Design of a Stripline based Isolator and Circulator at Ultra High Frequency band

A Thesis Submitted in Fulfilment of the Requirement for the Award of the Degree of

MASTER OF ENGINEERING

in Electronics and Communication Engineering

Submitted by

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DECLARATION

I, Manpreet hereby declare that the work presented in this thesis entitled "**Design of a Strip-line based Isolator and Circulator at Ultra High Frequency Band**" in fulfilment of the requirement for the award of degree of Master of Engineering (ECE) submitted at Electronics and Communication Engineering Department, Thapar Institute of Engineering and Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of **Dr. Rana Pratap Yadav**, Assistant Professor, ECED and **Dr. R. S. Kaler**, Senior Professor and HOD, EIED from July 2017 to July 2018. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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ABSTRACT

Ferrite circulator and isolator are being used immensely in the microwave industry and are being exploited extensively because of their unmatched properties and capabilities. In simple terms, a circulator is a ferrite loaded symmetrical junction consisting of a transmission line for signal transfer for one port to another. This transmission line could be a strip-line or even a micro-strip line depending upon the requirement. The circulator has a special property of transferring power from the incident port to the immediate port and isolating all the other ports. The non-reciprocal characteristics of ferrite under the influence of magnetic bias fields makes this action possible. An isolator can be thought of as the terminated equivalent of circulator. Theoretically, the circulator and the isolator can have any number of ports but practically three and four port circulators are the most popular. This thesis presents the method for designing a strip-line circulator and an isolator. The main modelling factors considered are the radius, the type of the magnetic field, the biasing configurations and the value of the dielectric constant. The radius of the ferrite disk and the biasing field required for the working are calculated and dependency of the various factors on frequency and other quantities involved is also stated.

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LIST OF ABBREVIATIONS

RF	Radio Frequency
EM	Electromagnetic
TEM	Transverse Electromagnetic Energy
TE	Transverse Electric
TM	Transverse Magnetic
DC	Direct Current
YIG	Yttrium Iron Garnet
CW	Clockwise
CCW	Counter Clockwise
VSWR	Voltage Standing Wave Ratio
dB	decibel
CMOS	Complementary Metal-Oxide-Semiconductor
UHF	Ultra High Frequency
SVM	Support Vector Machine
RMS	Root Mean Square
HDPE	High Density Polyethylene
FCL	Ferrite Coupled Line
HFSS	High Frequency Structure Simulator
IC	Integrated Circuit

CHAPTER 1
INTRODUCTION

The RF and microwave devices requires the circulators and isolators for their efficient and uninterrupted working. Both of these are the passive devices which finds their applications in microwave equipment due to their unmatched properties. The improvement in the stability, performance and reliability has been observed because of these devices. These microwave junction circulator and isolator has been playing an important role in various wireless communication systems in protecting and rooting the signals since its advent and its application can be found in commercial and military sides such as mobile phones, radar systems and so on. A circulator when terminated starts working as an isolator. An isolator can also be considered as a switching device which is used to disconnect some portion of a circuit and can have 2-port, 3-port, and 4-port depending upon the requirement.

The circulators and the isolators are also known as non-reciprocal devices which implies that their behaviour changes with the change in the direction. The main reason of this non-reciprocal behaviour of these passive devices are the ferrites. The ferrites has got properties due to which the performance of the circulator and isolator gets highly influenced. These properties will be discussed in this report. The details about the relation between magnetic field and the operation of Y-junction circulator and isolator will be dealt with in the chapters that follow. This chapter gives a brief introduction about the isolator, its design, and other related components. Strip-line transmission line is used for transmitting the signal from one port to other. This line has been preferred because of its some noticeable advantages which have been described further in this chapter.

1.1 TRANSMISSION LINES

The development of transmission lines have been considered as a great achievement in microwave engineering as these are able to provide low-loss transmission of power at higher frequencies. Earlier systems used waveguides, and coaxial lines for the transmission which provided with a lot of advantages but also had some disadvantages which cannot be neglected. Waveguides for example, has high power handling capacity but at low frequencies, they proved to be bulky as well as expensive. On the other hand, transmission lines proved to be a good alternate in the form of slot lines, micro-strip, and strip-line and so on. These lines proved to be low in cost, cheaper and can be easily united with active devices like diodes [1]. A basic diagram of a transmission line connecting a source and a load is shown below. In this a sinusoidal voltage source with some impedance Z_S, is connected with load Z_L which in most of the cases is an antenna. Transmission line of length L is used to connect this source and the load.

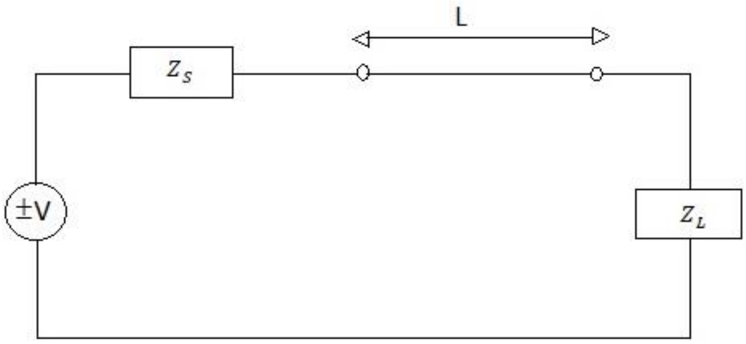

Figure 1.1 Transmission Line

Transmission lines basically transfer EM energy, or in other words it connects a source (transmitter or an electric generator) to a load (antenna). These lines channels the gap between basic circuit theory and field analysis and thus, plays a significant role in analysing the microwave circuits. Transmission line can be taken as a pair of electrical conductors which carries an electrical signal. These conductors have got some inductance per unit length calculated by using the shape and size of the line. Also they have some capacitance per unit length determined from dielectric constant of the insulation [2]. Transmission lines consisting of 2 or more than two conductors supports TEM waves, and lines which consists of one single conductor supports TE or TM waves [1]. Some common types of transmission lines being used are:

- Co-axial lines
- Strip-line
- Micro-strip lines
- Slot lines
- Coplanar lines

The uses of the transmission lines includes connecting the radio transmitters and the receivers with the antenna, for transferring the cable television signals or, routing a call, making computer network connections. The strip-line have been used in the thesis for the design as the metal ground planes of the strip-line provides RF shielding although it lets the magneto static bias field inside ferrite core.

1.1.1 Strip-lines

In 1950s, Robert M. Barrett of Air Force Cambridge Research Centre invented strip-line. It is a transverse electromagnetic (TEM) planar transmission line imparting itself to microwave integrated circuitry, and photolithographic fabrication. Strip-line provides with some noteworthy advantages for the manufacturing of microwave systems. The losses in the strip-line can be compared with coaxial lines and waveguides offering some important other features such as inexpensive to fabricate, light and small. It has proved to be valuable in the complex microwave circuits where there is a need to build numerous components into a compact space [3]. The construction of a strip-line involves the etching of the centre conductor on a ground substrate having thickness H/2. After this it is covered with another ground substrate [1]. Therefore, there are variations in the strip-line geometry and hence, the strip-line could be:

- Symmetric strip-line: the strip-line having the same dielectric substrate thickness above and below the centre conductor are the symmetric strip-line.
- Asymmetric strip-line: the thickness of dielectric substrate differ from each other for an asymmetric strip-line.
- Homogeneous strip-line: same dielectric constants are used above and below the conductor.
- Inhomogeneous strip-line: when different dielectrics are used then it is an inhomogeneous strip-line.

Strip-line supports TEM waves as it consists of two conductors and the dielectric used is the same i.e. homogeneous dielectric have been used. Figure below shows the propagation of electric and magnetic field in a strip-line.

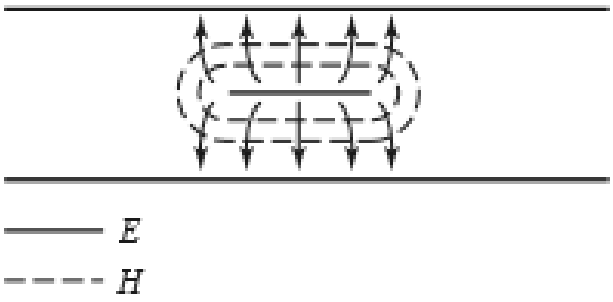

Figure 1.2 Field Line Configuration in Strip-line [1]

As observed from the diagram, homogeneous dielectric region contains all the fields or in other words, the field configuration remains inside the strip-line instead of being exposed outside. Instinctively, a strip-line can also be thought of as a "flattened out" coax as both are having a centre conductor which is enclosed completely by an outer conductor and a dielectric material is used to fill it. Also just like a coaxial cable, strip-line is non-dispersive, and does not have any cut off frequency. It consists of a thin conducting plate having a width W which is inserted between the two ground plates which are separated by H from each other. Any dielectric material can be used to fill this separation. In order to minimize the losses, air is used here. This dielectric behaves as an insulating material.

For a strip-line, characteristic impedance plays an important role. Along with this, width of the strip-line, the substrate thickness and also relative permittivity of dielectric are required for impedance calculation. An approximate equation for characteristic impedance is given as:

$$Z_0=\frac{60}{\sqrt{\varepsilon_r}}\ln\left[\frac{4\mathrm{H}}{0.67\pi\mathrm{W}\left(0.8+\frac{\mathrm{t}}{\mathrm{W}}\right)}\right] \tag{1.1}$$

Where, H, W,ε_r t can be defined from the following figure.

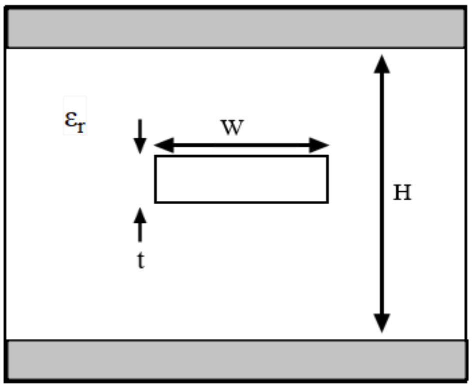

Figure 1.3 Strip-line Configuration

1.1.2 Advantages of Strip-line

- Strip-line is non-dispersive in nature.
- Strip-line has no lower cut off frequency
- Strip-line is non-dispersive in nature.
- Strip-line provides good isolation
- These transmission lines can be used to route RF signal

- Low attenuation loss

1.1.3 Disadvantages of Strip-line

- It is difficult to fabricate a strip-line and also an expensive process.
- The strip widths are narrow for a particular impedance because of th second ground plane.
- Tuning is complex.

Strip-line now-a-days finds its applications at various places some of which includes the transition from coaxial line to strip-line, in filters, directional couplers, microwave receivers, circulators and isolators.

1.2 FERRITE

Different materials behave differently when exposed to magnetic field. The behaviour of these materials is based upon the way in which electrons are interacting with the other electrons. Based upon this behaviour, the materials can be classified as:

- Diamagnetic materials, have got no unpaired electrons. All materials however shows some diamagnetic properties.
- Paramagnetic materials, has partially filler orbitals containing unpaired electrons and are known as non-magnetic because of their weak attractive force.
- Ferromagnetic materials, acquires unpaired electrons and maintains their magnetism even after the removal of external field.
- Antiferromagnetic materials, has got zero net moment because of the equal but opposite sub-lattice moments.
- Ferrimagnetic materials, behaves similar to ferromagnetic behaviour but has got lower value of saturation magnetization.

Out of these ferrimagnetic materials, or commonly known as ferrite is used in microwave devices as these devices are highly resistive (non-conductive), has low dielectric loss and reasonable dielectric constant. Ferrites are basically the magnetic ceramic materials as compared to the magnetic metals which are conductors, hence ferrites find their applications in microwave devices. Circulators using ferrites are preferred in radar systems where they behave as duplexers and can isolate the transmitters from the receivers [5]. The examples of these includes YIG, resources which are composed of iron oxides and other elements like aluminium, nickel and manganese. Ferrites have high resistivity and anisotropy at microwave frequencies. This anisotropy is responsible for the non-reciprocal behaviour of the components. When a DC bias field or internal field is passed through, the magnetic anisotropy can be induced in the ferrimagnetic compounds. The ferrites consists of magnetic dipoles which get aligned by the field and produces a non-zero magnetic dipole moment. A circularly polarized microwave signal whose direction of polarization is that of this precedence interacts sturdily with dipole moments, whereas the field which is polarized oppositely interacts less strongly as compared to that. The sense of polarization for a given direction of rotation, can change in accordance with direction of the propagation. Thus, the ferrite gets magnetically biased differently in different directions and the microwave signal then propagates through it. This effect is used in the fabrication of directional devices like isolators, gyrators and circulators. Some other advantageous characteristics of these ferrimagnetic materials includes an interaction with the applied signal which is controlled by just the simple adjustment of the strength of the bias field which has proved to be useful in a lot of control devices for example switches, phase shifters, and filters.

In general, the magnetic dipole moments are responsible for the magnetic behaviour of a material which occurs because of the electron spin. The magnetic dipole moment of an electron according to the quantum mechanical, is given by

$$m=\frac{q\hbar}{2m_e}=9.27\times10^{-24}\,\text{A-m}^2 \qquad (1.2)$$

Here,

$\hbar$ is Planck's constant divided by 2π,

q is the electron charge and,

m_e is the mass of the electron.

There is a growth in the effective current loop due to the electron in orbit and therefore an additional magnetic moment, but in comparison to the magnetic moment due to spin, this effect is generally insignificant. For measuring the relative contributions of orbital moment and spin moment to the total magnetic moment, Land'e g factor is used. The value of this factor is equal to one when the orbital motion is causing the moment, and g = 2 for the spin moment. Most of the ferrite microwave materials have got this g factor lying in between 1.98–2.01, hence g = 2 can be considered as a great deal. In solids, net magnetic moment is negligible because electron spin take place in pairs with opposite signs. Whereas, in the magnetic materials, a vast section of unpaired electron spins are present that is, left-hand spins can be more than the right-hand spins, or vice versa, however the orientation is in random direction because of which the overall magnetic moment is again small. In order to align the dipole moments in the same direction an external magnetic field is applied, because of which a large magnetic moment is produced. Due to the presence of exchange forces, the neighbouring electron spins remains aligned even once the external field is pulled off and the material is then believed to be permanently magnetized. Figure 1.4 [1] shows a spinning electron. As it could be seen that direction of a spin angular momentum of an electron is in reverse direction to that of the spin magnetic dipole moment.

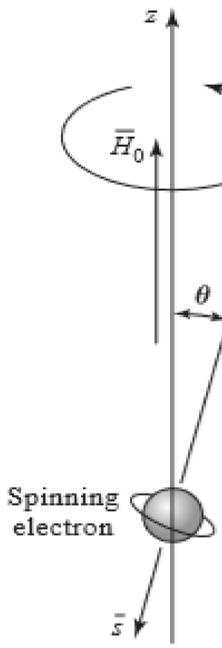

Figure 1.4 Spinning Electron [1]

Ferrites falls in the category of those magnetic material which has very high ohmic resistance. Because of this, they do not have any eddy currents and can be considered for their working at RF and microwave frequencies [6]. The working of the ferrites depends upon some factors such as the bias field H_0, and saturation magnetization M_s. The ferrite properties changes when they are subjected to strong fields from those displayed when weaker field is applied. The alterations can be seen as follows:

- If the ferrite absorbs large amount of power then that results in the temperature variations that can vary the material properties (especially saturation magnetization), ultimately of microwave devices.
- Ferrites when exposed to a great amount of peak-power levels exhibits non-linear properties. This non-linearity results in the decline in absorption at the resonance, and in some circumstances, may also lead in increase of absorption away from the resonance.

The non-linear effects arising at these levels, very often limits the performance characteristics of ferrite devices. At the same time, these effects may help in achieving certain aims, like for example in restraining the power provided to a sensitive element (for example an amplifier or a crystal detector) or to amplify a weak signal [7]. Ferrites has got some anisotropic permeability tensor. Whenever a ferrite is totally magnetized in a static external bias magnetic field alongside the z-axis, the permeability tensor is defined as:

$$\hat{\mu} = \begin{bmatrix} \mu & -i\kappa & 0 \\ i\kappa & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1.3)$$

$$\mu=1+\frac{\omega_m(\omega_0+i\alpha\omega)}{[(\omega_0+i\alpha\omega)^2-\omega^2]} \quad (1.4)$$

$$\kappa=\frac{\omega_m\omega}{[(\omega_0+i\alpha\omega)^2-\omega^2]} \quad (1.5)$$

$\omega_0=\gamma H_0$ represents the resonance frequency,

$\omega_m=\gamma 4\pi M_s$ implies the characteristic frequency which can be calculated from external bias magnetic field H_0 and magnetic saturation $4\pi M_s$,

γ indicates the gyromagnetic ratio,

α signifies the damping coefficient [8].

The increase in the strength of the bias field H_0, aligns some of the magnetic dipole moments along with H_0 till all of them gets aligned, also the magnetization extents an upper limit. The material is then magnetically saturated. Ms is known as the physical property of a ferrite ranging typically from 300–5000 G. Below saturation, ferrites prove to be very lossy at microwave frequencies. Because of this ferrites are functioned in the saturated state. The saturation magnetization depends upon temperature, decreasing with the increasing temperature. It could be understood by noticing that with the increase in the temperature, the vibrational energy of an atom increases thus, making it difficult in aligning all the magnetic dipoles. At high temperatures, the energy supplied by internal magnetic field is less than the thermal energy hence, zero magnetization is obtained. This temperature is the Curie temperature.

Microwave propagation can be controlled by static magnetic field in the microwave ferrite devices. These devices could be either reciprocal or non-reciprocal, or linear or non-linear, and the advancement of these demands a detailed awareness of magnetic materials, microwave circuit and also the EM theory. In contrast to a magnetic metal, ferrite is a magnetic dielectric which permits an EM wave to enter through it, thus letting an interface between the wave and magnetization within itself. This behaviour of all of the microwave ferrite devices can be elucidated from the following effects:

- Faraday Rotation- in this, there is the rotation of the plane of polarization of a transverse electromagnetic wave since the wave propagates through a ferrite in the same direction as of the magnetization,
- Ferromagnetic resonance- is an effect in which there is a strong absorption that occurs when a magnetic field which is elliptically polarized is perpendicular to the magnetization direction,
- Field displacement- it is type of the displacement of the field which results in more or less field in the ferrite region. This displacement is transverse to the direction of propagation,
- Nonlinear effects- these effects can be observed at high power levels in which amplification and frequency doubling are probable and minor losses may take place,
- Spin waves- these are the short-wavelength waves of magnetization which have the ability to propagate at any angle in magnetization direction. When the wavelength of this wave can be compared to the dimensions of the ferrite sample then it is known as a magneto static wave [9].

1.3 S-PARAMETERS

In order to predict that how a circuit works, the circuit behaviour has to be represented in the form of mathematical expressions or equations. Linearity being the first quantity to be measured. The circuit consisting of linear elements, can be characterised by a set of linear equations linking to its independent and dependent quantities, like currents and voltages. "S" in the S-parameters indicates scattering. Before the 1950's, the network parameters like the Y- and Z-parameters or also known as admittance and impedance matrices were considered as the primary method for describing the circuit performance. Where these impedance and admittance matrices relates the port voltages and currents, the scattering matrix relates the voltage wave incident on the ports to the wave reflected from the ports. At higher frequencies, it becomes difficult to relate the conception of voltages and currents to network performance - especially in the networks which uses transmission lines or waveguides. Whereas, the S-parameters are associated with power waves and are capable of avoiding a lot of these type of issues.

The scattering matrix can be considered as a mathematical model which is used to measure the propagation of RF energy through a multi-port network. For a RF signal incident at one port, a part of it gets reflected, whereas some part of it arrives into the incident port ultimately exiting at (or scattering to) some or all the other ports in which it either gets amplified or gets attenuated. And the left over incident power gets disappeared as heat or as the electromagnetic radiation.

S-parameters are basically the complex numbers, which have both the real and imaginary parts or it can also be thought of as having magnitude and phase parts, as both of these for an incident signal gets effected by the network. But most of the times, the magnitude of the signal is only considered. S-parameters are mostly definite for a particular frequency and also the system impedance, and for any non-ideal network, varies as a function of frequency.

S-parameters are demonstrated in a matrix format, where the number of rows and columns equals the number of ports in a network. For the parameter Sij the j subscript represents the input port and the "i" subscript represents the output port or in other words, the 1st number in the subscript is the countering port, whereas the second is the incident port. Parameters alongside the diagonal are mentioned as reflection coefficients since they represents to what is happening at a single port.

Consider the 3-port network shown, with V representing the amplitude of the incident voltage wave that is incident on port n and v being the amplitude of the reflected one from port n. The scattering matrix, defined as the relation between the incident and the reflected wave can be represented as:

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{1.6}$$

$$[v]=[S][V] \tag{1.7}$$

To determine any specific element of the scattering matrix,

$$S_{ij}=\frac{v_i}{V_j} \tag{1.8}$$

This means S_{ij} can be found by the input port j with an incident wave and by determining the reflected wave amplitude v. S_{ii} is referred to as reflection coefficient which looks into the port i with all the other ports being terminated for the matched loads, and S_{ij} is the transmission coefficient from the port j to port i again with all the other ports being terminated for matched loads.

The following information is required for stating a set of S-parameters:

- Frequency
- Characteristic impedance which is often 50 Ω
- Distribution of port numbers
- Circumstances that can disturb the network, for example temperature, voltage, or current, wherever appropriate.

A network could follow the following properties:

- Reciprocity

  A network follows reciprocity if the network is passive and consists of only the reciprocal materials which can have an impact on the transmitted signal, like cables, attenuators. For a reciprocal network following condition has to be satisfied,

  $$S_{mn}=S_{nm} \tag{1.9}$$

  Or, the scattering matrix is its transpose. The networks including non-reciprocal materials such as the systems having magnetically biased ferrite in the transmission medium will be non-reciprocal. Examples of these includes isolator, amplifier and a circulator. A 3-port network cannot be reciprocal, perfectly matched and loss-free simultaneously.

- Symmetric

  When a network is reciprocal i.e. $S_{21}=S_{12}$ or the input and the output reflection coefficients are equal i.e. $S_{11}=S_{22}$, then the network is symmetric.

- Lossless

  A network is said to be lossless and passive if its scattering matrix is unitary. This implies that the matrix product of transpose of conjugate of the matrix and the matrix equals the unit matrix.

  Mathematically,

  $$S^{\dagger}S = 1 \tag{1.10}$$

Where, $x^\dagger = (x^*)^T$ is the conjugate transpose of x.

A key point about scattering parameters is that when all the other ports are matched then only, reflection coefficient going inside the port n is equivalent to S_{nn}. Likewise, the transmission coefficient from port m to n is equivalent to S_{mn} when all the ports are matched. The S- parameters are the properties of the network itself where the assumption is made that the network is linear, and requires the matching of all the ports. If the excitations of a network are varied that doesn't affects its scattering parameters, yet at a given port can vary the reflection coefficient, or even the transmission coefficient in between the ports.

1.3.1 Applications of S-Parameter

S-parameters are used for understanding the performance of a unit under the practical operating conditions by evaluating the outputs from various arms with some terminations. For example in a balanced mixer. This matrix finds its application in a waveguide Magic Tee or also known as side-outlet tee. This device comprises of a combination of an E-plane and H-plane waveguide tee and S-parameters make the evaluation easy. The properties of this device are represented by a 4×4 scattering matrix [10]. S-matrix plays an important role in antenna designing and also other devices such as circulator and an isolator.

1.4 ISOLATOR

Isolator is one of the utmost useful microwave ferrite components and a recent topic of interest exhibiting unidirectional transmission features. Scattering matrix of a two-port isolator has the following arrangement:

$$[S]=\begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \tag{1.11}$$

Which indicates that both of the ports are matched, and the transmission follows only from port 1 to the port 2. The scattering matrix of an isolator is not unitary which indicates that the isolator might be lossy. Also [S] is not symmetric, as it is a non-reciprocal device. An isolator can has 2-port, 3-port, and 4-port. This thesis concentrates on a 3-port isolator. A 3-port circulator and a 3-port isolator are shown below in the figure.

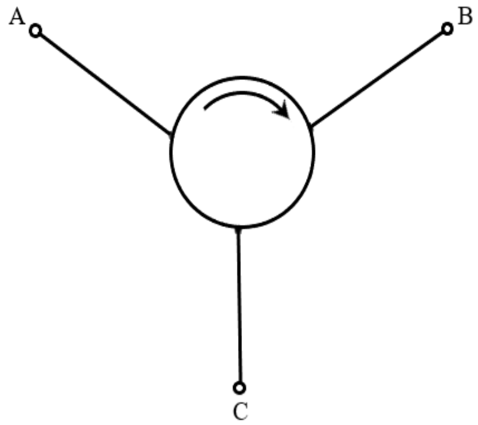

Figure 1.5 Circulator

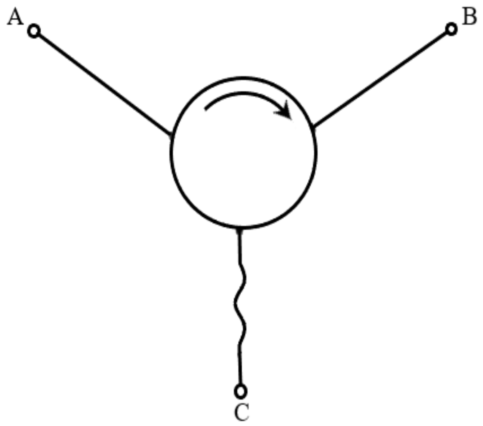

Figure 1.6 Isolator

An isolator is a non-reciprocal, passive device which has the property that energy can flow only in one direction. The Y-circulator has been developed practically and has been explained on a philosophical system basis in terms of the scattering matrix behaviour [11]. Qualitative descriptions advise that the device necessitates non-reciprocal field displacement within the ferrite. All the isolators are the correspondent of the terminated circulators. The termination can be done by using an absorber such as a resistor of value 50Ω. This leads to the matched condition required for its working. The working of an isolator can be thought of as similar to that of a circulator except that one port is isolated and hence the power gets absorbed. The isolator can use strip-line or a micro-strip transmission line depending on the requirement. This thesis focuses on a strip-line Y-junction isolator.

Shown below are the two different ways in which energy can flow in an isolator. It could be either in a clockwise or anti clockwise direction. Figure 1.8 shown below illustrates s a clockwise terminated isolator.

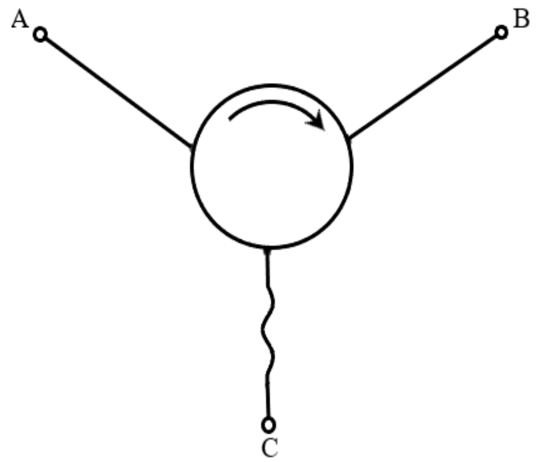

Figure 1.7 Terminated CW Isolator

The isolator operating in counter clockwise direction is shown below.

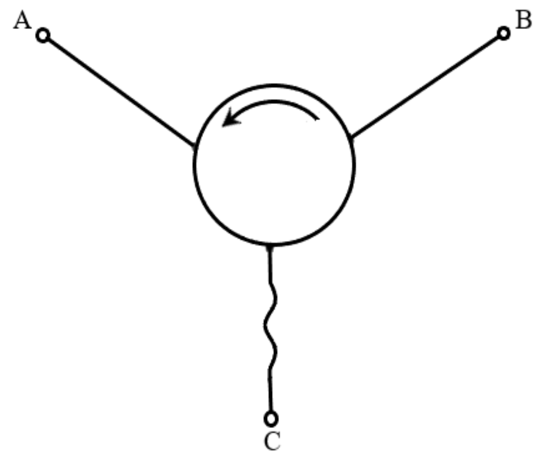

Figure 1.8 Terminated CCW Isolator

Isolator is a useful device being used for isolating the components and therefore the reflections does not contribute to gain ripple, lead to instabilities or unwanted oscillations. A circulator is a ferrite device which can have any number of ports. A three-port Y junction circulator is a device permitting the flow of microwave energy in one direction only that is from port 1 to port 2, then from port 2 to port 3 and port 3 to port 1 and the left over port is known as the decoupled port. An isolator has this third port isolated and hence any reflections from the output port does not affect the input port, as the isolator is primarily designed to save the input source such as generator from the reflections coming from the output source. These reflections can be thought of as a bad VSWR.

1.4.1 Types of Isolator

There are mainly 3 types of isolator used which are discussed below:

1.4.1.1 Resonance Isolator

The isolator operating near gyromagnetic resonance are known as resonance isolator. There is a ferrite slab or a strip fixed at a definite point in a waveguide in these isolators. A magnetized ferrite slab which is positioned in the plane of circularly polarized magnetic field displays different phase shifts and attenuations for both the directions of propagating waves. Resonance isolators operating on this phenomenon employs really thin ferrite slabs so that the obvious resonance characteristic of the ferrite effective permeability for one direction of propagation could be exploited [12]. This isolator geometry provides with the advantage that it is easy to bias the full-height slab by using a C-shaped permanent magnet externally, without any demagnetization factor. But, it has got some drawbacks also as listed below:

- The internal magnetic field cannot be polarized circularly accurately because of which the attainment of zero forward attenuation is not possible.
- The isolator has got relatively narrow bandwidth, as represented by the linewidth, ΔH, of the ferrite.

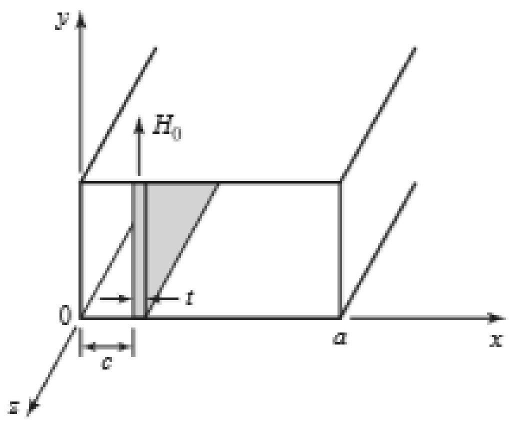

Figure 1.9 E-Plane Full Height Slab [1]

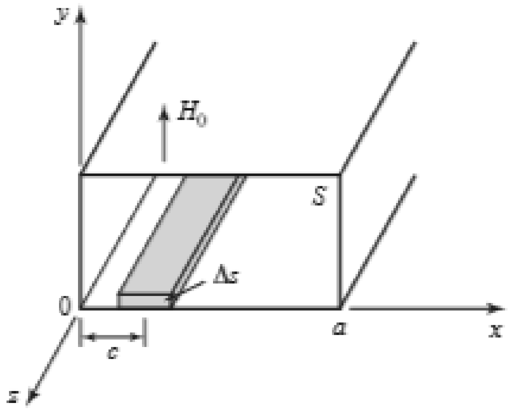

Figure 1.10 H-Plane Partial Height Slab [1]

1.4.1.2 Field Displacement Isolator

In this isolator the E-field distributions of forward and reverse wave in a ferrite slab-loaded waveguide could be altered. Field displacement isolator uses thick ferrite slabs. The field distribution must differ very much for both directions of propagation, and hence, place of the slab has to be selected accordingly. Because of this, the suitably situated absorbing material inside the waveguide discriminates amongst the directions of propagation hence attenuating the waves in one direction by providing isolation, whereas the one in the opposite direction (transmission) remains unaffected [12]. As shown in the figure 1.11, the electric field for the forward wave can disappear from sideways of the ferrite slab at x=c+t. This field displacement isolator, relatively being a compact device provides with high values of isolation. And a smaller bias field is required as compared to the resonance isolator because of the reason that even below gyromagnetic resonance, it can operate well. The foremost difficulty in scheming a field displacement isolator is in determining the design factors.

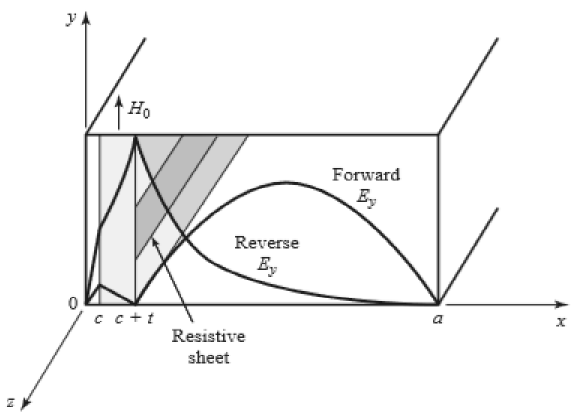

Figure 1.11 Geometry and Electric Fields of a Field Displacement Isolator [1]

1.4.1.3 Ferrite Isolators

The geometry of a ferrite isolator is shown in figure 1.12 [11]. Strip-line is used as the transmission line and hence the name strip-line Y-junction isolator. The configuration consists of two ferrite disks, centre conductor, strip-line conductor and two ground planes. The strip-line junction isolator having 3-ports consists of a symmetrical ferrite-loaded 3-arm strip-line junction. The junction is in the form of a thin circular metallic disc, around the edges of which three centre conductors of the strip-line are connected symmetrically at 120◦ intervals, which forms the three ports of the isolator. The ferrite disks fill the gap present in between the ground planes and centre conductor and strip-line conductor. The DC bias magnetic field is applied to the ferrite normal to the ground planes. The ferrite can have any shape, but for mathematical convenience, the circular geometry is chosen and is considered as the simplest. The ferrite can operate in two different modes: one is when the magnetic bias field is less than the ferromagnetic-resonance field which can be used at high frequencies and the other one with a higher magnetizing field which is used for lower frequencies so that the low field losses can be avoided [13]. The ferrite isolator with strip-line is used in this thesis.

The ferrite isolators are capable of handling high power, does not consume DC power and provides with high isolation [14]. An important property of an isolator is the isolation which is defined as the measure of how well an isolator is capable of decoupling the energy that enters port 2 from whatever is attached to port1.

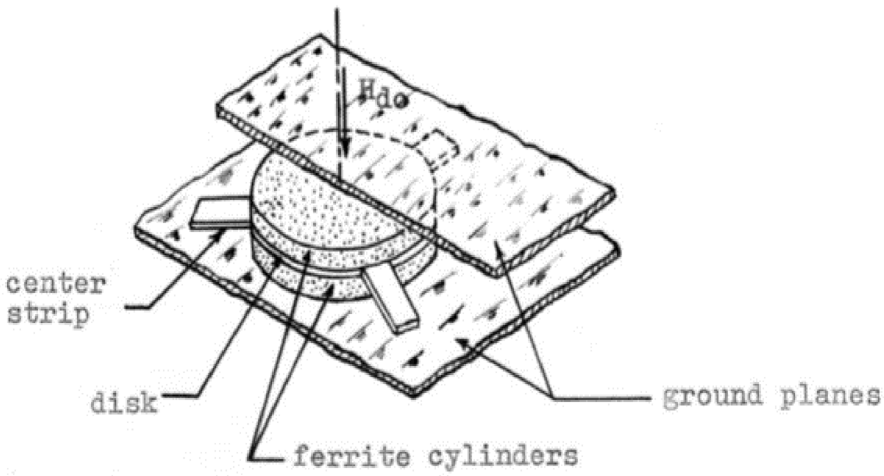

Figure 1.12 Strip-line Junction Isolator

There are three basic specifications which define the working of an isolator and a circulator are briefed below:

- Insertion Loss- Insertion loss describes the loss of energy when a signal is transferred from one to the other port. Isolators and circulators being the passive components, signifies that a signal which travels over them has to use its own energy. A signal travelling through a device gets attenuated and this attenuation is known as insertion loss. Higher the insertion loss, more energy is used by the isolator or circulator. The energy is transformed into heat on its way over the device. The loss is frequency dependent and increases with the operating frequency. The insertion loss is of the order of 0.4 dB for the octave bandwidth units, 0.15 dB for narrowband units, and 1.7 dB for certain broadband units. Basically it is the proportion of the output to the input power and is measured in dB.

  Mathematically,

$$\text{Insertion Loss}=10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)\ (\text{dB}) \tag{1.12}$$

- VSWR- is defined as the proportion of maximum to minimum voltage of a standing wave which is generated by an inadequate impedance match where the two boundaries meet. This wave is created by the energy reflecting off from the boundary, and traveling back the way it came from. In case of the circulators and isolators, it is the degree of the amount of the signal that was sent through the isolator and how much of it got reflected back towards the transmitter. There is a need of low VSWR value signifying that the energy being reflected back at port 1 of the isolator/circulator is less. If the energy gets reflected back towards the transmitter, it could either disrupt it, or destroy it completely. This can happen due to an open or short circuit in a system, where the impedance matching is not proper. VSWR is defined as

$$\text{VSWR}=\frac{1+|\Gamma|}{1-|\Gamma|} \tag{1.13}$$

$$|\Gamma|=\sqrt{P_{ref}/P_{in}} \tag{1.14}$$

  Where, P_{ref} is the reflected power in watts,

  P_{in} is the input power in watts,

$|\Gamma|$ is the reflection coefficient magnitude which defines the reflective property of a port.

- Isolation- this is the most important property of an isolator. It is the measure of how well an isolator can decouple the energy entering the second port from whatsoever is attached at the input port. An isolator shows isolation for the reason that a termination is attached to any one of the port of the device. Greater is the isolation value, lesser will be the interference from the signal on one port relative to an adjacent port. There is an element known as the load element present inside this termination. With the perfect matching done with the isolator, this element dissipates any energy it come across as heat thus, preventing it in its tracks. Isolation dependents upon two things: the feature of the termination, and VSWR of the terminated port.

1.4.2 Applications of the isolator

Microwave isolator can be thought of as a transmission line with non-reciprocal attenuation. Isolator helps to reduce the frequency pulling of an oscillator because of the reflections coming from the load. The maximum gain in present high-gain traveling-wave tube amplifiers is inadequate, for the reason that reflections coming from the output end makes the tube oscillate above certain critical gain. So isolators are used in these tubes to overcome this limitation without affecting the tube performance. Isolators can be used in colour television to diminish the ghost effects produced by the reflected signals on the line between the television receiver and the antenna [15]. The common application is in the system of safety for sensitive equipment connected in a chain. This can be achieved by deploying an isolator at the output of a transmitter. Isolator may be used for decoupling a transmitter or a receiver from its antenna. A transmitter connected to an antenna gets influenced be the impedance changes of the antenna which could be due to snow or any near-by-obstacles. The isolator with an isolation of 20dB can avoid this situation.

CHAPTER 2
LITERATURE SURVEY

This chapter overviews the work done for isolators and circulators and also other related components. This approach of studying and understanding the research done helps in performing the project better.

W. E. Fromm [3] summarized the characteristics and applications of the strip-line working in the various frequency bands. The strip-line offers some noteworthy benefits in the fabrication of the microwave equipment. He presented the components like transitions to coaxial line, directional couplers, attenuators and filters. These components finds applications in practical high performance microwave circuits working in the frequency range of 2500-10,000 MHz and has been described by Fromm in his paper. Different experiments were performed to investigate the physical limitations, attenuation, power handling capacity and environmental effects on the strip-line. This transmission line proved to be comparable and has got some significant advantages over the conventional transmission lines. The method for the fabrication of strip-line is also presented.

M. E. Hines *et al.* [4] presented an analysis of the mode of propagation in strip-line and micro-strip line having some width by utilising a ferrite slab as the dielectric material which is magnetized perpendicularly to the ground plane. Approximate methods are provided for the isolators and phase shifters by using numerical calculations and the results are obtained experimentally. If the edges are loaded symmetrically, non-reciprocal behaviour can be obtained. These transmission media were used in a new type of isolator and phase shifter. Approximate methods are presented which are based on the solutions of Maxwell's equations. The main objective of the work was to provide field configuration of various modes, approximations for the propagation constants and a design theory for these non-reciprocal devices which are used practically in these configurations. A new type of isolator and phase shifter exploiting the field displacement effect of dominant mode has been described and by using the approximation techniques, a theory for the modes of propagation are presented in wide ferrite strip-line and micro-strip devices. Physical description of the wave pattern was also provided.

J. J. Green *et al.* [7] presented the ferromagnetic resonance theoretically which is capable of working at high peak-power levels along with the investigational outcomes about threshold RF magnetic field and also about its dependency on composition, frequency, and temperature. He also pointed out on how the experimental results can be related to device applications. He discussed about the ways in which the properties of the ferrite material can be influenced so that they can work on high peak-power levels. The two possible mechanisms were given first one is in which the unstable spin waves are having half the frequency and the other one in which they are having the same frequency as the applied signal. The properties of the ferrites changes when they are exposed to strong fields or in other words at microwave applications. If a large amount of power is absorbed by the ferrite, this leads to temperature variations and thus, properties of the device are influenced. Ferrites also exhibit non-linear properties when they are subjected to large peak-power levels. Experiments were performed to study the effects of temperature, porosity, anisotropy and frequency on the relaxation rates.

W. Tong *et al*. [8] presented a frequency tunable ferrite loaded waveguide isolator. Inside this waveguide near the sidewall, the two-pairs of ferrite cylinders are positioned having the magnetization in the opposite directions. A method was proposed and experimentally verified to reduce the forward transmission loss which occurred due to the use of magnetic photonic crystals. So instead of them, ferrite rods were used. These crystal lattice inhibited backward transmission but high losses in forward transmission. The approach for designing tunable waveguide isolator is presented. The tuning of the bias magnetic field, there is a drift in the magnetic surface Plasmon resonance frequency. Thus, for a given size of the waveguide and within a certain range, the working frequency is tunable. The capability of two ferrite rods to cause one-way propagation is also demonstrated.

J. D. Adam *et al*. [9] reviewed the progress and current position of the microwave ferrite technology. The physics and fundamentals of ferrite devices were introduced, followed by a historic version of advancement of the ferrimagnetic spinel and garnet (YIG) materials. He also discussed some of the fundamental ferrite components, such as circulators, isolators, phase shifters, and some of the nonlinear devices. Circulators are used in the microwave systems which consists of a single aperture antenna for both sending and receiving for directing of incoming and outgoing signals to the transmitter or the receiver as suitable. The 3-port circulator is one of the most commonly used circulator. Therefore, Adam focused on three-port circulator particularly, on “symmetric” three-port circulators but also discussed about other forms of circulators.

A. Beyer *et al*. [12] investigated a ferrite isolator both theoretically as well as experimentally. This isolator is based on fin-line technique. The fin-line field distributions shows parallel properties and hence displacement isolator can be realized by using the metal waveguide isolators operation. In order to investigate the field theoretical problem, a field expansion technique for an isolator model is offered. It was observed that the field displacement isolator principle is comparatively extra operative and broad band than the resonance isolator principle therefore, it was used for designing of a fin-line device. Furthermore the validity of the fin-line field displacement method for realizing an isolator is verified experimentally. The isolator works at the frequency of 11 GHz.

H. Bosma [13] explained the physical principle of the circulator using the superposition of the radiating modes. The dependency of the physical dimensions such as radius on frequency, bias field and magnetization was observed. He stated that when a gyromagnetic material in the form of a circular disk is placed in between the infinite plane conductors and are axially magnetized, then the disk can support cylindrical modes without any field variation in axial direction. The boundary-value problem was studied. The calculation for the electric field intensity distribution for the ferrite disk was done. Also, the investigation of the plane wave propagation in the gyromagnetic medium was done as well as experimented. Eigen resonances of the ferrite disk were also referred. The two modes of operation of the circulator were stated, first one being the magnetic bias field less than the resonance field which can be used for the higher frequencies and helps in reducing the size of the external magnets and the other in which the magnetizing field is higher which finds its applications for lower frequencies so that low field losses can be avoided in the ferrite. The theoretical and experimental results were compared.

J. F. Chang *et al.* [14] proposed a new technique of realizing an isolator without the use of a ferrite. A common source amplifier and a directional coupler is used in this technique. This amplifier is a unilateral component. The concept and design procedures were presented. The isolator worked quite well and the performance was comparable to a ferrite isolator, except the bandwidth. There was a 1dB compression point of the output power of the insertion loss which is high and is due to the passive nature of the directional coupler, but as the input power increases, reverse isolation declines. TSMC 180-nm CMOS was used to develop the 24-GHz monolithic microwave integrated circuit isolator. Based on this isolator, quasi circulator was designed as well as fabricated. The conditions for functionality were derived and non-ideal properties of the common source amplifier in the isolator were described analytically. The results for the noise figure and linearity were shown. Without ferrites also, the isolator still exhibited high isolation and low insertion losses. Because of these proposed isolators, the linearity of the quasi-circulator could be increased.

B. N. Enander [15] described a new ferrite isolator in which a helical transmission line was used. The benefit of this being that there is no need of any external magnetic field. This is possible when the closed rings of soft ferrites are used having a square loop magnetization curve. This isolator can be used in travelling-wave tubes and with some adjustments, it can be used as an isolator or modulator with helical and hallow waveguides. The isolator consists of ferrite rings which are magnetized once and remains in that state. The magnetization is achieved by passing current through the ferrite cylinder. The closed ring form of the ferrite keeps it saturated even after the current removal. A variety of ferrite materials with different helices were used to determine the dependence of the properties of isolator on its physical dimensions and its material properties. The backward and forward losses were measured and a slotted line was used to investigate the standing wave ratio. The loss in the isolator due to the influence of circumferential magnetic field was measured. It was observed that corresponding to a circumferential field, by sending a current pulse, switching of the loss can be from a high to low value and vice versa can be done. The loss of the circuit is a function of frequency.

H. Bosma [16] presented the simplified boundary-value problem of the Y-junction strip-line circulator and calculated the circulation parameters required. He used Green's function method for the solution. He took forward his previous work done on the Y-junction circulators and tried to overcome the inaccuracies in his previous paper. The circulator can be used in UHF region of the radio spectrum. Bosma also evaluated the frequency characteristics and proposed a general method for broad-banding the device. The results were verified experimentally and a description of circulation mechanism along with the conditions required for the circulatory action were given. Junction circulator is a member of a large family of non-reciprocal devices. Many assumptions were made for making the calculations easy. The main assumptions that were considered includes, the electric field is present in the axial direction only and in this direction, there is no variation in the electric field, the edges of the ferrite disks can be assumed to be as magnetic walls, the azimuthal magnetic field at the ferrite disk edge is considered to be zero and, because of the presence of symmetry in the balanced strip-line, one ferrite disk is the mirror image of the other and hence the calculations made for one ferrite disk are applicable on the other disk.

B. A. Auld [17] considered the scattering matrices and the associated quantities for the study of symmetrical junction circulators and its tuning procedures. He used the eigen values of the scattering matrix for synthesizing the circulator. The procedure proved to be useful in the designing of the compact circulators which are of the form of waveguide junctions which contains ferrite obstacles. The synthesis procedure along with the structural symmetries of circulator was listed and the conditions required for the eigen values of the scattering matrix were stated. When an anisotropic material is placed within the junction, the eigen values gets affected. These changes were used in the form of an expression. This theory was applied to different types of circulators and for a 3-port circulator, results were presented. He said that in order to control circulator action, two independent variables are sufficient. He used a method in which the microwave circuit is considered as a waveguide junction which is characterized by the scattering matrix. This method can be applied to the circuits having small losses.

H. Bosma [18] discussed the lumped element circulator and the strip-line circulator and determined the magnetization and bias field values for the operation at both above and below resonance. Bosma divided the non-reciprocal ferrite devices into three groups. First one being based on the Faraday rotation, the ones which makes use of the non-reciprocal field effects in rectangular waveguides forms the second group and the third one is having the junction circulators. The dependence of the device specifications like for example insertion loss and power capability on parameters such as, linewidth, dielectric loss tangent, etc., is alike for these different groups of the non-reciprocal devices. But bandwidth and insertion loss dependence on ferrite magnetization and polarization field is definite for a particular group. A general model was introduced to check this dependence for junction circulators. Bosma made two restrictions for his research. Firstly, the discussion was confined to the symmetric junction circulators only as these circulators are having rotation symmetry and all of their ports are equivalent. Secondly, the circulators having 3-ports were considered the reason being that a three-port symmetric junction circulator has got a three-fold rotation symmetry.

E. N. Skomal [19] determined the design parameters for the junction circulator and explained it as two contracting surface waves or in other words he assumed that a bound surface wave propagates through the ferrite cylinders and an incident RF field propagates as a surface wave bound tightly to the boundary of ferrite cylinder. The incident wave which is directed by air-dielectric interface of the ferrite cylinder is linearly polarized parallel to the ferrite axis, after which it is assumed that the incidence wave divides and propagates in opposite directions around the cylinder as two linearly polarized signals. Constructive and destructive interference of the components occurs at the two output ports. This can be done by the proper selection of the ferrite parameters such as cylinder diameter, magnetic bias field and saturation magnetization. The requirements for reinforcement at the outputs were proposed by him and then compared with the experimental data. The dependence of ferrite diameter on the free space wavelength was also done theoretically and then verified experimentally. The inter-relationship among saturation magnetization, ferrite linewidth, applied magnetic field and circulator insertion loss was also observed in the theory.

E. N. Skomal [20] developed a high power S-band load isolator in which a dielectric loaded waveguide along with a composite ferrite was used. The isolation provided and the insertion loss were measured and also the amount of power absorbed by the ferrite was calculated as the isolator operated at high average power in the reverse direction. A useful approach has been provided for the calculation of reflection coefficient. A method was proposed to increase the average power handling capacity of the ferrite in which a high Curie temperature tip of ferrite which was situated at the load end and vertically constricted waveguide was used to reduce the size of the magnet.

M. Singh *et al.* [21] offered a technique for the detection and classification of a variety of shunt faults on the transmission lines for dependable operation of the protection schemes. Transmission lines need protection because of the occurrence of 85-87% faults in the lines. The programming tools available helps in identifying the type of fault in the lines. Some tools can extract information from the signal. A methodology for the fault detection and on lines using SVMs is presented. The algorithm calculates the RMS value of the transient energy of pre and post-fault signals of three line currents and voltages. Wavelets have been used for extracting the information from the original signal. The proposed scheme proved to be fast and accurate and a robust classifier for digital distance protection.

A. D. Sutherland [22] verified the predictions of Siegman on the inherent noise of an isolator. Sutherland examined the behaviour of common two port isolator for the verification. Siegman on the basis of a thermodynamic argument concluded that the isolator is an equivalent of a terminated circulator as far as it is about their inherent noise. Analysis was done and it was discovered that a Faraday rotation isolator behaviour was exactly the same as of the terminated circulator. The main objective of the paper was to validate that the Siegman's conclusion. Sutherland found that there were some restraints about what should be the source of that noise. Thus, it was concluded that one resistive source of Nyquist noise must be included at least to get proper isolation between input and output ports. That noise originates from the input port. And it was established that Siegman's thermodynamic proof on equivalence of the isolator to the terminated circulator cannot be denied. The observation was made of the electric field orientation at different cross-sections of the device.

H. Bosma [23] analysed the scattering matrix of lossless 3-port junctions having 3-fold rotational symmetry. It was observed that circulators can be obtained if the eigen values having unit magnitude are at an angle of 120°. for a lossy junction, the eigen values does not have unit magnitude. For a circulator, eigen values needs to be at 120° and also have large equal values. If both the conditions are not satisfied simultaneously, asymmetry is induced in device properties. For understanding this better, H-plane 3-port junction was considered. He assumed that electric field is in the axial direction only and that there is no dependence of the field properties on the axial direction. It was observed that the losses diminishes the eigen values magnitudes. It was demonstrated that the designing of the circulator is possible for some optimum bandwidth and insertion loss. Also, the ferrite material requirement can be formulated. A method is proposed to increase the bandwidth of the circulator.

Y. Lin *et al.* [24] fabricated a low loss and high-frequency magnetic composite using $Y_3Fe_5O_{12}$ (YIG) ultrafine particles which are implanted in HDPE matrix by means of low-temperature hot-pressing technique. This investigation was done on magnetic and dielectric attributes of the composites and it was observed that there was an increase in the volume of the ceramic fillers, the permittivity and permeability. Composites cut-off frequencies were taken above 700 MHz. Because of the low resistivity of YIG, composites have got high dielectric losses and in the lower frequency range they tend to decrease with frequency. It was observed that there is a worthy frequency stability of the permittivity and permeability, also there were low dielectric and magnetic losses within the measurement. These magnetic composites finds applications in capacitor-inductor integrating devices like for example in EM interference filters used in RF communications.

W. Marynowski *et al.* [25] exhibited an alternate configuration of a 4-port circulator using micro-strip ferrite coupled line technique. It is a planar device employing two 3-port circulators which consists of ferrite coupled line junction along with a T junction. The same arm connects both the circulators because of which the problem of anti-parallel magnetization is avoided without increasing the device width. Simulation as well as experimental results shows the device feasibility. By applying termination by using the matched loads to two ports of the couple line circulator, a double isolator was constructed which operates in the range of 9 to 18 GHz. This isolator provided better isolation than -20 dB and insertion losses are better than -3 db. This cascade of coupled line sections is known to provide better higher isolation and broader bandwidth as compared to single ferrite couple line designs. The proposed configuration is in such a way that the circulator is a fully planar circuit. It was observed that the measured results were in good agreement with the simulated results and were lying within the investigated frequency band.

W. Marynowski *et al.* [26] investigated the non-reciprocal devices which consisted of ferrite coupled line junction. The coplanar line technology was used to design the structure with the reduction of the ground half-planes into strips. The ferrite is positioned in between the two dielectric sections. The ferrite slab is magnetized longitudinally which is placed at the top and bottom of the strips in this ferrite section, which is then enclosed with the dielectric layers. This dielectric section contains the junction ports. Spectral domain approach was used to obtain the wave parameters and the field distributions of modes propagated in dielectric and the ferrite sections and mode matching technique was used for obtaining the scattering matrix of the junction. Non-reciprocal behaviour of all the devices was observed. An explanation is also provided for the double isolator providing better isolation as compared to the circulator. For a double isolator, two different structures were realized and results were observed. The first structure was terminated by using coaxial loads and in the second structure, the matching of the ports was done by using lumped resistor. . The design of the circulator and the isolator by using the S-matrix of the junction were investigated and the outcomes were compared with the simulation results and with measured ones. A good agreement was observed in the results.

B. Saurabh *et al.* [27] studied the four popular feeding techniques which are micro-strip line, coaxial probe with both of the contacting schemes, proximity coupling for both non-contacting schemes and aperture coupling. A micro-strip patch antenna can be fed by two methods- contacting and non-contacting. RF power in the contacting method is fed straight to the radiating patch by using a connecting element like a micro-strip line. In the non-contacting method, EM field coupling is done for the transmission of power between the micro-strip line and radiating patch. Advantages and disadvantages of these feeding techniques have been discussed. Results for the radiation pattern and bandwidth for individual antenna designs are provided in the paper and comparison has been done.

M. Cao *et al.* [28] proposed a method for designing a circulator built on FCL. He also made an attempt to reduce the length of the circulator. This can be achieved by using suitable matching networks. Closed-form expressions for mandatory matching impedances and resultant bandwidth of the matched device by using ferrite perturbation theory, were derived. Centred on this investigation, a design for strip-line FCL circulator was acquired, whose length was shortened by a factor of three. He designed and fabricated a micro-strip FCL circulator which was half of the optimal length. The simulation and measurement results demonstrated the possibility of a circulator based on FCL with reduced length. A general scheme for matching of the lossless non-reciprocal 3-port is also presented. It was shown that by the addition of suitable matching networks, length of the FCL circulator can be reduced. This reduction in length leads to reduction in bandwidth. For matching, the matching impedances were calculated by using impedance matrix. The usefulness of the ferrite perturbation theory has been demonstrated in the paper.

H. Razavipour *et al.* [29] presented the design, simulation result of a structure for X-band high-power, low-loss and low-bias, triangular shaped ferrite waveguide circulator. Due to the triangular shape of ferrite post, dual circulation property is obtained. The observation on the effects of circulator's structure constraints, like ferrite factors and magnetic DC bias, on the isolation, insertion and return loss was made. Dual band designs with a 20dB return loss, 20dB isolation and 0.1dB insertion loss in dual frequency in X-band with only a magnetic bias of 10 Oe were obtained. A method has been provided to keep the ferrite safe as it crashes when the electric or magnetic fields amplitude is increased to a very high value. Thus, the ferrite is placed in the dielectric substrate. In order to increase the bandwidth and reduce the insertion loss, different methods have been presented. The results by using different ferrites in the final designs were observed.

G. P. Rodrigue [30] reviewed the status of microwave ferrite materials and devices. The theoretical understanding of the ferrite widespread in the mid-1950s. Progresses in the materials, engineering of garnets and ferrites in the 1960s and 1970s are also defined alongside the evolution of circulators and phase shifters and the existing stages of performance attainable in circulators and phase shifters and future challenges and opportunities are debated. The objective was to trace the best noteworthy expansions in the field, and also to present a perception of the work done.

CHAPTER 3

RESEARCH GAPS, OBJECTIVES AND METHODOLOGY

3.1 GAPS AND PROBLEMS ENCOUNTERED

- The maximum research done on circulators and isolators are at the higher frequencies because the losses increases as the frequency decreases. These passive devices works better at higher frequencies.
- Ferrite material selection is an important part that has to be taken care of. There are different materials available. A good quality material helps in reducing the losses in the device.
- The radius, magnetic biasing and the magnetic saturation of the ferrite and width of the strip-line are mainly responsible for the device working. A proper relation in between these values is important.
- The ports should be matched for proper working of the device else there are reflections.

3.2 OBJECTIVE

- The antenna systems needs to be protected against back reflections as these reflections can damage the costly transformer. Isolators are really popular and are being deployed in these antenna systems. For providing these systems the protection besides providing high isolation and low insertion loss, the isolator is designed and simulated and analysed using the S-parameters.
- Circulators and isolators are the passive devices which are being used extensively in the microwave and RF systems due to their unmatched properties. One of the limitation of these systems is the size. These circulators and isolators are compact in size and lightweight and hence not making the system bulky.

3.3 METHODOLOGY

The following section describes the steps involved for the simulation of the circulator and isolator:

- Detailed study of the circulators and isolators.
- Overview of HFSS software

- Understanding of mathematical equations and calculations involved of the relations between different parameters required in designing and observing their dependency on each other and on frequency.
- Simulation of the circulator and isolator by using required magnetic biasing and analysing the output by observing the S-parameters obtained after simulation.

CHAPTER 4
ISOLATOR AND CIRCULATOR AT ULTRA HIGH FREQUENCY BAND

The 3-port circulator and isolator is a non-reciprocal junction having one input port, one output port, and an isolated port. It is a matched network, thus reflection coefficient must be zero, and any power reflected from the load will be absorbed. As also mentioned above, the isolator is equivalent to a terminated circulator. Here, the method for designing a strip-line circulator and an isolator is presented. The main modelling factors considered are the radius, the type of the magnetic field, the biasing configurations and the value of the dielectric constant. So, all the calculations done below are same for both. The schematic of the junction is shown below

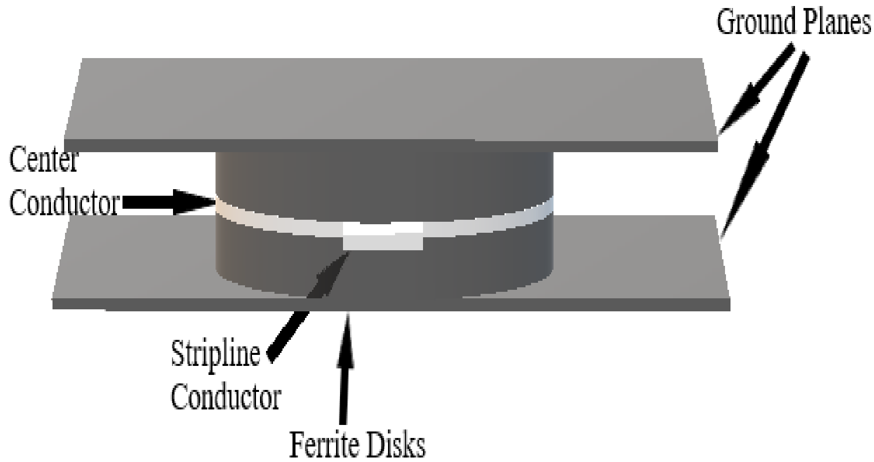

Figure 4.1 Strip-line Isolator Configuration

All the calculations have been made at a frequency of 450 MHz. Strip-line transmission line has been used and S-parameters are used for observing the behaviour and working of the device. HFSS was used for verifying the results with the theory. HFSS is a 3D EM simulation software used to design and also for simulating high-frequency electronic products such as RF or microwave components, IC packages, antennas, antenna arrays, high-speed interconnects, filters, connectors and printed circuit boards.

The structure has two ferrite disks, centre conductor, strip-line conductor and two ground planes. The ferrite disk fills the space between the ground plate and the centre conductor. The ground planes can be of any dielectric. Air is chosen as the dielectric material in this design as this helps in reducing the losses. The centre conductor and the strip-line conductor can be any conductor like aluminium or copper. Manganese ferrite aluminate is the ferrite material used having specific permittivity ϵ=14.2, magnetic saturation $4\pi M_s$=1750 Gauss, line width ΔH=150Oe.

The scattering matrix S for a cyclic and symmetric 3-port is in the form

$$S=\begin{bmatrix}\alpha & \gamma & \beta\\ \beta & \alpha & \gamma\\ \gamma & \beta & \alpha\end{bmatrix} \tag{4.1}$$

Where, the elements of S satisfies the following relations,

$$|\alpha|^2+|\beta|^2+|\gamma|^2=1 \tag{4.2}$$

$$\text{And, } \alpha\beta^*+\alpha\gamma^*+\beta\gamma^*=0 \tag{4.3}$$

The ideal condition for circulation in a 3-port is met if

$$\alpha=\gamma=0 \tag{4.4}$$

$$|\beta|=1 \tag{4.5}$$

These conditions can be met with the correct selection of values of R and $4\pi M$ and when all the conductors are perfect along with the lossless media. A proper adjustment of R, $4\pi M_s$, ω and H_i are important for the circulation and this is known as circulation adjustment. The thickness t of the centre and the strip-line conductor is approximately zero. Impedance matching is an important feature for the proper working of the device. The two ground planes are at a distance of u, which is two times the thickness of a ferrite disk. The strip-line conductors are connected at the edges of the centre conductor at equal intervals of 120°. The configuration of a centre conductor is shown in figure 4.2. Other parameters are also defined in the configuration.

If, Ψ is the strip-line width angle and can be defined as

$$\Psi=\sin^{-1}(W/2R) \tag{4.6}$$

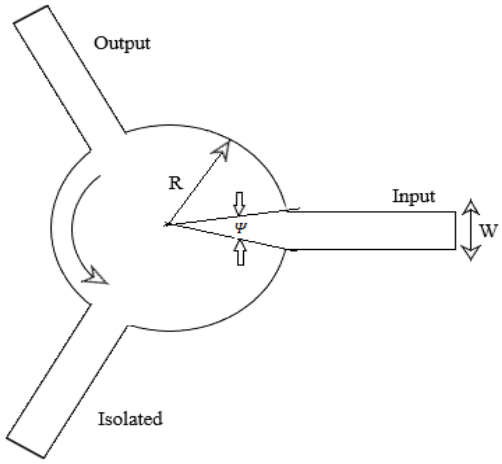

Figure 4.2 Centre Conductor Configuration

Where, W is the width of the strip-line and R is the radius of the center conductor and W must not be too large as compared to R

$$\frac{W}{R}<0.75 \tag{4.7}$$

The electric and magnetic field intensities on both the sides of the centre conductor are directed opposite but are equal. As per the boundary conditions of the strip-line, the magnetic field intensity remains constant over the width of the strip-line and has a zero value elsewhere. All the calculations are done in accordance with

$$W<R \tag{4.8}$$

Internal DC magnetic bias field is responsible for the working of the ferrite and the properties of the ferrite varies with the change in the field. It is assumed that the field in the disk is independent of the z-direction and the electric field intensity is having the z-component only.

The ferrite parameters ϵ, μ, μ_{eff} and κ are to be known before any further calculations. The ferrite used here are biased above the resonance that is, $\kappa/\mu \ll 1$. Effective permeability μ_{eff} and intrinsic wave number κ are defined as

$$\mu_{eff}=\left(\frac{\mu^2-\kappa^2}{\mu}\right) \tag{4.9}$$

$$\kappa^2=\omega^2\mu_0\epsilon_0\mu_{eff}\epsilon \quad (4.10)$$

$$\text{And, } \mu=1+\frac{hm\left(h^2-1\right)}{\left(h^2-1\right)^2-s^2} \quad (4.11)$$

$$\kappa=\frac{m\left(h^2-1\right)}{\left(h^2-1\right)^2+s^2} \quad (4.12)$$

Where,

$$m=\frac{4\pi M}{H_0} \quad (4.13)$$

$$h=\frac{H_i}{H_0} \quad (4.14)$$

$$s=\frac{\Delta H}{H_0} \quad (4.15)$$

$4\pi M$ is the saturation magnetization, ΔH is the line width of the ferrite and H_0 is the quantity used for the reference only and is given by

$$H_0={}^{\omega}/_{\gamma}=160 \quad (4.16)$$

Where,

$$\gamma=2\pi\cdot 2.8\text{MHzOe} \quad (4.17)$$

H_i and R can be calculated as

$$H_i=\sqrt{\frac{\lambda}{W\sqrt{3}}H_0\cdot 4\pi M-4\pi M} \quad (4.18)$$

$$R/\lambda = \frac{1.84}{2\pi\sqrt{\epsilon}}\sqrt{\frac{H_i}{H_i+4\pi M}} \tag{4.19}$$

The width of the ferrite W is restricted as

$$W < \frac{\lambda}{30} \tag{4.20}$$

As it can be observed that H_i and R/λ are independent of the frequency and H_0 is inversely proportional to λ for the same W and 4πM. W must be small for higher frequencies and h>4. For the circulator, W=15mm and u=11mm at a frequency of 450 MHz. Using these, the other parameters calculated have the values as H_i=936.43 Gauss and R/λ=0.0460. From these, h=5.826, R=30.67mm and W/R=0.489. The length of the transmission line is calculated by using

$$L = \frac{\lambda}{4} = 167mm \tag{4.21}$$

Where,

$$\lambda = \frac{c}{f} = 666.67mm \tag{4.22}$$

A strip-line junction circulator design along with its coordinates in HFSS is shown below

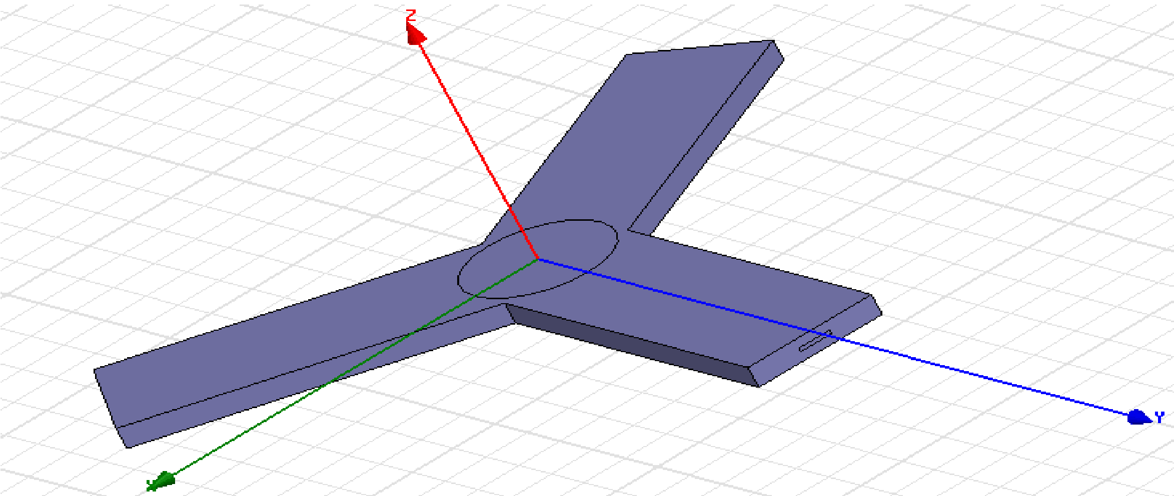

Figure 4.3 Design of the Circulator

RESULTS

4.1 For the strip-line Y-junction circulator

The working of the circulator can be analyzed by using the S-parameter vs. the frequency graph. The characteristics of the same are shown below. The S-parameter and the associated significance of that parameter have also been stated.

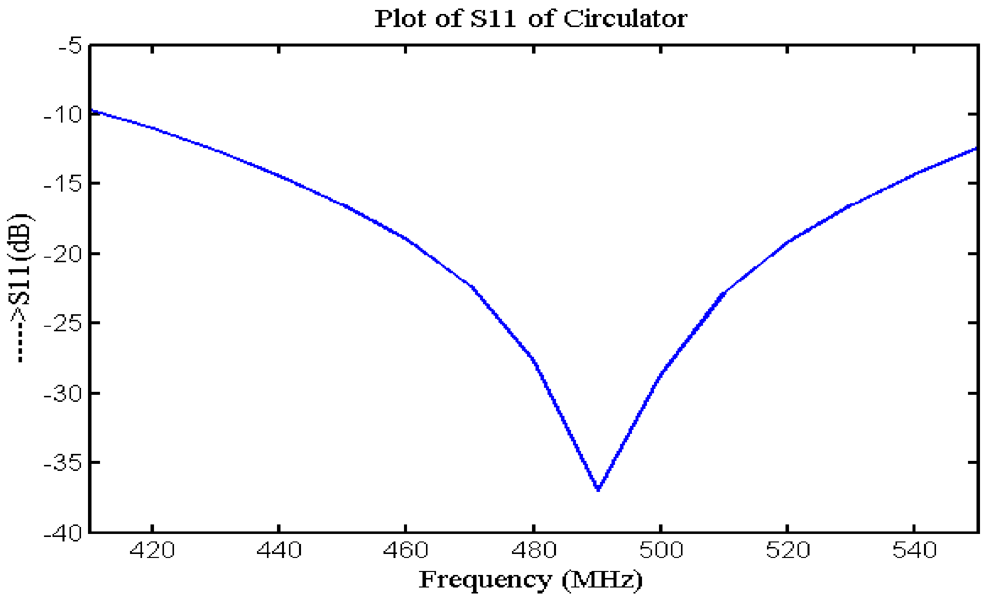

Figure 4.4 S_{11} Characteristics vs Frequency

The circulator operates in the UHF region from 420 MHz to 540 MHz. S_{11} represents the reflections from the output port to the input port. The circulator is able to block the reflections quite precisely and the value for S_{11} lies between -36dB to -40dB.

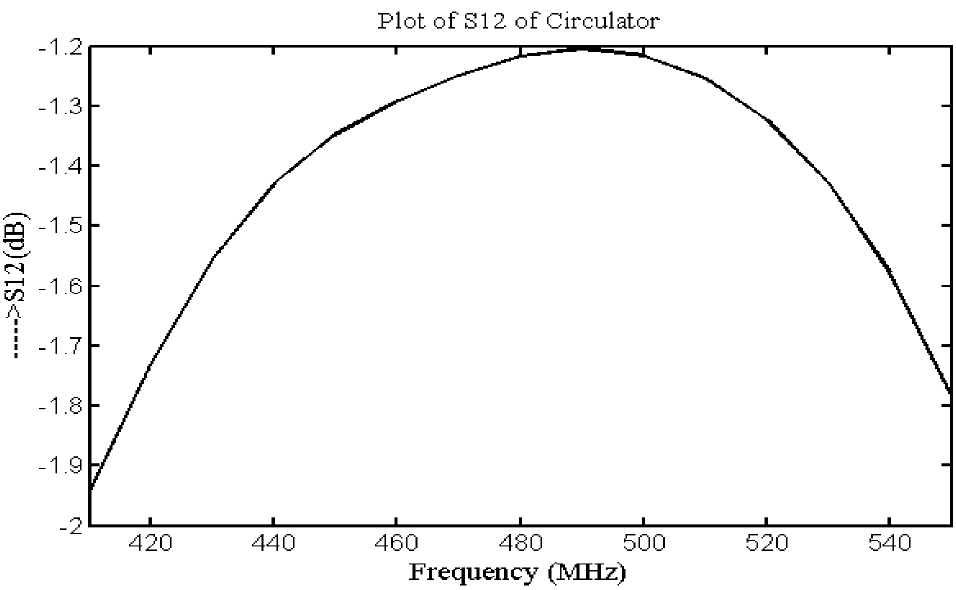

Figure 4.5 S_{12} Characteristics vs Frequency

Since, it is a 3-port device, one is the input port (S_{11}), second is the output port (S_{12}) and the left over port is the decoupled port (S_{13}). S_{12} lies approximately at -1.2 dB which means that the port is able to receive a good amount of power.

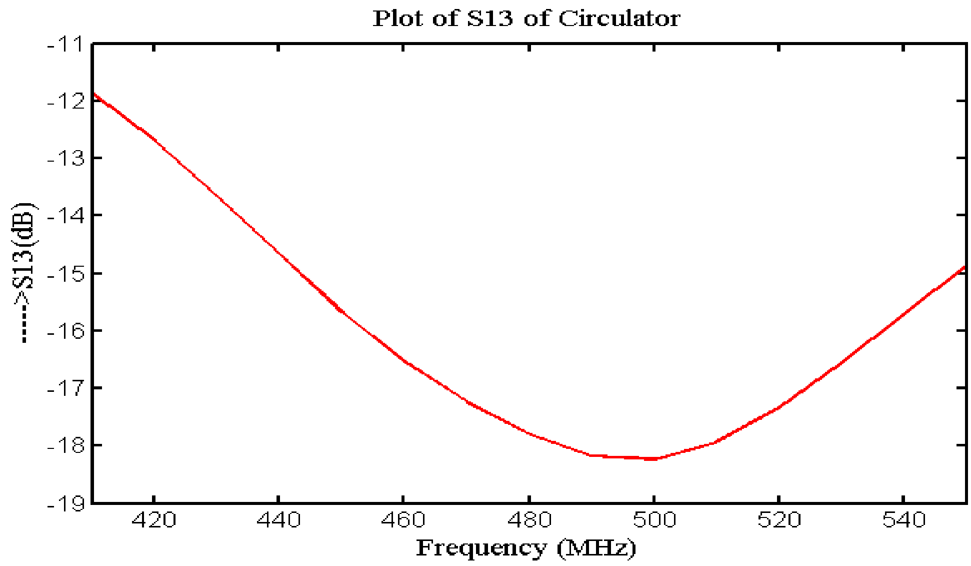

Figure 4.6 S_{13} Characteristics vs Frequency

The value obtained for S_{13} shows that the power is getting transferred to the immediate port and not to the decoupled port.

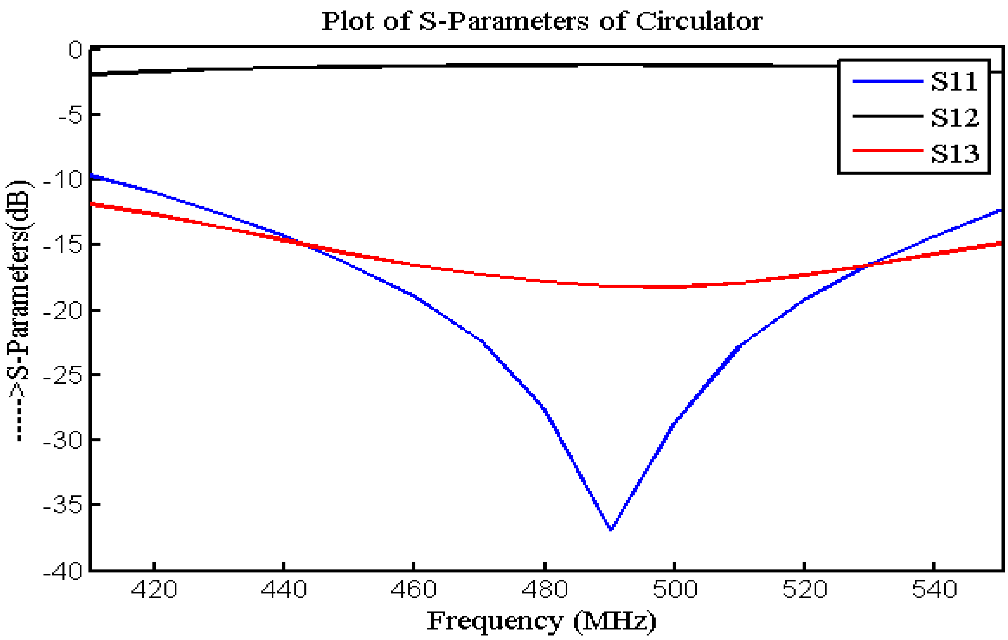

Figure 4.7 Comparison of the three S-parameters

Figure 4.7 shows the three S-parameters i.e., S_{11}, S_{12}, S_{13} with respect to each other.

4.2 For the strip-line Y-junction isolator

The resistor of 50Ω is used to provide termination at one of the port of the circulator. The design of the isolator is the same as that of the circulator shown above.

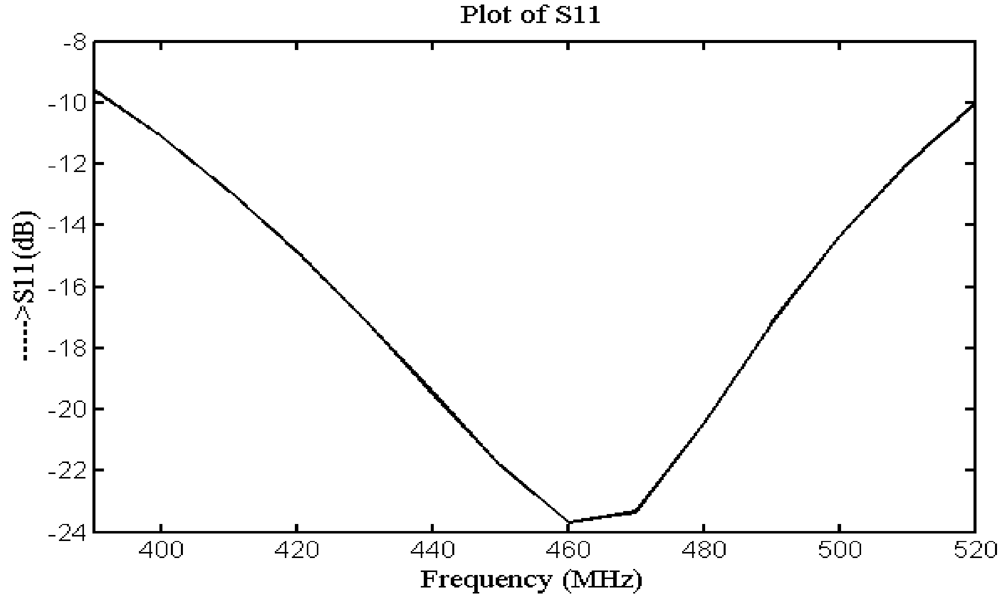

Figure 4.8 S_{11} Characteristics vs Frequency

As it could be observed from the graph, the isolator works in the UHF range starting from 400 MHz to 520 MHz. The S_{11} value lies approximately at -24dB.

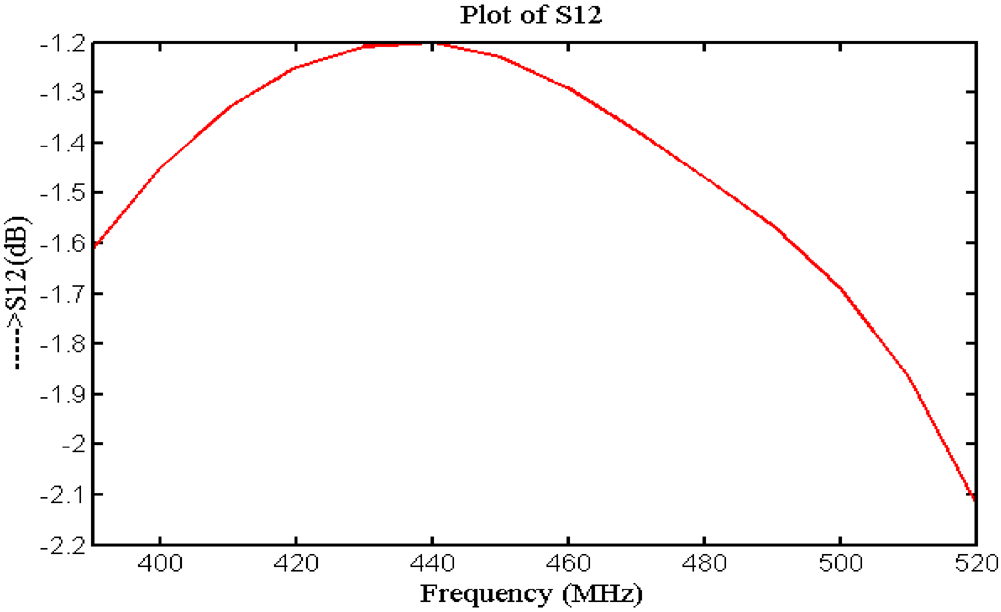

Figure 4.9 S_{12} Characteristics vs Frequency

S_{12} represents the amount of power transferred from input port, here it is port1 to the output port or the port2. The value lies somewhat at -1.2 dB.

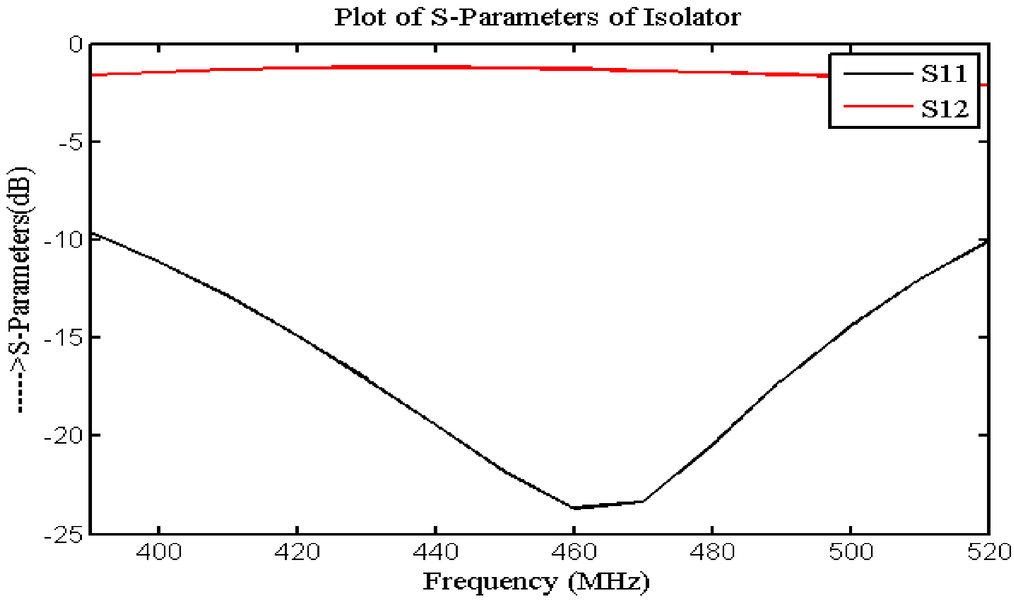

Figure 4.10 Comparison of both the S-parameters

Figure 4.6 compares the two S-parameters and shows the working of the device in the range. There is a loss in the power while travelling from input to output port. This loss can be explained by the ferrite material used. Manganese ferrite aluminate is the commercially available ferrite in which the power losses are high. Better and good quality ferrites can be used to reduce these losses.

Calculations for the isolator working at the frequency of 27.2 MHz:

For this frequency, λ=11061.9mm therefore, L=2765.47mm.

By using,

$$H_0 = {}^{\omega}/_{\gamma} = 9.68 \tag{4.23}$$

And for W=288.79mm and u=200mm the bias field and the radius using manganese ferrite aluminate as the ferrite material as per the calculations are $H_i = -483.808$. The magnetic bias field obtained is a negative value. As we know that the magnetic field exists in the foam of a loop and there are no such things as magnetic charges that exists. And hence, the negative value of a magnetic field is not possible.

CHAPTER 5

CONCLUDING REMARKS AND FUTURE SCOPE

The circulator and the isolator working in the range of 420 to 540 MHz is designed and simulated in HFSS. The devices are analyzed by using the S-parameters. The circulator is able to transfer a good amount of power to the adjacent port. Talking about the isolator, the device is able to stop the reflections coming from the output port by deploying the 50 ohm resistor on one of its port. As observed, the device covers a good amount of bandwidth in the UHF range and finds its application in the systems involving power generators. The isolator can be used to block the power coming back as reflections from the output as these reflections could destroy the generator. It has been observed that it is difficult to obtain an isolator operating at lower frequencies. A ferrite material of higher grade has to be used so that the losses can be reduced further.

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