$ and RF magnetic field $\bar{h}$.

$$\bar{H} = \bar{H_0} + \bar{h} \tag{4.7}$$

Due to this magnetic field intensity magnetization in the material consist of dc magnetization $\bar{M_0}$ and RF magnetization $\bar{m}$.

$$\bar{M} = \bar{M_0} + \bar{m} \tag{4.8}$$

Above quantities have components as follows

$$\bar{H_0} = \begin{bmatrix} 0 \\ 0 \\ H_0 \end{bmatrix} \tag{4.9}$$

$$\bar{h} = \begin{bmatrix} h_x \\ h_y \\ h_z \end{bmatrix} \tag{4.10}$$

$$\bar{M_0} = \begin{bmatrix} 0 \\ 0 \\ M_0 \end{bmatrix} \tag{4.11}$$

$$\bar{m} = \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \tag{4.12}$$

Now putting these values of components in the (4.6) and expanding it would result in following equations

$$\frac{dm_x}{dt} = -m_y\gamma(H_0 + h_z) + h_y\gamma(M_0 + m_z) \tag{4.13}$$

$$\frac{dm_y}{dt} = m_x\gamma(H_0 + h_z) - h_x\gamma(M_0 + m_z) \tag{4.14}$$

$$\frac{dm_z}{dt} = -m_x\gamma(h_y) + h_x\gamma(m_y) \tag{4.15}$$

Now the values of h_x, h_y, h_z and m_x, m_y, m_z be very small as compared to value of H_0. Thus small signal approximation is

$$\frac{dm_x}{dt} = -m_y\gamma(H_0) + h_y\gamma(M_0) \tag{4.16}$$

$$\frac{dm_y}{dt} = m_x\gamma(H_0) - h_x\gamma(M_0) \tag{4.17}$$

$$\frac{dm_z}{dt} = 0 \tag{4.18}$$

If the time dependency of RF magnetic field is of the form $\exp^{j\omega t}$ then above differential equation could be solved and relationship between magnetization m and magnetic field intensity h could be obtained. This relationship gives susceptibility tensor.

$$\bar{m} = \mu_0[\chi]\bar{h} \tag{4.19}$$

where

$$\chi = \begin{bmatrix} \chi_{xx} & \chi_{xy} & 0 \\ \chi_{yx} & \chi_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4.20}$$

And

$$\chi_{xx} = \chi_{yy} = \frac{\omega_m\omega_0}{-\omega^2 + \omega_0^2} \tag{4.21}$$

$$-\chi_{yx} = \chi_{xy} = \frac{j\omega_m\omega}{-\omega^2 + \omega_0^2} = -j\kappa \tag{4.22}$$

Where $\omega_m = \frac{\gamma M_0}{\mu_0}$ and $\omega_0 = \gamma H_0$

ω_0 is called precession frequency. ω is frequency of applied RF wave. Now in order to stabilize the motion of magnetization vector damping factor is required to be introduced. Thus equation (4.6) becomes

$$\frac{d\bar{M}_0}{dt} = -\gamma(\bar{M}_0 \times \bar{H}_0) - \frac{\alpha}{|M|}(\bar{M} \times \frac{d\bar{M}}{dt}) \tag{4.23}$$

Due to introduction to this damping factor, value of susceptibility tensor would get changed. This new value of susceptibility is complex and could be resolved in real and imaginary parts $\chi_{xx} = \chi_{xx}^{'} + \chi_{xx}$and $\kappa = \kappa^{'} + \kappa^{"}$.

$$\chi_{xx}^{'} = -\frac{\gamma M_0\omega_0[\omega_0^2 - \omega^2(1-\alpha^2)]}{[\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.24}$$

$$\chi_{xx}^{"} = -\frac{\gamma M_0 \omega\alpha[\omega_0^2 + \omega^2(1+\alpha^2)]}{[\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.25}$$

$$\kappa^{'} = -\frac{\gamma M_0 \omega[\omega_0^2 - \omega^2(1+\alpha^2)]}{[\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.26}$$

$$\kappa^{"} = -\frac{2\gamma M_0 \omega_0 \omega_0^2 \alpha}{[\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.27}$$

Now permeability $\mu_r = 1 + \chi_{xx}$, thus from susceptibility matrix permeability matrix could be obtained by adding unity matrix to the susceptibility matrix

$$\mu_r = \begin{bmatrix} \mu_r & j\kappa & 0 \\ -j\kappa & \mu_r & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.28}$$

In most cases, α^2 is much less than unity, so the $\omega^2(1-\alpha^2)$ terms in the equation could be changed to ω^2. The elements of permeability tensor now are

$$\mu_r^{'} = 1 - \frac{\gamma M_0 \omega_0[\omega_0^2 - \omega^2]}{[\omega_0^2 - \omega^2(1+\alpha^2)]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.29}$$

$$\mu_r^{"} = -\frac{\gamma M_0 \omega\alpha[\omega_0^2 + \omega^2]}{[\omega_0^2 - \omega^2]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.30}$$

$$\kappa^{'} = -\frac{\gamma M_0 \omega[\omega_0^2 - \omega^2]}{[\omega_0^2 - \omega^2]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.31}$$

$$\kappa^{"} = -\frac{2\gamma M_0 \omega_0 \omega_0^2 \alpha}{[\omega_0^2 - \omega^2]^2 + 4\omega^2\omega_0^2\alpha^2} \tag{4.32}$$

If we make external magnetic H_0 field applied to ferrite zero, then magnetization M_0 inside ferrite would also become zero resulting in $\omega_0 = 0$. Putting these values in (4.29) to (4.32) would lead to $\mu_r^{'} = 1$ and rest of the quantities $\mu_r^{"}$, $\kappa^{'}$,$\kappa^{"}$equal to zero. Thus relative permeability would become 1 and ferrite behaves as normal isotropic material having scalar permeability. By removing external magnetization, ferrite losses its anisotropy property.

We can observe from equations (4.29) to (4.32) that when value of ω is equal to ω_0 then value of $\mu_r^{'}$, $\mu_r^{"}$, $\kappa^{'}$,$\kappa^{"}$ would become maximum. Here maximum value of imaginary part of κ i.e. $\kappa^{"}$ and $\chi_{xx}^{"}$ shows losses in the material. Thus circulator should never be used around this region. The effective permeability of ferrite for RF field being in direction transverse to the direction of propagation is given by following equation.

$$\mu_e = \frac{\mu^2 - \kappa^2}{\mu} \tag{4.33}$$

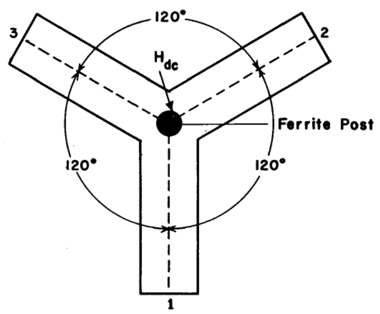
The detailed study on ferrites is given in reference [12].

Chapter 5

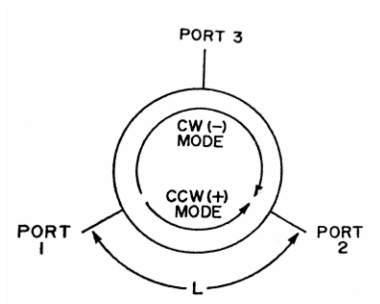
Operation and Design of Circulator

5.1 Basic Principle of Circulator

The ferrite junction circulator consists of a junction of three microstrip lines having an angle of 120° between them. They are connected in center to form a symmetrical Y shaped junction. The structure is three fold symmetric, i.e. it is identical seen from any port as shown in Fig.5.1(a).



(a) Y junction circulator



(b) Rotating mode in three port circulator

Figure 5.1

The RF wave is split into two different counter rotating components in clockwise and anticlockwise direction when it is coupled to the ferrite. Standing wave patterns are generated inside the ferrite disk by this counter rotating components of the RF wave. When ferrite is magnetized, propagation constant of two components will not remain same & thus standing wave pattern in the disk will get rotated. If this standing wave pattern is rotated such that maxima occurs at one port & minima occurs at another port then power will transfer at that port where standing wave maxima is situated and the port with standing wave minima is isolated.

For the circulator action to occur the two modes shown in Fig.5.1(b) must travel at different velocities. There must be phase difference of $2N\pi$ between clockwise mode(-) and anticlockwise mode(+) for coupling from port 1 to port 2.

$$2\beta_{-}L - \beta_{+}L = 2N\pi \tag{5.1}$$

where β is phase constant of positive and negative travelling wave. L is the distance travelled by the wave and N is any integer. The negative wave must travel twice the distance the positive wave travels to reach port 2.The two wave components must have phase difference of an odd multiple of π for port 3 to be decoupled.

$$\beta_{-}L + 2\beta_{+}L = (2M - 1)\pi \tag{5.2}$$

where, M is any integer. On solving equation (5.1) and (5.2), we get

$$\beta_{-}L = \frac{4N + 2M - 1}{3}\pi \tag{5.3}$$

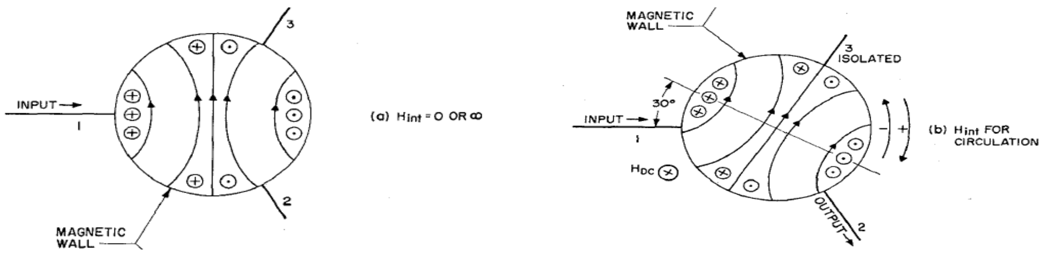
$$\beta_{+}L = \frac{2N + 4M - 2}{3}\pi \tag{5.4}$$

For the perfect condition of circulation operation, equation (5.3) and (5.4) must be satisfied. The propagation constant of the two counter rotating modes propagating in ferrite is given by following equations.

$$\Gamma_{+} = j\omega\sqrt{\mu_0\varepsilon}\sqrt{\frac{\mu^2 - \kappa^2}{\mu}} \tag{5.5}$$

$$\Gamma_- = j\omega\sqrt{\mu_0\varepsilon} \tag{5.6}$$

Equations (5.5) and (5.6) are derived in Ref [17]. From equations (5.5) and (5.6) the relative permeability for + mode and mode are $\mu_{r+} = \frac{\mu^2-\kappa^2}{\mu}$ and μ_{r-} respectively. The standing wave pattern under unmagnetized condition and magnetized condition is given in Fig. 5.2(a) and Fig.5.2(b) respectively.



(a) Fields under unmagnetized condition (b) Fields under magnetized condition

Figure 5.2

The RF magnetic field is circularly polarized. If the ferrite is unmagnetized the counter rotating modes will resonate at same frequency. At the output two signals with equal magnitude and phase will appear at port 2 and port 3 as shown in Fig.5.2(a). So under unmagnetized condition, circulator acts as coupler. If the ferrite is subjected to a dc magnetic bias field, the two counter-rotating modes are no longer resonant at the same frequency, thus the ferrite loaded cavity is excited at a frequency intermediate between the resonant frequencies of the two modes. The impedance of the mode having the higher resonant frequency will have an inductive reactance and that of the other mode will have a capacitive reactance component. If the frequency is chosen such that the two reactive components are equal and opposite, the total impedance will be real under magnetized condition. If the degree of mode splitting is chosen such that the phase angle of impedance of each mode is 30° at the operating frequency, then the standing wave pattern will be rotated by 30° as shown in Fig.5.2(b). The standing wave pattern will present a null in the field at port 3 and no power is transmitted to that port.

It is difficult to define the boundary of the cavity of the junction, and calculation of the operating frequency becomes difficult even if it is possible to obtain expressions for the fields in the ferrite and the air at the junction. One important property of the three-port junction circulator is that ideal circulator action is obtained when the junction is matched. Therefore, one method of obtaining broadband performance is to use external matching networks. Use of waveguide stepped impedance transformer and quarter-wave transformers are common. In microstrip junction circulator it is achieved using quarter wave transformer.

5.2 Region of Operation

The operating region of circulator in terms of applied magnetic field is divided among three parts. They are below resonance, above resonance and at resonance. For three regions there are different conditions that must be followed. As discussed in above section if value of $\frac{\omega_0}{\omega} = 1$ then the ferrite is operating in resonance region. But in this region the imaginary part of permeability tensor becomes infinite which leads ferrite to become lossy and absorbs all power applied to it. To avoid this situation the ferrite must be operated in either above resonance $\frac{\omega_0}{\omega} < 1$ or in below resonance $\frac{\omega_0}{\omega} > 1$.

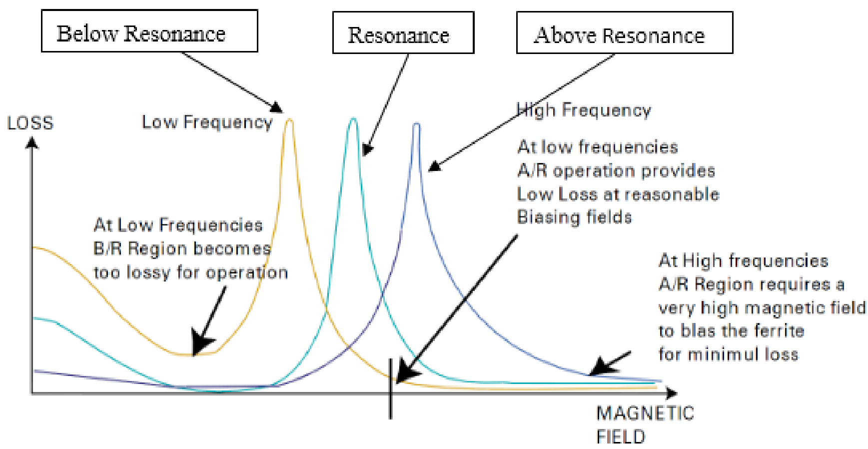


Figure 5.3: Magnetic operating regions

In the below resonance region, the value of saturation magnetization is low which increases the peak power handling capacity of the circulator. But on the other hand the lower saturation magnetization decreases the bandwidth of the circulator. But in above resonance region, high magnetic bias is required for high frequency operation. So to have high frequency the ferrite must be operated in below resonance region so that the required magnetic bias is decreased. But if the saturation magnetization is decreased in above resonance region then the need of higher magnetic bias field also decreases. So keeping all the above points in mind and based on the priority of the desired parameter the region of operation must be selected. Here, the below resonance region is selected. In general, junction circulators below 2 GHz are developed in AR mode; for circulators above 2-3 GHz, BR operation is utilized. Hence in this project for X-band junction circulator, below resonance operation is used.

5.3 Design Flow

Depending on the specifications the design of ferrite junction circulator primarily follows the following steps.

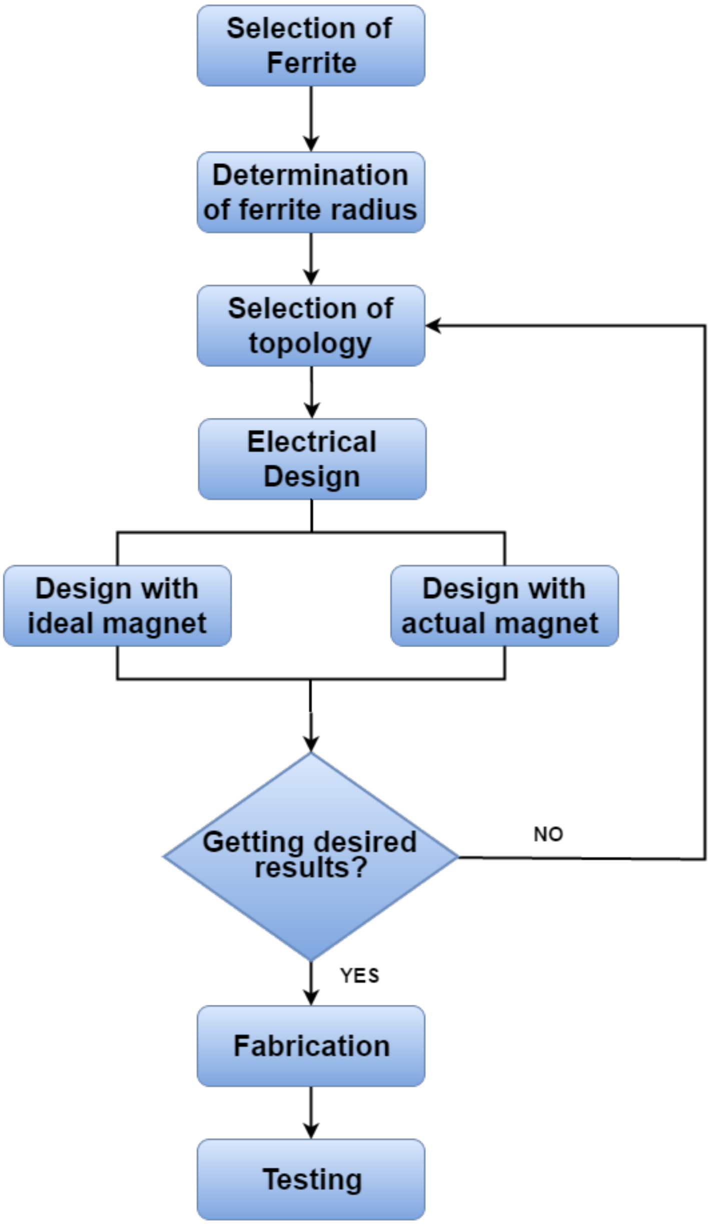


Figure 5.4: Design Flow

5.4 Selection of Ferrite

Selection of ferrite material nearly affects all design parameters of circulator like frequency and bandwidth of circulator, RF power level, insertion loss and ambient temperature range. That is why selection of appropriate material is important. Selection of ferrite basically does not depend on the microwave transmission medium whether it may be strip line or waveguide. The most important ferrite properties which should be considered in design are ferrite saturation magnetization, resonance line width and if ferrite is expected to operate over large temperature range then curie temperature of ferrite should also be considered.
Ferrites are basically divided into two classes: Garnet and Spinel

- Garnet: The mineral commonly known as black garnet has general formula $Ca_3Fe_2Si_3O_{12}$. A new compound Yttrium Iron Garnet (YIG) is formed by replacing silicon by iron and calcium by a rare earth element like yttrium. The net magnetic moment of ferrite material can be varied by substituting aluminum instead of iron in YIG the net magnetic moment can be changed. Spin wave line width can be changed by adding rare earth element like gadolinium, holium or dysprosium.

- Spinel: The general formula of spinel is $MgAl_2O_4$. Microwave ferrites (spinels) are similar in crystal structure with a general formula of MFe2O4 where M can be any one from Al, Co, Li, Mg, Mn, Ni, Ti, Zn or any one combinations of these ions.

Manufacturing of ferrite

Ceramic Techniques are used to manufacture ferrite. In the first step of manufacturing of ferrites, the raw materials are ground in correct particle size and are mixed in correct proportions in presence of water or methylated spirit to have homogeneity. The mixture is dried at a temperature lower than that used for final firing. The firing helps to initiate the partial reaction between the raw materials. After this process the material is mixed with a binder like distilled water for helping in shaping the material easier. Many processes like extruding, pressing and casting helps the paste to be formed in desired shape. Gentle heat is applied to the shaped parts to drive off the binder.

In next step, the ferrites are fired in a carefully controlled temperature between 1000° and 1500°C. It may take from four hours to seven days for this firing process to last depending on the material. By this process the ferrites produced are polycrystalline which have non uniform orientation of crystal lattice.

It is possible to purchase the ferrite in an unmachined way then cut and grind them as many industries may not have enough facilities and laboratories to manufacture ferrite. The unmachined ferrite may be of any shape and sizes but they can be machined to desired shape and size having smooth finished surface. It is very difficult to machine ferrite as they are hard, brittle and have low thermal conductivity. So diamond wheels and sometimes carbide wheels are used to grind these materials. During the grinding operation water must be used as a coolant. While a surface grinder is used to ground the surface of ferrite, the same machine using diamond cut-off wheel is used to slice the ferrite edges. Proper cleaning of ferrite must be done after machining as any surface impurities can degrade electrical performance of the ferrite. Dimensional tolerances of finished ferrites parts play a very important role. Generally, thickness tolerance of ferrite is around 0.0005 inches, while that for diameter of disc or altitude of triangle it is 0.005 inches. It is usually desirable to have smoth finished surface instead of having sharp corners in ferrite.

Other important aspect of selection of ferrite material is grain size. A reduced grain size normally up to 10-20 m can increase the threshold in below resonance region where peak power threshold can cause higher insertion loss at higher peak levels. Smaller grain size has a disadvantage of higher cost.Ferrites may be triangular or disk shaped. Disks prove very cost effective where smaller ferrites are used while triangular ferrites are cost effective for larger ferrites. Now, the smaller ferrites are normally used in below resonance region so disks shaped ferrites are used in below resonance units and triangular ferrites are used in above resonance units.

The dependence of specification of circulator on the properties of ferrite material is given by Henk Bosma [3] which is stated in the Table I.

Device Specifications	**Material Properties**
Isolation	Saturation Magnetization $4\pi M_s$
Phaseshift	Polarizing Magnetic Field H_{dc}
Insertion loss	Resonance Linewidth ΔH
Bandwidth	Magnetization $4\pi M$ and internal polarizing field H
High-power capability	Critical field strengthh_{crit}

Table I: Dependence of specifications on properties of ferrite material

From application point of view different specification dictates different optimum choice of ferrite material. So there is a trade of to be done as per the following table.

APPLICATIONS	CUSTOMER REQUIREMENT	EFFECT ON CHOICE OF MATERIAL
Low level power circulator	Low insertion loss High directivity Compactness Widest possible frequency band Wide temperature range	ΔH_{eff} minimum ΔH minimum ϵ maximum M_s adjusted to frequency α as low as possible
High level power circulator	Power behavior Low insertion loss Temperature stable	ΔH_k high ΔH_{eff} and ΔH as as possible compatible with ΔH_k
Isolator below resonant frequency circulator	Low insertion loss Narrow frequency band	ΔH_{eff} minimum M_s and ΔM_s function of frequency ΔH according to the required band

Table II: Parameter requirement

The critical magnetic microwave field h_c, from which the nonlinear effects appear, depends on the pplied static filed. The nonlinear effects are associated with the excitation of the spin waves, the ttenuation of which is described by Δ_k. The critical magnetic field h_c is related to $Delta_k$ as follows.

$$h_c min = \frac{2f\Delta H_k}{\gamma M_s} \tag{5.7}$$

The higher value of ΔH_k is required for the high power behavior. So as per the requirement of high power in this application, the ferrite material must possess the characteristic of ΔH_k being high while ΔH_{eff} and ΔH as low as possible.

5.5 Specification of Circulator

The objective of the thesis is to design and develop X-Band microsrtip junction circulator with following major specifications.

Center frequency	9.6 GHz
Bandwidth	±400 MHz
Insertion loss	<0.4 dB
Isolation	>20 dB
Return loss	> 20 dB

Table III: Specification of Circulator

5.6 Design Theory

Important papers by early workers like Bosma[2][3], Fay and Comstock[1], Simon[5], Wu and Rosenbaum[9] in designing of microwave circulator are reviewed. No universal equations exist for working microwave circulator. Most circulator designs are based on empirical method. But to begin with initial design, here design equations given by Fay and Comstock are used. Most of early workers have worked on stripline and waveguide circulators. Design algorithms for stripline junction circulators can be applied to microstrip circulator except that transmission line impedances must be computed using equations of microstrip transmission lines.
Key dimensions of microstrip circulator configuration is shown in Fig.5.4.

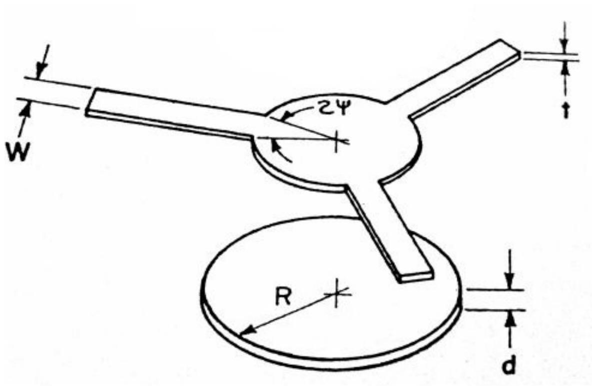


Figure 5.5: microstrip circulator configuration

The dimensions are related as,

$$\sin \psi = \frac{W}{2R} \tag{5.8}$$

The effective permeability of the magnetized ferrite is given by,

$$\mu_{eff} = \frac{\mu^2 - \kappa^2}{\mu} \tag{5.9}$$

The solutions of electromagnetic field equations involve the Bessel function of Nth order. For practical circulator N=1 so we have

$$J_1^{'}(KR) = 0 \tag{5.10}$$

where J denotes Bessel function and K is wave number given as,

$$K = \omega \sqrt{\mu_0 \epsilon_0 \mu_{eff} \varepsilon} \tag{5.11}$$

Solving equation (5.10) we get

$$KR = 1.84 \tag{5.12}$$

From the above equation we can calculate the radius of ferrite cylinder.
For narrow bandwidths, the circulator VSWR is related to admittance phase angle as,

$$VSWR = \sec^2\theta = \frac{Y_r^2}{G_r^2} \tag{5.13}$$

Designing procedure is started from given VSWR from that we get admittance phase angle. Next, required Q_L is calculated from equation (5.14).

$$Q_L = \frac{\tan\theta}{\frac{f2-f1}{f0}} \tag{5.14}$$

where f2-f1 = BW, f0 = center frequency

After Q_L is known frequency splitting factor $\frac{\kappa}{\mu}$ is calculated as

$$\frac{\kappa}{\mu} = \frac{0.71}{Q_L} \tag{5.15}$$

If the circulator is operated in below resonance region, and ferrite can be considered as just saturated in that case mu=1 and

$$\mu_{eff} = 1 - \kappa^2 = 1 - \frac{\gamma^2 M_0^2}{\omega^2} \tag{5.16}$$

$$Y_{eff} = \sqrt{\frac{\epsilon_0 \varepsilon}{\mu_{eff}\mu_0}} \tag{5.17}$$

$$G_r = \frac{Y_{eff}|\frac{\kappa}{\mu}|}{\sin\psi} \tag{5.18}$$

Y_r can be calculated by equation (5.13)

Unloaded Qu is given as,

$$Q_u = \frac{1}{\frac{\gamma^2 4\pi M_s \Delta H}{2\omega^2} + \tan\delta} \tag{5.19}$$

Chapter 6

Introduction to CST STUDIO SUITE

CST STUDIO SUITE is a special tool for the 3D EM simulation of high frequency components. The unparalleled performance of CST STUDIO SUITE making it first choice in technology leading R& D departments [15].

CST STUDIO SUITE enables the fast and accurate analysis of high frequency (HF) devices such as antennas, filters, couplers, planar and multi-layer structures and SI and EMC effects. Exceptionally user friendly, CST STUDIO SUITE quickly gives you an insight into the EM behavior of your high frequency designs.

CST promotes complete technology for 3D EM simulation. Users of our software are given great flexibility in tackling a wide application range through the variety of available solver technologies. Beside the flagship module, the broadly applicable Time Domain solver and the Frequency Domain solver, CST STUDIO SUITE offers further solver modules for specific applications. Filters for the import of specific CAD files and the extraction of SPICE parameters enhance design possibilities and save time. In addition, CST STUDIO SUITE can be embedded in various industry standard workflows through the CST user interface.

CST STUDIO SUITE is seen by an increasing number of engineers as an industry standard development tool. It can simulate over a wide range of frequency by dividing whole structure into many meshes.

6.1 Design Steps In CST STUDIO SUITE

1 Set units

2 Set background material

3 Define structure

4 Set frequency

5 Set excitation

6 Set boundary conditions

7 Set field monitor

8 Start solver

9 Analyze result

The magnetic simulation is done by Magneto static Solver of CST STUDIO SUITE. By changing the problem type from high frequency to low frequency and selecting M static option Magneto static Solver is selected. The design steps in Magneto static Solver in CST STUDIO SUITE follow the following steps.

- Define permanent magnet
- Set magnet material
- Set field monitor
- Start magneto static solver
- Analyze result

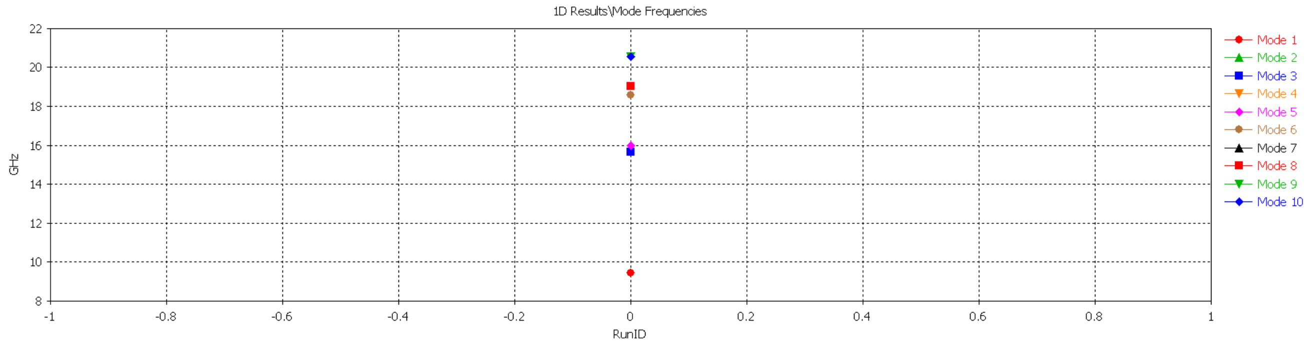


Figure 6.1: Eigen mode frequencies

6.2 Different Solvers Overview

To design specifically microstrip circulator here we have used two types of solvers in CST Microwave Studio.

- Eigen mode solver The eigen mode solver is used to calculate finite modal field distributions in a closed structure. It supports both types of meshes: hexahedral and tetrahedral. It doesnt need excitation ports to be defined. Before we start our final modeling of the structure we should use eigen mode solver to check mode frequencies.
  Here we have used basic structure with just substrate and conducting disk and checked it with eigen mode solver for different mode frequencies. It is shown in the Fig. 6.1. Here we have considered only mode1 and 2, higher order modes are eliminated because of losses. Each time by changing the radius of disk we will get different mode frequencies. This is useful to decide the ferrite radius. For radius of 2.1 mm we are getting around 9.5 GHz at mode 1 and 2 so it is preferable for further modeling.

- Frequency Domain Solver Frequency solver is same as transient solver. It delivers electromagnetic near and far fields as well as S parameters. It is used for applications like, stripline circuits, packaging problems, network parameter extraction, patch antennas, conformal antennas, filters and diplexers and optical filters etc. Frequency range must be set before using frequency domain solver. After defining the range of frequencies and background, one should define waveguide ports to define excitation. The proper definition of ports is important for accurate S parameters computation. There are three types of ports available in CST.

- Discrete edge ports
- Discrete face ports
- Waveguide ports

Discrete edge ports can be viewed as lumped circuit elements with internal resistor and current source in parallel. These ports consist of a single lumped element in center connected to perfectly electrically conducting wires to the structure. Voltage or current relation is to be introduced in element then S parameters are calculated. Any discrete port can be defined as voltage or current source.

Discrete face ports are similar to discrete edge ports. Here only the difference is instead of conducting wire, perfect electrical conducting faces are connected to the structure. It introduces lower inductance than discrete edge port.

Waveguide ports are most suitable for obtaining accurate results. They provide low level of reflection and distortion than the other two. Also de- embedding can be performed easily by changing the reference plane of the port. Here we have used waveguide ports as we want high accuracy in results and de-embedding has to be performed when both high frequency and magnetostatic solver run simultaneously.

Frequency domain solver parameters can be edited from the dialog box shown in Fig.6.2.

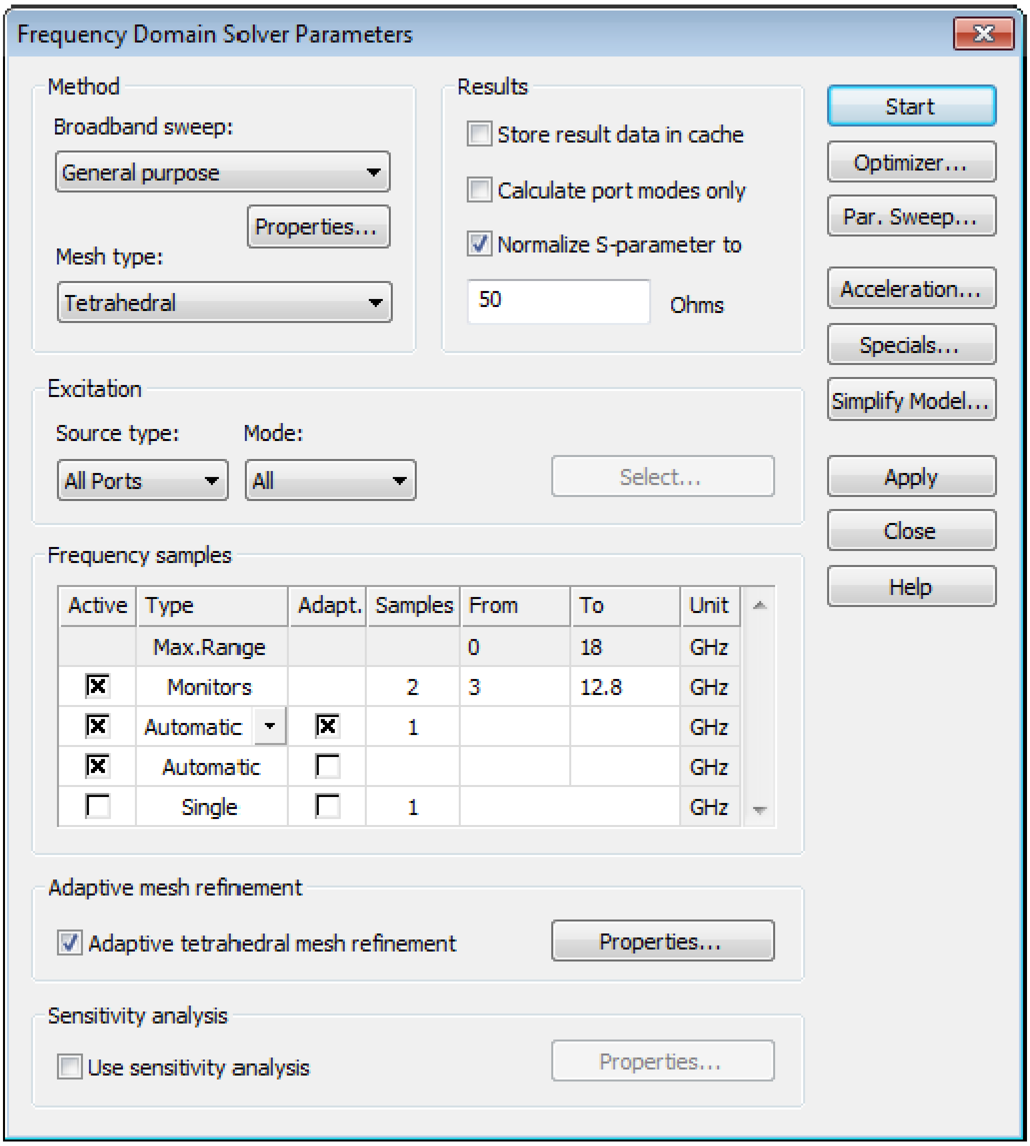


Figure 6.2: Frequency domain solver parameters

Chapter 7

Design and Simulation

Specifications for the design of X band Microstrip Junction Circulator with center frequency of 9.6 GHz provided by SAC, ISRO are as given in Table III of section 5.5.

7.1 Selection of ferrite

Ferrite material Yttrium-Calcium-Vanadium-Indium or Zirconium Y220 is selected based on comparative study of ferrites provided by the TEMEX CERAMICS [14]. Ferrite properties of Y220 are as given in Table I.

Ferrite	Y220
Saturation Magnetization ($4\pi M_s$)	1950G
Curie Temperature T_c	205°
Resonance Linewidth ΔH	10 Oe
Effective Linewidth ΔH_{eff}	2 Oe
Spin wave Linewidth ΔH_k	1 Oe
Dielectric Constant ε_r	15.4
Lande Factor g_{eff}	2.01
Dielectric Loss tangent $tan\delta$	2×10^{-4}
Magnetization Temp. coefficient α	$3.1 \times 10^{-3}/°C$

Table I: Properties of Y220 Material [14]

7.2 Determination of ferrite radius

To begin with basic design of circulator, here the shape of ferrite is kept as cylinder. Different approaches are given in papers of Bosma[2], Fay and Comstock[1], Simon[5] for ferrite geometries and sizing.

Here, we have used Eigen mode solver of CST Microwave Studio to decide the ferrite radius. Mode frequencies are observed with different radius of ferrite and finally selected the radius on which mode 1 and mode 2 frequencies are nearby center frequency with required null in the center. The E field pattern is also observed in mode 1 and mode 2 and compared as given in [1].

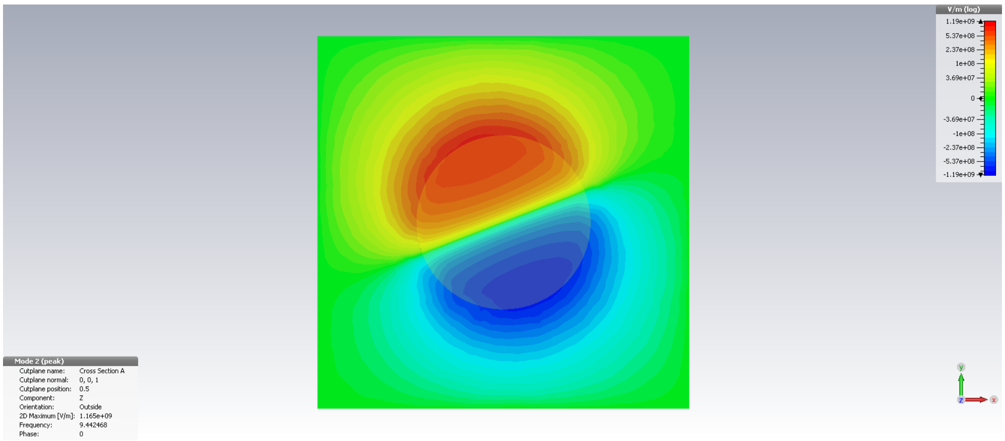


Figure 7.1: E field Of Circulator

E_z component of electric field is shown in Fig.7.1. It is same as standing wave pattern shown in [1] with unmagnetized disk. In the upper potion the E field is coming outward of the plane and in lower portion it is going inside of the plane. Also the frequency of mode 2 is 9.44 GHz. Based on that initial selected radius of ferrite is 2.1mm.

7.3 Electrical Design

7.3.1 Prototype 1

This design consists of triangular substrate with ferrite cylinder inserted in the center of the structure and ground plane placed below the substrate. Three microstrip lines each 120° apart from each other connected to conducting disk as shown in fig. Different stubs of different width and length are used for matching purpose.The structure is three fold symmetric. Y220 is used as ferrite material in this design.
The properties of ferrite material Y220 (Yttrium - Calcium - Vanadium - Indium or Zirconium) is shown in Table I of section 7.2.

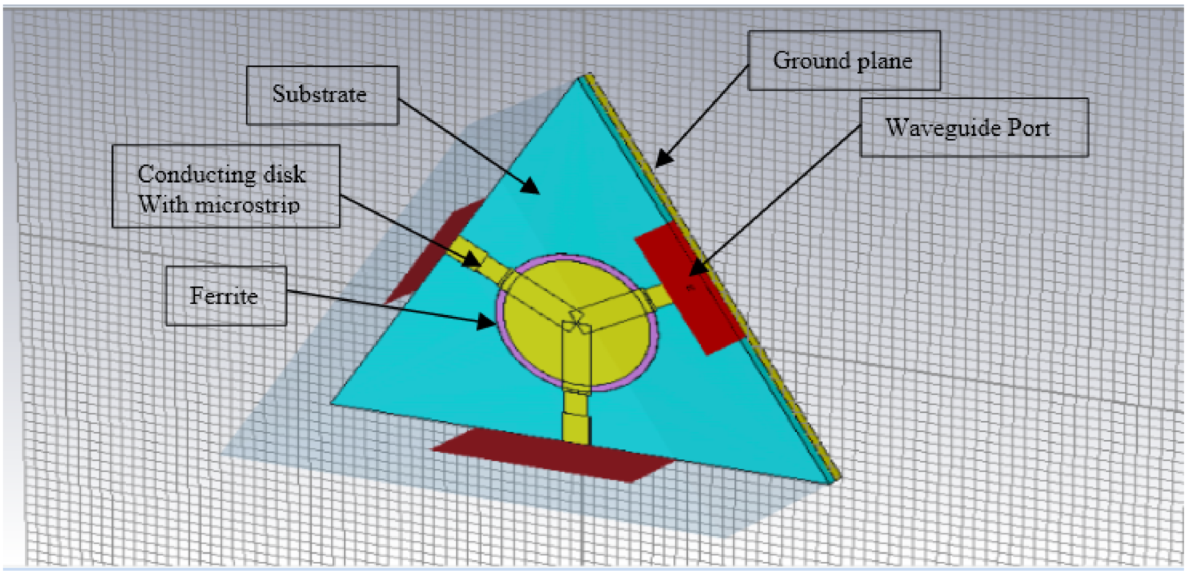


Figure 7.2: Electrical Design of Prototype 1

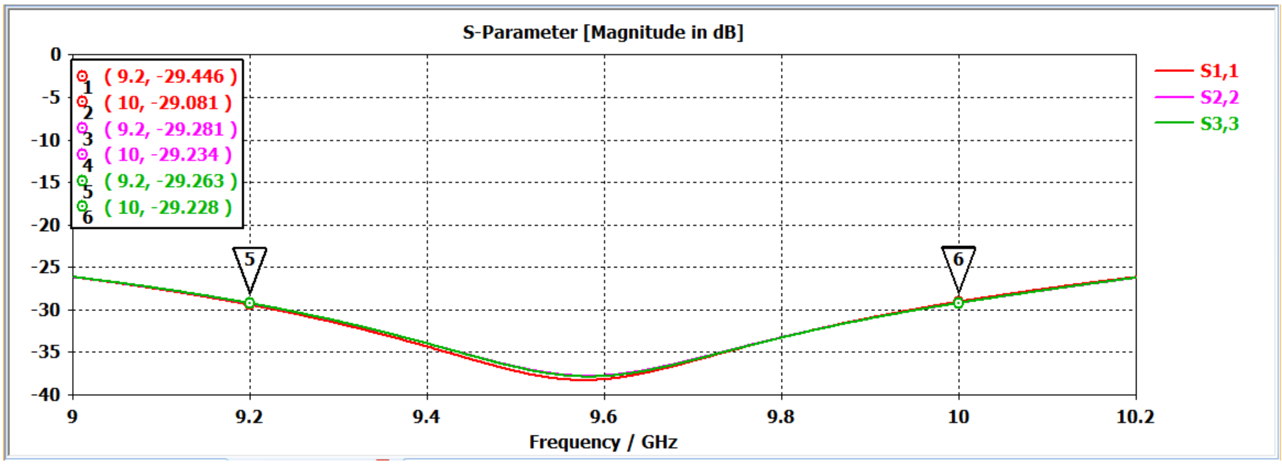


Figure 7.3: Return loss of Prototype 1

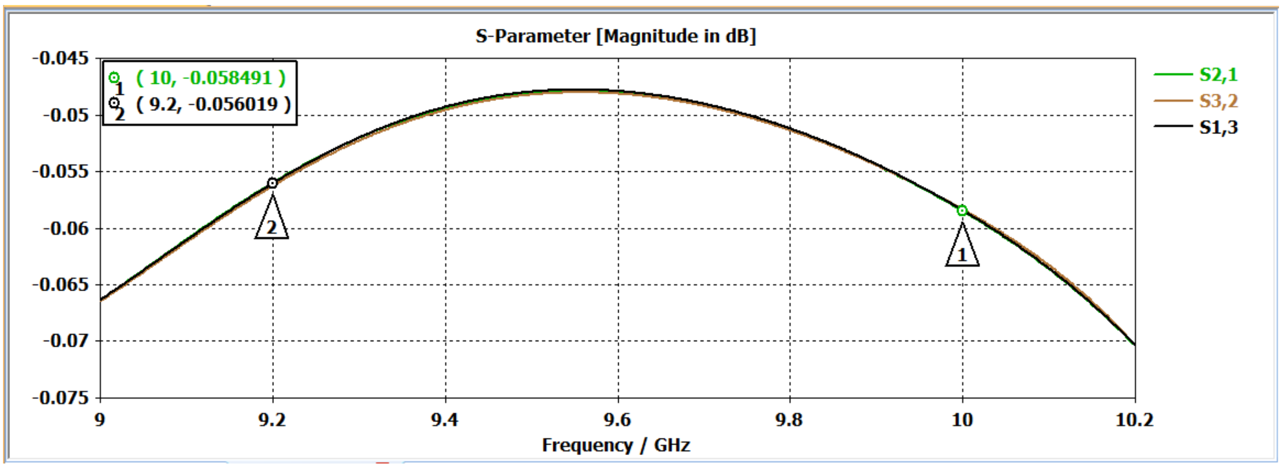


Figure 7.4: Insertion loss of Prototype 1

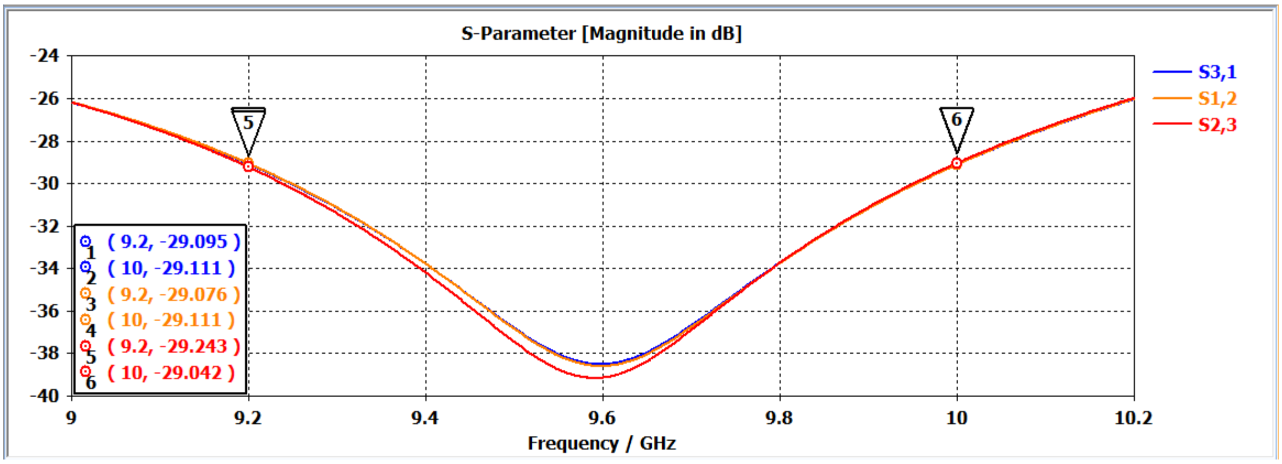


Figure 7.5: Isolation of Prototype 1

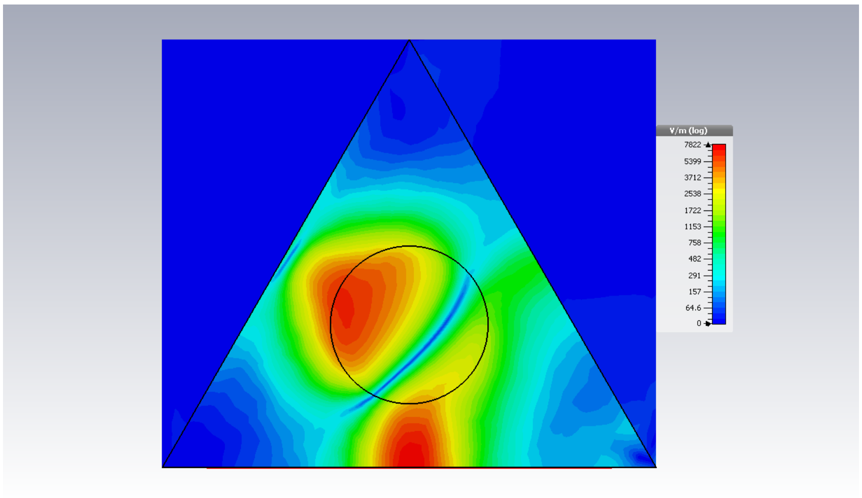


Figure 7.6: EM Field of Prototype 1

7.3.2 Discussion on prototype 1

In this design ferrite is kept gyrotropic with required settings in Frequency domain solver. This is ideal condition where magnetic field is uniform at each and every point of ferrite. Matching is accomplished empirically using parametric sweep. S parameters for prototype 1 is shown in Fig.7.3 to Fig.7.5. Here, it can be seen that return loss and isolation achieved are >29 dB and insertion loss is <0.058 dB which are better than estimated. Fig.7.6 shows EM field in the structure which clearly reveals that port 3 is isolated and maximum amount of E field is coupled from port 1 to port 2. Though this prototype exhibits desired results, it is quite inappropriate to integrate this with other components as the substrate is triangular. So, there is a need to bend two stubs related to port 2 and port 3. This leads us to prototype 2.

7.3.3 Prototype 2

This design consists of rectangular substrate as two stubs related to port 2 and port 3 are bent 30°. Three microstrip lines 120° apart from each other are connected to center conducting disk. Different stubs of different length and width are used for matching purpose. The structure is electrically three fold symmetric.

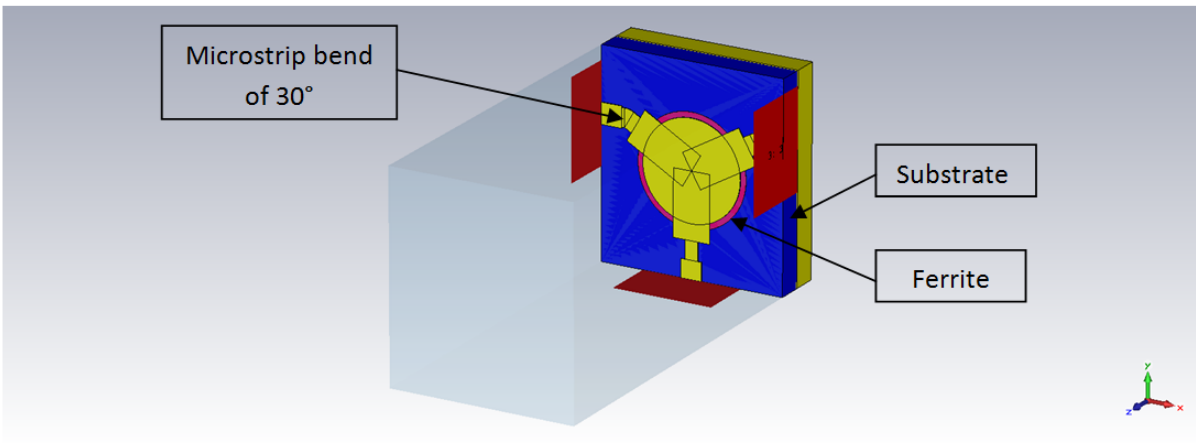


Figure 7.7: Electrical Design of Prototype 2

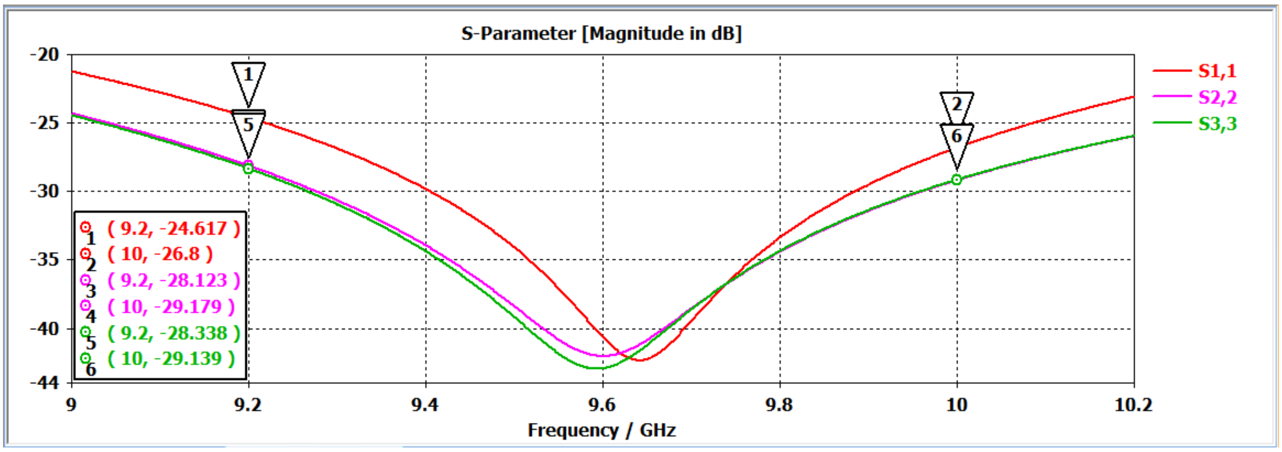


Figure 7.8: Return loss of Prototype 2

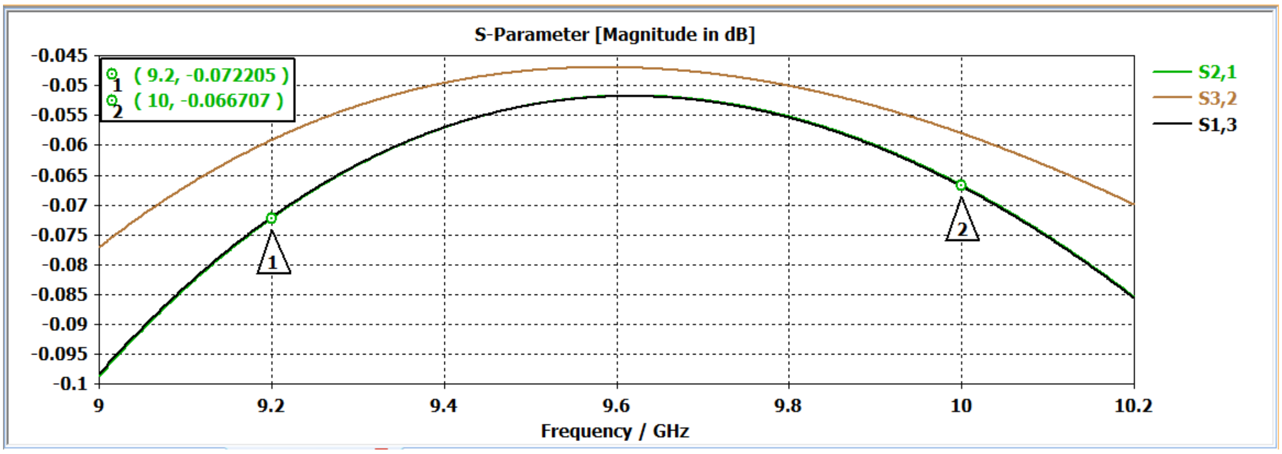


Figure 7.9: Insertion loss of Prototype 2

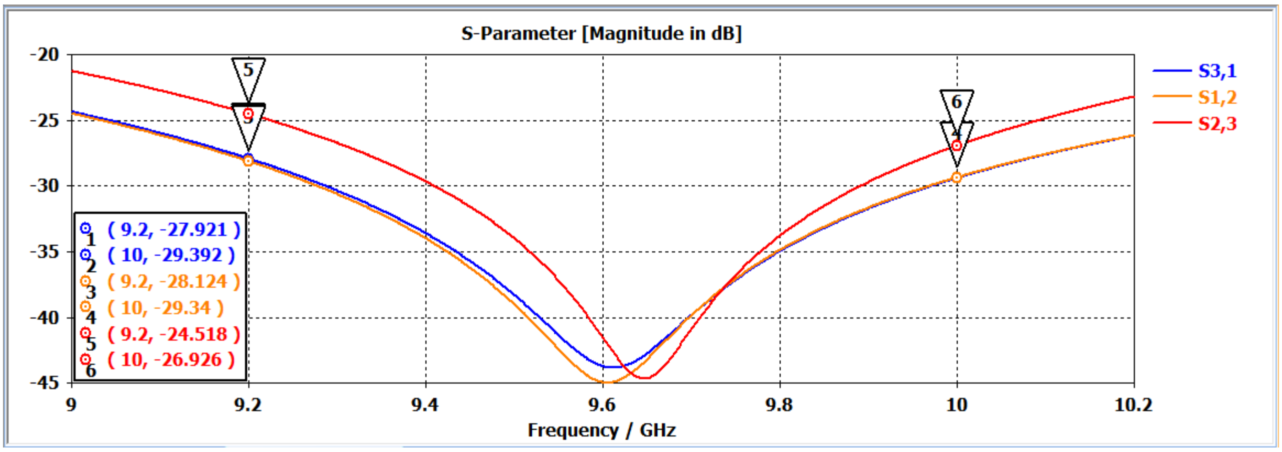


Figure 7.10: Isolation of Prototype 2

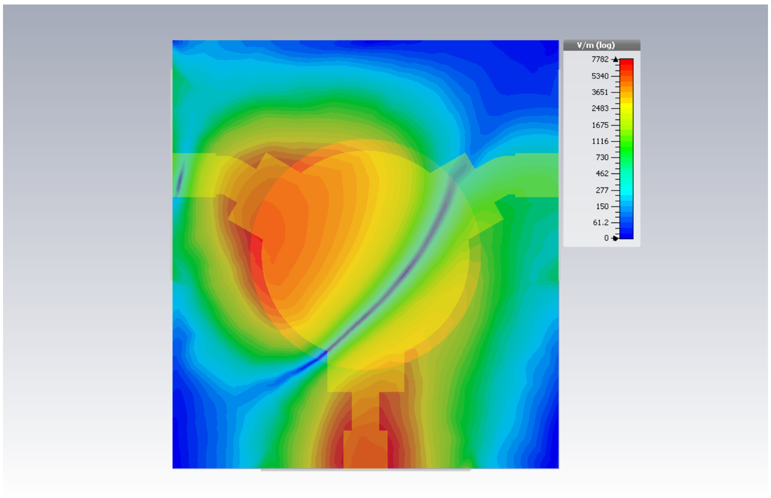


Figure 7.11: EM Field of Prototype 2

7.3.4 Discussion on prototype 2

This prototype is also simulated using Frequency domain solver keeping ferrite gyrotropic . The design is electrically three fold symmetric. Matching is accomplished empirically using parametric sweep. S parameters for prototype 2 are shown in Fig.7.8 to 7.10. Return loss and Isolation achieved are > 26 dB and Insertion loss achieved is < 0.07 dB which are better than estimated. Fig.7.11 shows EM field for signal propagating from port 1 to port 2. Port 3 is isolated and maximum amount of e-field is coupled from port 1 to port 2. This design is advantageous in terms of fabrication and integration with other MIC components than prototype 1. Here, as ferrite is biased by providing hint of 10 Oe, the magnetic field is uniform at each and every point in the ferrite. This exhibits ideal magnetic behaviour. Practically, the magnetic field will not be uniform inside the ferrite. To have an idea of actual magnetic behaviour we are moving forward to magnet circuit design combined with high frequency simulation. This is explained in chapter 8.

Chapter 8

Magntic Circuit Design and Magnetic Simulation

After calculating the radius and length of ferrite from the design equations the simulation is done in CST Studio Suite. The next step in the design process of the circulator is design of magnetic circuit. This magnet provides required field at the center of the ferrite that had been chosen in simulation process to get the required result. The magnet circuit design also has two steps, magnet design and selection of magnet material.

8.1 Magnetic Circuit

Magnetic circuit of a circulator involves many components like shields, pole pieces, shunts and return as shown in Fig.8.1.

- **Pole pieces:** The function of pole pieces is to make the flux density in ferrite more uniform along whole surface. If pole pieces are not used then flux density will remain only at the edges of the ferrite. If this happens then the ferrite will be partially magnetized or sometimes not magnetized which leads to high insertion loss and generally poor circulator performance. There are mainly two tasks of pole pieces: to homogenize the magnetic field and to shape the field. For below resonance operation the diameter of pole pieces must be always greater than of the magnets diameter so that the pole pieces can absorb all the leakage flux at the edge of magnet. The pole pieces must have altitude slightly larger than that of magnet. The best material used for manufacturing of pole pieces is cold rolled steel because of following reasons. First, it is cheaper than pure iron which requires special processing to attain high purity and second it has high saturation flux density. The other advantage of cold rolled steel is that it has smooth finish across the edges which do not require further machining like hot rolled steel.

- **Shunts:** Shunts are used to decrease the magnetic field supplied by the magnet to the ferrite [13]. If it is not possible to demagnetize a magnet, shunts are used.

- **Return:** Return provide closed path for the magnet to complete the magnetic circuit. Without return the magnets will be linked magnetically with each other by long flux paths through air. This is not efficient as this requires increase in size of magnet to supply more field at the center of ferrite material.

- **Shields:** Shields provide magnetic shielding to prevent interaction between the circulator magnetic circuit and external magnetic field. It also improves the circuit efficiency by helping to return magnetic flux.

8.2 Magnet Design

The length and the area of the magnet is given by following equation.

$$L_m = \frac{B_g L_g}{H_m} \tag{8.1}$$

$$A_m = \frac{B_g A_g}{B_m} \tag{8.2}$$

where B_m = Flux density at operating point

H_m = Magnetizing force at operating point

L_g = Air gap length

A_g = Air gap area

B_g = Air gap flux density

A_m = Area of magnet pole

L_m = Length of magnet

The detail derivation is given in Ref. [13]. The magnetic flux density at a distance X from the magnet is found by the following equation.

$$B(X) = \frac{B_r}{2}[\frac{L+X}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}}] \tag{8.3}$$

Where, B_r is flux density of magnet

X is the distance from the surface of the magnet Equation 8.3 is for finding flux density at X distance from the surface of one single cylindrical magnet. But in circulator two magnets with return path is used. Return path is used to complete the magnetic circuit from one magnet to another. If return is not used than the magnetic flux lines passes through the longer distance compared to magnets with return. So larger magnet of high intensity should be used to provide required magnetic field at the center of the ferrite. So magnets with return path are used. Equation for two magnets with air gap between them and connected with each other through return path is derived from equation 8.3. Figure 8.1 shows two magnets with return path and point P placed in between air gap of two magnets. To find flux density at any point P in between magnets is found using equation 8.3 by addition of B(X+P) and B(X-P) where X+P and X-P are substituted instead of X in above equation. Also L is replaced by 2L in equation 8.3 when return is used. From the above equations the values of radius and height of magnet is calculated.

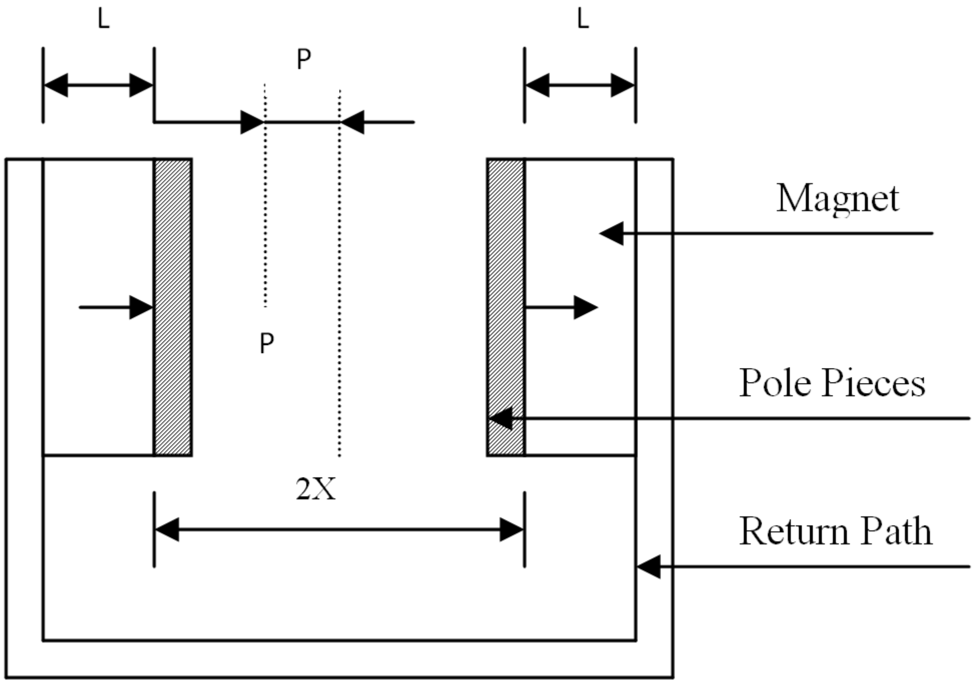


Figure 8.1: Two magnets with return path

8.3 Selection of Magnet

Depending on the value of flux density obtained from above equations the magnet must be selected. The strength of the magnet depends on the flux density of the magnet. The basic criterion of selecting magnet is the energy product of magnet. It is defined as the maximum product of flux density and magnetic intensity taken from material demagnetization curve. It provides the information of size of the magnet required to provide the particular magnetic field. The other important factor is the coercive force (H_c) of the magnet. It is defined as the field required to bring the flux density to zero. Magnets with large coercive force should be selected. If Hc is low then the magnet will require to charge very frequently which is not recommended. Keeping all the values and requirements in mind Samarium- Cobalt (Sm-Co) of type 2 17 manufactured by DEXTER MAGNETIC TEHNOLOGIES is used. It has energy product of 28 MGOe and Br of 11.0 KG while the value of (H_c) is 10.4 KOe. The

BH curve of SmCo S2820 magnet is shown in Fig.8.2.

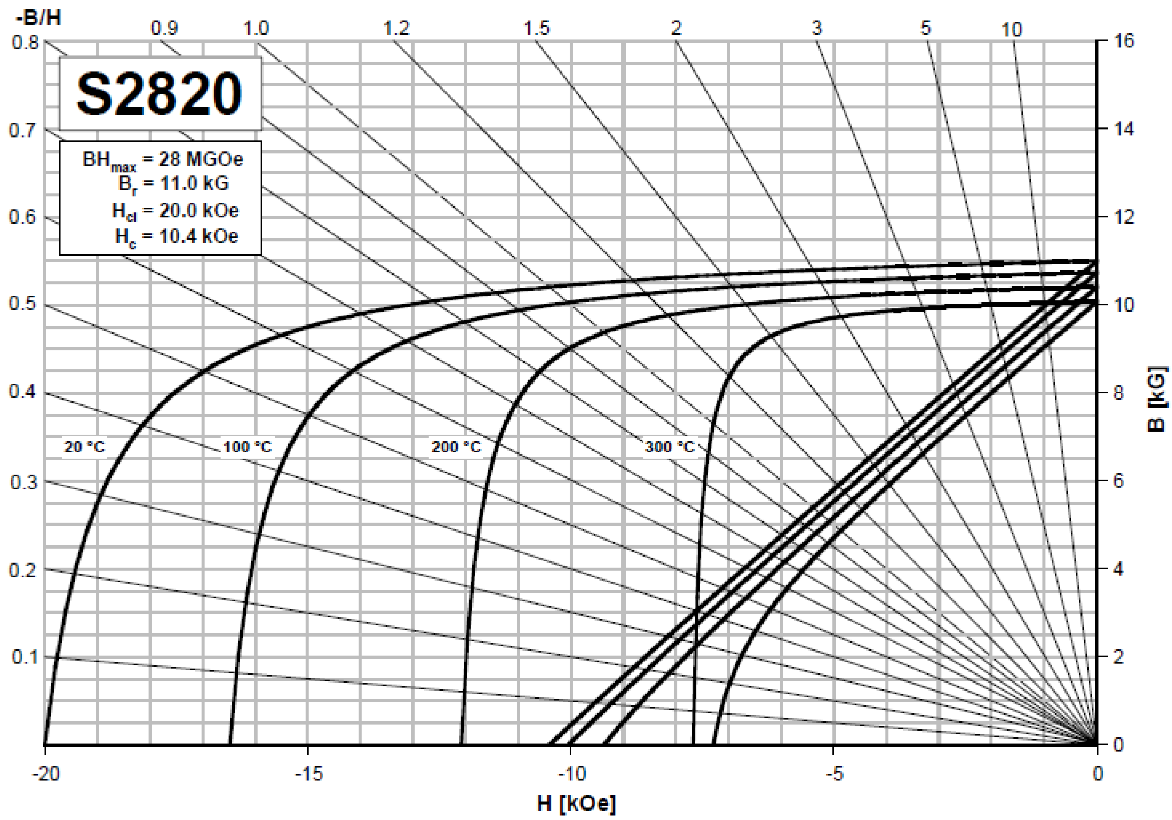


Figure 8.2: B-H Curve of DEXTER MAGNETIC TECHNOLOGIES SmCo S2820 [17]

8.4 Simulation with Magnet

The magnetic simulation is carried out using Magneto static solver of CST Microwave Studio. This solver calculates static H- field inside the ferrite. This exhibits actual magnet behavior as the magnetic field generated by magneto static solver will be non uniform. Field distribution across the ferrite can be seen in Fig.8.3.

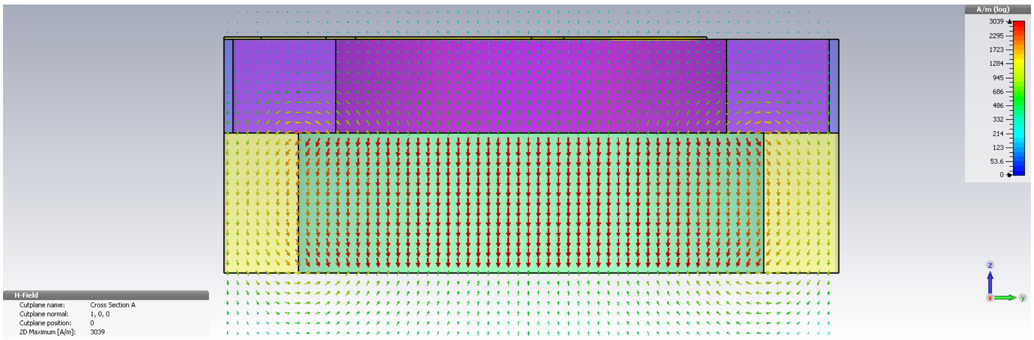


Figure 8.3: Static H field in ferrite

Two types of magnetic circuit is designed for prototype 2. In one design magnet is placed on lower side of ferrite and in second design it is placed on upper side. Other magnetic components are not considered here as they are not required for microstrip configuration.

8.4.1 Prototype 2 with Lower Magnet

Fig.8.4 shows prototype 2 with lower magnet. Static H-field generated by magneto static solver can be observed from Fig.8.3. S parameters for this prototype is shown in Fig.8.5 to Fig.8.7 The total losses will increase due to non uniform magnetic field in ferrite.

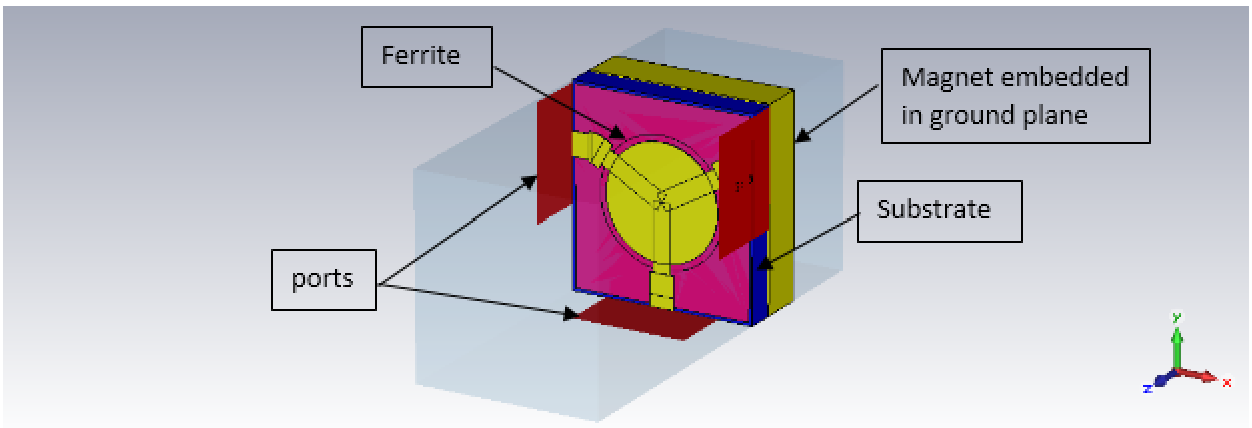


Figure 8.4: Prototype 2 with Lower magnet

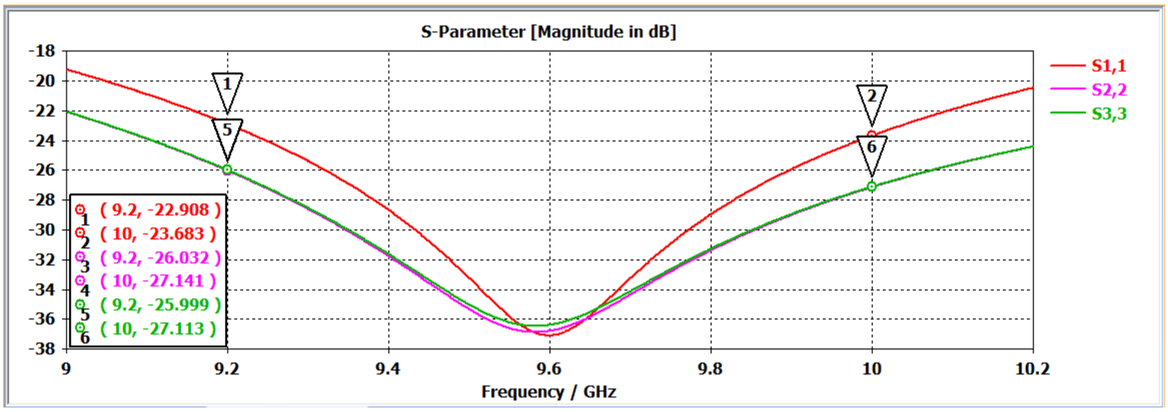


Figure 8.5: Return loss

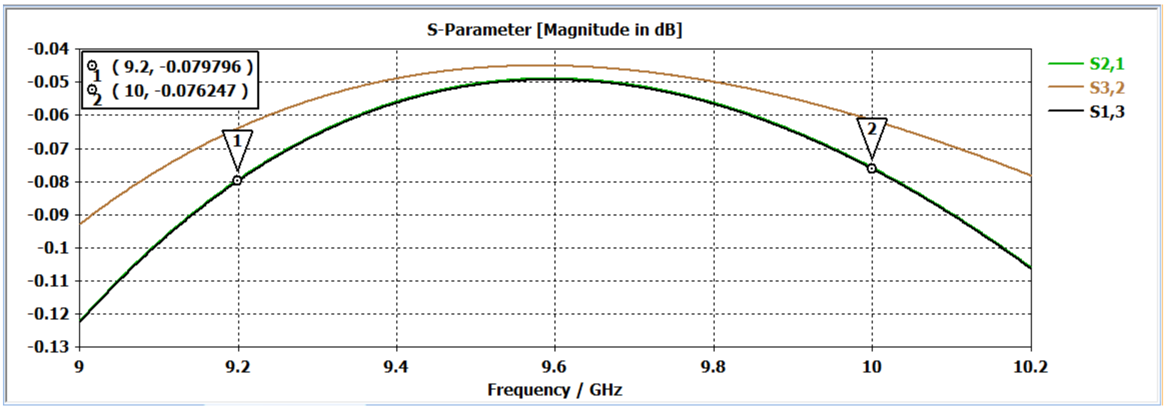


Figure 8.6: Insertion loss

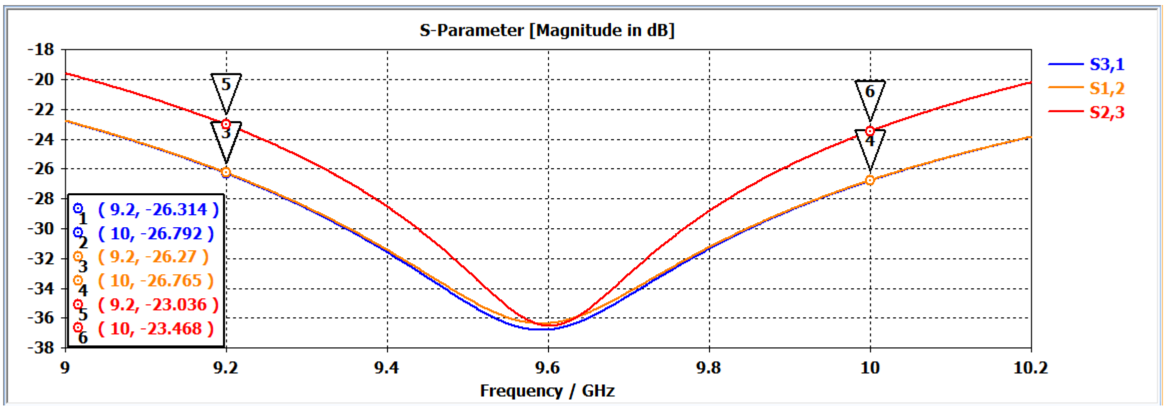


Figure 8.7: Isolation

8.4.2 Prototype 2 with Upper Magnet

Fig.8.8 shows prototype 2 with upper magnet. In lower magnet configuration one can not attach bigger magnet if required as it is embedded in ground plane. To overcome this limitation we go for upper magnet configuration. S parameters for this are shown in Fig.8.9 to Fig.8.11. This is the final design for X band Microstrip Circulator. The required materials are under procurement to further go for fabrication and to validate results. Because of availability of the ferrite material and to prove the concept, X band Waveguide Circulator is fabricated and tested successfully. This is given in next chapter in detail.

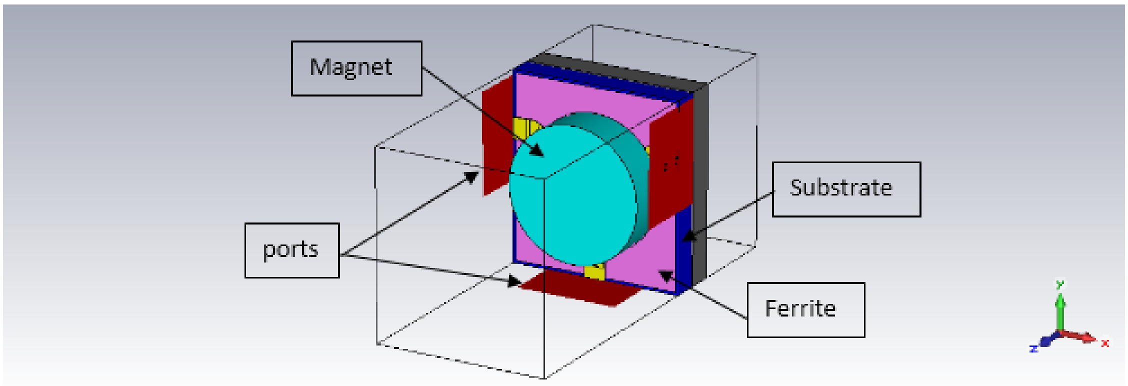


Figure 8.8: Prototype 2 with Upper magnet

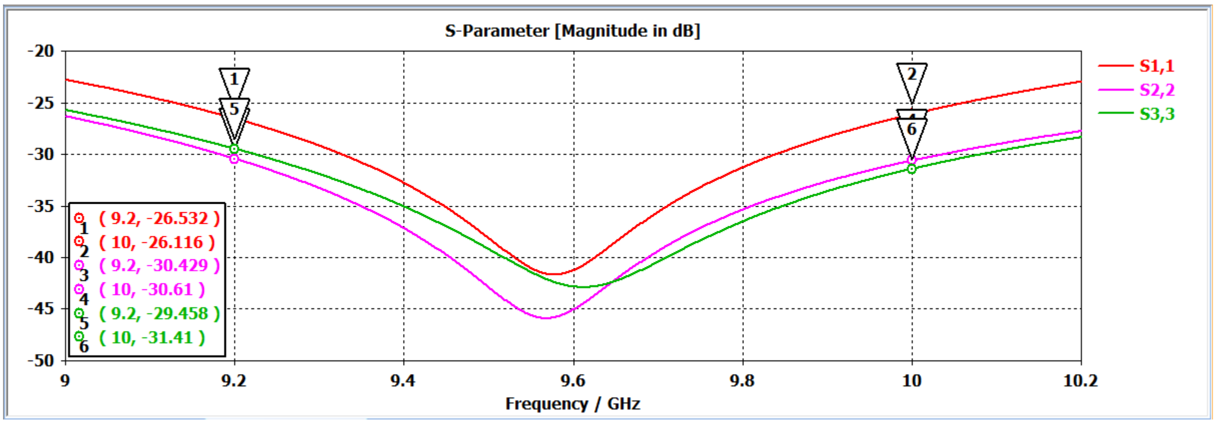


Figure 8.9: Return loss

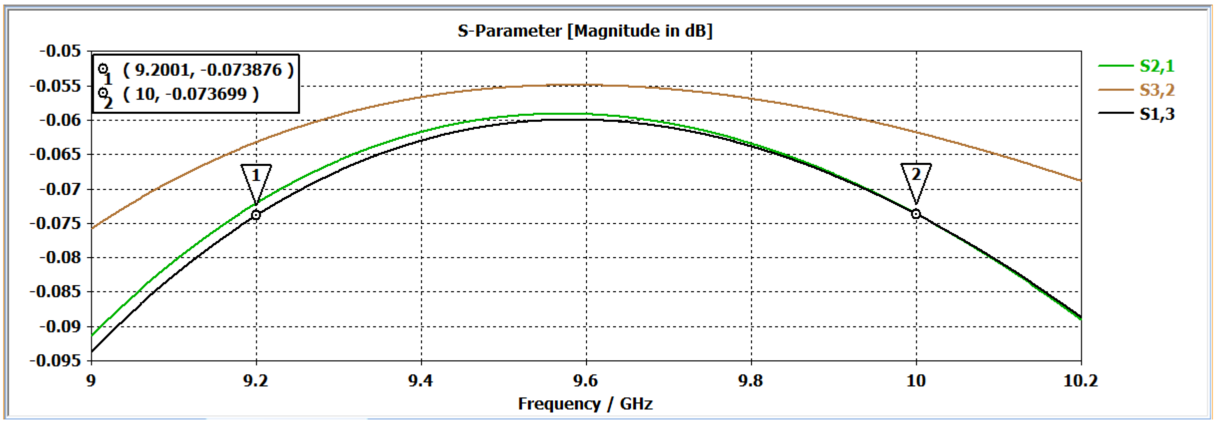


Figure 8.10: Insertion loss

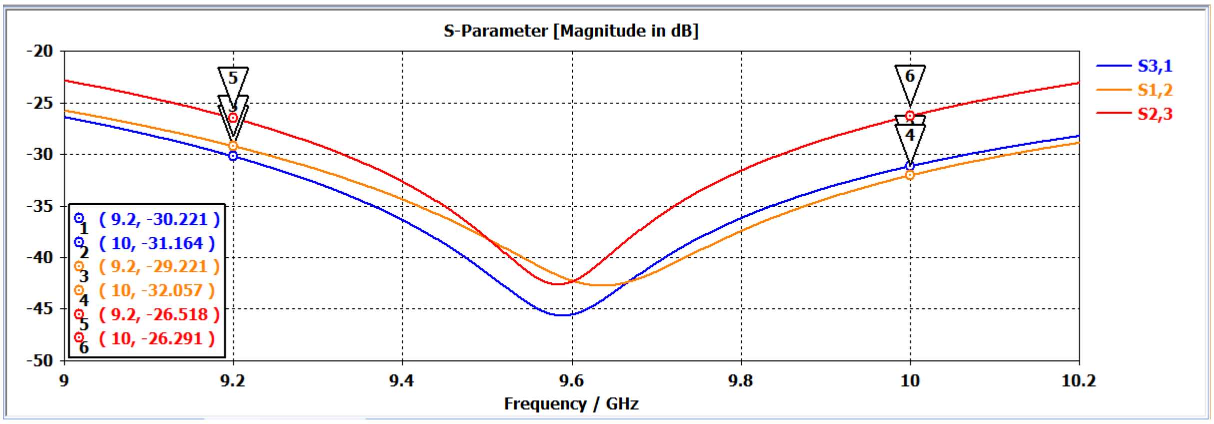


Figure 8.11: Isolation

Discussion

As clearly visible from S parameters of prototype 2 with lower and upper magnets, Results obtained are better with upper magnet configuration. The brief comparison of S parameters at 9.6 GHz is given in Table I.

S Parameters (dB)	**Lower Magnet**	**Upper Magnet**
S11	-37.08	-41.23
S22	-36.78	-45.04
S33	-36.37	-42.82
S21	-0.048	-0.045
S32	-0.045	-0.044
S13	-0.049	-0.049
S31	-36.78	-45.55
S12	-36.34	-42.25
S23	-36.51	-42.33

Table I: S parameters at 9.6 GHZ

It can be seen from Fig.8.5 to 8.11 that as the field was uniform with ideal magnet, return loss and isolation achieved were $>$ 27 dB and insertion loss $<$ 0.072 dB where as in lower magnet configuration return loss and isolation are $>$ 23 dB, insertion loss is $<$ 0.079 dB. In upper magnet configuration return loss and isolation are $>$ 26 dB, insertion loss is $<$ 0.073 dB. Insertion loss of upper magnet is lower than that of lower magnet and is higher than ideal magnet. In all three configuration we get better results than the main objective.

Chapter 9

Fabrication and Testing

9.1 Fabrication

The ferrite used in prototype 1 and prototype 2 is under procurement. Due to unavailability of Y220 and to prove the circulator concept fabrication and testing of X-band waveguide junction circulator is done. X-band waveguide junction circulator is shown in Fig.9.4. A cylindrical ferrite at top and bottom of the junction with metal post on both sides is used. Metal post and iris are used for matching purpose. The ferrite used in this topology is N28 manufactured by TEMEX Ceramics. The major parameters of garnet N28 is given in Table I as below.

Parameters	**Specifications**
Saturation Magnetization ($4\pi M_s$)	2800G
Curie Temperature (T_c)	550°
Resonance Linewidth (ΔH)	200 Oe
Effective Linewidth (ΔH_{eff})	50 Oe
Spin wave Linewidth (ΔH_k)	25 Oe
Dielectric Constant (ε_r)	13
Lande Factor (g_{eff})	2.3
Dielectric Loss tangent ($tan\delta$)	6×10^{-4}
Magnetization Temp. coefficient (α)	$0.8 \times 10^{-3}/°C$

Table I: Parameters of N28 Material

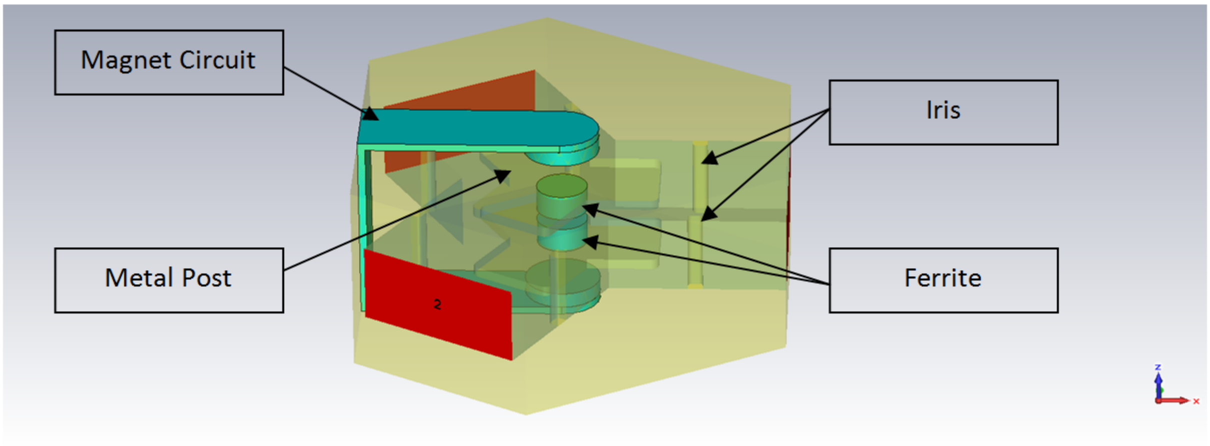


Figure 9.1: X band waveguide junction circulator

9.1.1 Machining of ferrite

The process of machining of very brittle material like ceramics, ferrite, silicon, graphite, etc. generally uses a diamond coated milling, grinding tool actuated by ultrasonic cutter. It uses high frequency electric signal that is converted into oscillating mechanical motion through piezoelectric motors. This high frequency causes the diamond coated cutting tool to expand and contract in pulsating manner at frequency of around 20,000 times per second. At the expansion of the tool the cutting takes place. The material is broken into very small pieces when the diamond collides with the surface of the material. The cutting tool is also simultaneously rotated at speeds between 3,000 and 4,000 rpm in addition to the oscillation. The dimensional accuracy of material is maintained by the rotation of the tool that exposes the full cutting surface. It also serves the dual duty of removing cut particles from the work place. Machining is done wet. Water is used as coolant in all the operations. These tools are specially developed and matched to the material so that the erosion of the diamond is in sync with the cutting requirements. If the tool sheds the grit too quickly, tool life will suffer. If it hangs onto the grit too long, machining efficiency and the surface finish tolerances are negatively impacted. This system is capable of surface finishing of 0.2 micron efficiency.

9.1.2 Assembly

The waveguide housing of circulator is made up of aluminum alloy AL 6061. It is an alloy of aluminum containing major elements like Aluminum and Silicon. The other elements present in this alloy are Iron, Copper, Zinc, Titanium, Manganese, Chromium etc. The composition of AL 6061 is mentioned in table II in detail. The properties of AL6061 are given in Table III.

Elements	**Composition**
Silicon	0.4-0.8
Magnesium	0.8-1.2
Iron	Max 0.7
Copper	0.15-0.40
Zinc	Max 0.25
Titanium	Max 0.15
Manganese	Max 0.25
Chromium	0.04-0.35
Other	0.05

Table II: Proportion of elements in AL 6061

Density	$2.7 g/cm^3$
Melting point	580°C
Thermal conductivity	$173\ W/mK$
Electrical Resistivity	$3.7 - 4 \times 10^{-4}$

Table III: Properties of AL 6061

AL 6061 is used due to its major properties which are mentioned below:

- Medium to high strength
- Good toughness
- Good surface finish
- Excellent corrosion resistance to sea water
- Widely available

In assembly process of circulator, the ferrite is attached to dielectric spacers using Epotek H74 adhesive. This adhesive is also used to attach dielectric spacers to the waveguide housing.

9.2 Testing

Testing of X band waveguide circulator shown in Fig.9.4 is done using Power Network Analyzer (PNA). PNA is a vector network analyzer which measures magnitude as well as phase. The general test setup diagram is given in Fig.9.2. The setup involves PNA, coaxial probes and Device Under Test (DUT). Here DUT is the circulator. To test the fabricated 3-port circulator with a 2 port PNA, the third port of the circulator is terminated using matched termination. The same process was repeated for all the 3 ports sequentially. As the interface of PNA is coaxial and that of circulator is WR90 waveguide, so coaxial to waveguide adapters are used for all the ports of circulator during measurement.This is shown in Fig.9.3.

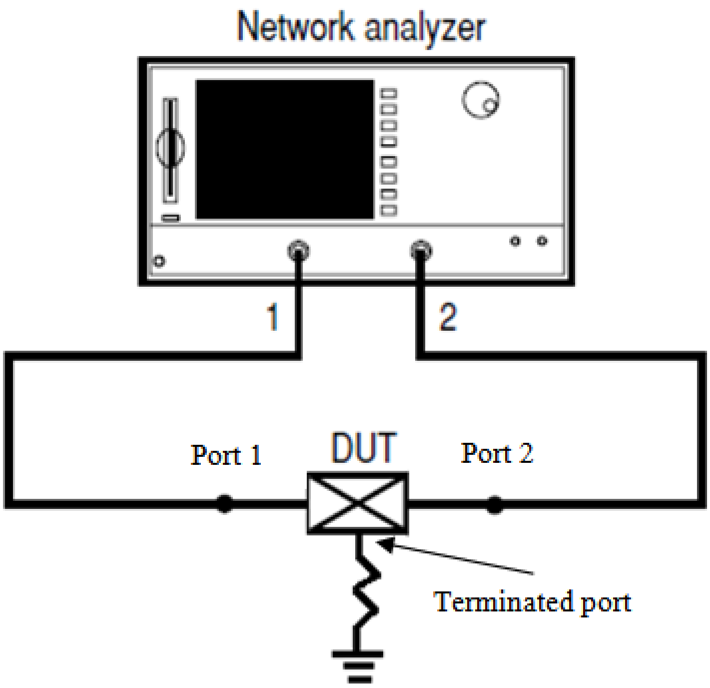


Figure 9.2: Test setup diagram

Figure 9.3: Waveguide to coaxial connector

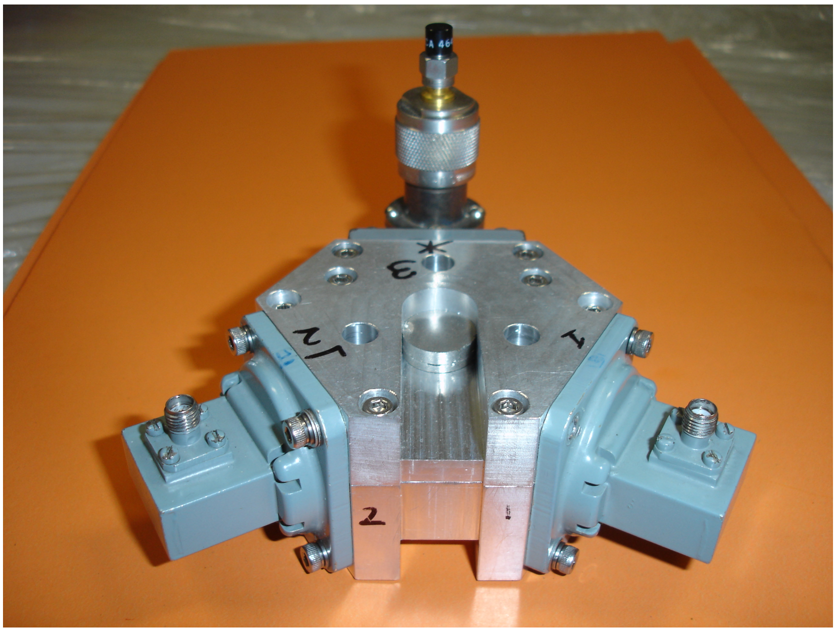


Figure 9.4: Circulator Hardware

9.3 Experimental Results

The S parameters for X band waveguide circulator is measured using PNA. At a time S parameters between two ports are measured with remaining port terminated by matched load. This process is repeated for all three ports till all S parameters are measured. Measured results are shown in Fig.9.5.

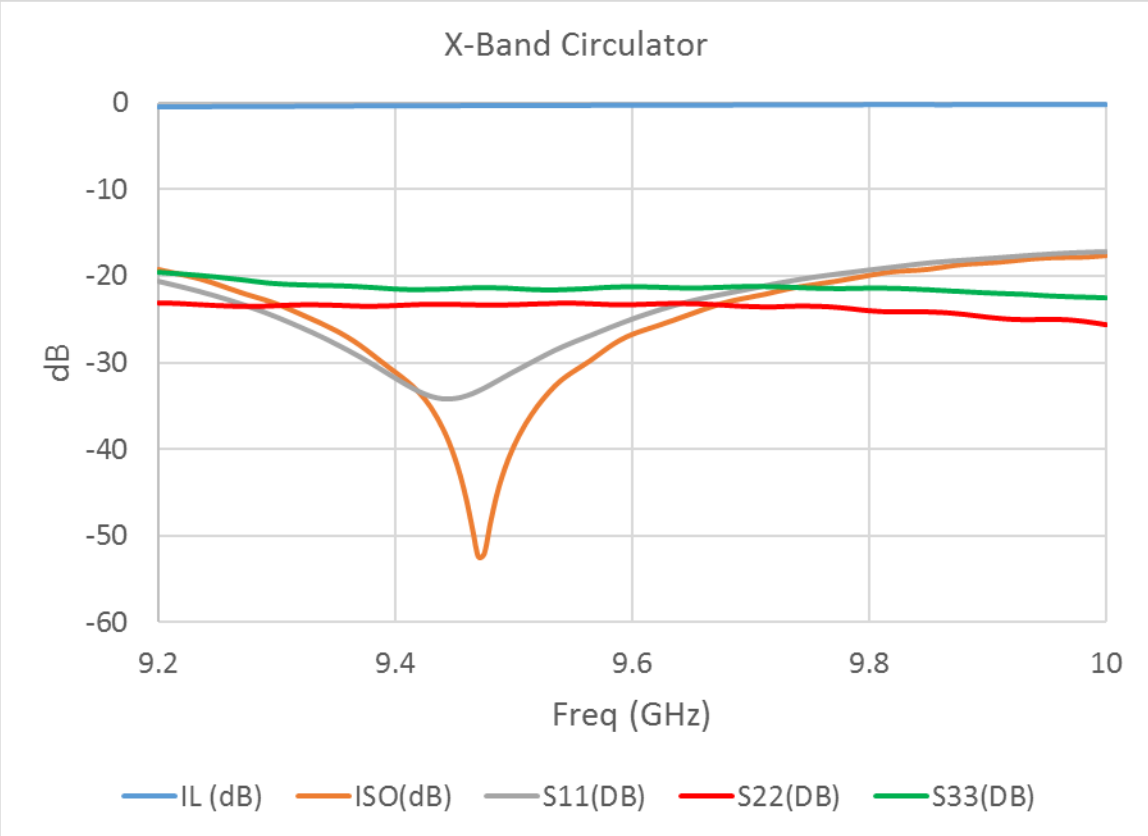


Figure 9.5: Measured S Parameters

9.3.1 Discussion

Circulator exhibits satisfactory performance in the frequency band of 9.2 GHz to 9.9 GHz, i.e. for 700 MHz bandwidth.Performance in the desired frequency band (9.2 to 10 GHz) is satisfactory, viz. 0.4 dB insertion loss and 18 dB isolation (worst case value).

Chapter 10

Conclusion and Future Work

10.1 Conclusion

X Band Microstrip Circulator Prototype is simulated using CST Microwave Studio. Two prototypes are prepared with ideal magnet from which prototype 2 is simulated with two types of magnet designs. Isolation and return loss achieved are > 26 dB and insertion loss achieved is < 0.073 dB. 30 dB Isolation Bandwidth achieved is 805 MHZ which covers entire band from 9.2 to 10 GHz. Better results are achieved with both types of magnet designs as shown in Table I of section 8.4.2 which are better than the given specification in 5.5 Table III.

10.2 Future Scope

In future, Hardware fabrication and testing of X band microstrip circulator, prototype 2 can be carried out to validate the simulated results. This work can be extended to four port junction circulator as well.

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