

Ferrite with High Magnetization and Duplex Antenna System for Front-end Communication

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Abstract

Ferrite with High Magnetization and Duplex Antenna System for Front-end Communication

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Wireless and satellite communication systems demand a high data rate, which necessitates operating at Millimeter-wave bands. Thus, new efficient antennas and microwave devices are developed, which play an essential role in the design of an efficient frontend future communication system. Many challenges exist related to the present material properties and conventional challenges related to fabrication. Most printed circuit board (PCB) based guiding systems suffer from high dielectric and radiation losses, support surface waves, and excite cavity modes. In addition, copper cladding surface roughness introduces losses and affects the substrate's equivalent dielectric constant. Surface roughness would introduce invisible air gaps between two conducting surfaces creating a parallel plate (loosely referred to as PEC-PEC) waveguide supporting substantial signal leakage and losses due to the surface impedance. The newly developed printed gap waveguide technology would resolve such a problem by changing one of the plates with a magnetic conductor surface, thus, suppressing the leakage. This will be loosely referred to as PEC-PMC. As the magnetic conductor physically does not exist, an engineered artificial magnetic conductor (AMC) surface is realized by a periodic structure that has to be designed for the required frequency band. The Dissertation aims to highlight some of these issues and solve some electromagnetic problems. In addition, a problem related to the limitation of the commercial ferrite materials that limit the bandwidth and possibly its application at mm-wave frequencies is tackled by building in-house new ferrite material capable of overcoming such problems. In-house disks of ferrite with high-magnetization made of nickel-zinc are presented in terms of their properties and application in the circulator design at mm-wave frequencies, which is considered a significant contribution of this Dissertation.

The dissertation comprises three parts. The first part presents a design of an integrated multilayer horn antenna providing wide bandwidth and high gain. For the first time, a solution is provided to

control the leakages due to the surface roughness from imperfect copper cladding using the PEC-AMC configuration of the horn radiator that is realized by a multilayer of PEC-AMC. In each layer of the horn, the opening is surrounded by periodic cells to suppress leakage and surface waves. In addition, the upper surface surrounding the horn's opening is covered by EBG mushroom cells to act as a soft surface that suppresses the surface currents around the horn aperture and reduces edge diffraction, improving the radiation characteristics of the horn. The proposed horn antenna achieved 11 dBi gain and 20.5 % impedance bandwidth, with better than 26.5 dB co- to cross-polarization in both E- and H-planes within $\pm 90^\circ$. Most existing PCB-based circulators encounter massive dielectric losses, leading to spurious radiation and surface waves, degrading the system's overall performance. In the second part, this problem is resolved using printed gap waveguide technology that provides a packaged, low-loss, planar, cost-effective solution. The printed gap waveguide circulator provides 28.5% impedance bandwidth with better than 10 dB return loss and 12 dB isolation level throughout the operating frequency from 28.5-38 GHz. The first and second parts are integrated to form a full-duplex antenna system on the same layer with the proper matching between their ports. These studies highlight the advantages of using the gap waveguide technology, which could be a step towards standardizing this technology.

The final part of the work focuses on fabricating high-magnetization ferrite powder, which was baked at a different temperature to verify the structural and magnetic properties. Later, the manufactured powder is pressed with a hydraulic machine to form a disk shape that can be used in the mm-wave spectrum. The microwave industry's highest available saturation magnetization is around 5300 (G). In this work, different ferrite disks were fabricated with Nickel-zinc ferrite (NZF) composition utilizing different heat treatment atmospheres to heat the powders. The proposed technique provided a magnetization of 9500 (G), 1.8 times higher than the magnetization in microwave and space industries. This will open a new doorway for the microwave and space industry supporting various future applications in the mm-wave spectrum. From the industrial point of view, only the standard ferrite diameter and thicknesses are available in the market, and a custom-made disk requires much time and is expensive. A simple technique is described to fabricate the ferrite disk. Later, the same ferrite disk is deployed with a circulator operating in the mm-wave range with excellent measured isolation and return loss below -20 dB at the center frequency of 28 GHz.

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Dedication

Well, I think I can write at least a few more dissertations describing your patience, sacrifice, encouragement & dedication. Without Your sacrifice, this would not be possible & I do not have the slightest doubt about that. When everything looked so distant on my difficult days, it was you who helped me realize I could overcome all the hurdles. You are the best thing that ever happened to me. The last seven years were not easy for us. I am dedicating this work to you, my Dear Fariyan.

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List of Acronyms

3D	Three-Dimensional
5G	Fifth Generation
AMC	Artificial Magnetic Conductor
BW	Bandwidth
CST MWS	Computer Simulation Technology Microwave Studio
DRA	Dielectric Resonator Antenna
DUT	Device under Test
EBG	Electromagnetic Band Gap
EM	Electromagnetic
FEM	Finite Element Method
FDTD	Finite Difference Time Domain
FSS	Frequency Selective Structure
MSL	Microstrip Line
MMW	Millimeter- Wave
PEC	Perfect Electric Conductor
PCB	Printed Circuit Board
PMC	Perfect Magnetic Conductor
PPW	Parallel Plate Waveguide
RF	Radio Frequency
RGW	Ridge Gap Waveguide
RX	Receiver
SIW	Substrate Integrated Waveguide
SIGW	Substrate Integrated Gap Waveguide
SLL	Side Lobe Level
TE	Transverse Electric Wave
TEM	Transverse Electromagnetic Wave
TM	Transverse Magnetic Wave

TX Transmitter

Introduction

1.1 Overview

The technological advancement in the communication sector has led us to a dynamic platform through secure wireless networks, high signal integrity, and high-performance RF front-end components. The remarkable growth in wireless communication systems has demanded broader frequency bands and more extensive coverage. To ensure these requirements, Millimeter-wave (mm-wave) frequency bands from (30-300) GHz should be utilized for short-distance communication, enabling the frequency re-use [1], [2]. Utilizing mm-wave frequencies would allow for higher data rates, typically exceeding one GBPs [3], [4]. On the other hand, the design of the physical layer becomes very challenging, and the path loss of electromagnetic waves would be significant due to the oxygen absorption level [4], [5]. The high oxygen absorption level and path loss limit the wireless communication range. Fig. 1.1 highlights the atmospheric attenuation at different frequencies.

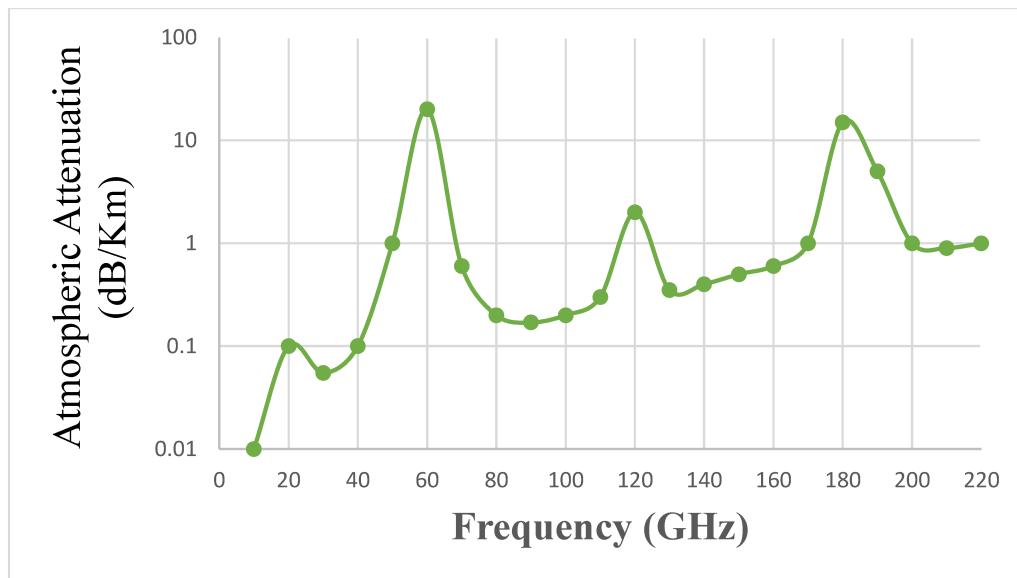


Fig. 1.1: Atmospheric attenuation at different frequency bands re-plotted using data from [4].

It is evident from Fig. 1.1 that as the frequency increases, the atmospheric attenuation rises simultaneously. At 60 GHz, the attenuation is the worst, making it a free band for short-distance communications. The carrier frequency at 60 GHz delivers unprecedented data rates, several tens of gigabits per second, allowing high-definition data transfer, sensing, and radar applications [7].

Moreover, many technical, mechanical, and environmental factors, such as rain, stormy weather, scattering effects, and diffractions, degrade the overall performance at mm-wave bands [6]. Efficient high-gain antennas must be used to compensate for the aforementioned undesired path loss [7], [8]. From the Friis Transmission Equation, it can be understood that increasing the antenna gain can compensate for the attenuation from the medium. Much work was performed to design high-gain antennas for mm-wave applications [9]-[12]. However, many innovation rooms are still available to support high-performance microwave components using low-loss guiding systems. The feeding network technology could be the leading cause of losses, which can be improved by implementing a proper low-loss guiding system.

1.2 Problem Statement

1.2.1 Modern Guiding Structures:

Many technological and mechanical challenges exist in fabricating and integrating the RF front ends in the mm-wave range. These challenges include size compactness, cost efficiency, and low-loss structures. It becomes crucial at the mm-wave range, where the traditional printed circuit board (PCB) based guiding system suffers from high dielectric and radiation losses [13]. Microstrip lines are simple, planar low-cost guiding structures that support quasi-transverse electromagnetic (Q-TEM) mode. However, while designing a feeding network with a microstrip line technology, there are possible leakages in the form of radiation losses at network discontinuities and bending in an open structure [14], [15]. In addition, microstrip lines support cavity modes and unwanted radiation, which is not desirable in the mm-wave range [20]. For surface-mount monolithic microwave integrated circuits (MMIC), PCBs and co-planar waveguides are preferable due to their high metal pattern resolution. Moreover, both active and passive devices can be easily mounted because both the feedline and grounds are on the same side of the PCB [17], [18]. Both microstrip lines and CPW suffers from high insertion loss in the mm-wave range due to lossy dielectric materials.

The rectangular waveguide is a low-loss guiding structure with low attenuation and high-quality factors. It can handle high power and supports transverse electric (TE) and transverse magnetic (TM) modes. In a rectangular waveguide, the waves bounce back and forth within the sidewalls while travelling in the propagation direction [19], [21]. The fabrication complexity increases for a rectangular waveguide at the mm-wave range as the pipe cross-section dimension decreases as the frequency increases, complicating the feeding network's manufacturability [21]. Thus, machining the groove gap waveguide can be a possible solution where the ridge is removed with a groove embedded with the periodic cells on both sides. However, ensuring electrical contact between the cover conducting plate and the walls of the grooves becomes a big challenge. This usually requires excessive screws to tie the two pieces to ensure electrical contact. A substrate-integrated waveguide (SIW) is considered supplementary to a rectangular waveguide, as the same dominant mode approximation can be considered. The rectangular waveguide side walls are replaced by two rows of metallic vias inserted in the PCB material [22], [23]. However, SIW is a waveguide filled with a dielectric material and side walls that are not solid, which is realized adequately by metallic vias to prevent leakage. Although the structure is much simpler and cheaper than conventional waveguides, the losses at the mm-wave bands are significant due to the dielectric, rough sidewalls, and thin height. An air-filled substrate-integrated waveguide (SIW) replaces the dielectric with air to reduce the losses and enhance the power handling capability [24]. However, one major drawback of this structure is leakage from the accidental gaps in PEC-PEC configurations [27]. Therefore, there is a need to revisit the design techniques in terms of fabrication flexibility, enhancing the performance of the 5G communication transceiver system.

1.2.2 Surface Roughness in Multilayer PCB Laminates

One critical problem with multilayer PCB structures is surface roughness or imperfect flatness. At the mm-wave, the contribution of copper cladding to the performance of PCB becomes more substantial, mainly from the surface irregularities of the copper foils. Two problems arise from that, depending on the application. The conductor roughness from the dielectric side causes the surface conductivity to be different from the actual conductivity of the cladding. In addition, the effective dielectric relative permittivity also becomes different from the value provided by the

manufacturer [26]. The second application is due to the outer conducting surface. In some applications, an mm-wave device can be structured from multi-dielectric substrates that assume electric contact between the exterior conducting surfaces of the substrates. However, conducting surface roughness or imperfect flatness surfaces may introduce invisible gaps that could cause leakage of the vertical polarization between surfaces [25]. For different Rogers laminates, the copper cladding varies between 0.3 μm to 1.3 μm . In [27], a contactless air-filled substrate-integrated waveguide (CLAF-SIW) structure was designed to measure the effect of the gaps. The measurements indicated a likely gap of 10-20 μm between the PEC- PEC layers. The gap can cause a detrimental impact on the mm-wave range because the PEC-PEC configurations can cause possible leakages [28]. Although the intention is to have perfect electrical contacts between the surfaces without conducting glue, any accidental gaps could exist due to surface roughness or non-flat surfaces. Therefore, almost any invisible tiny gaps can cause leakage, deteriorating the overall system. This problem is almost overlooked by engineers designing mm-wave devices made of multilayers of substrates for cost reduction. Typically, surface roughness relates to the quality of the printed metalization as far as its smoothness and particle size, while gluing the conducting layer (the cladding) on the surface could create air gaps. If air gaps are excessive, then they can create their own multi-layer structure and should be accounted for at mm-wave frequency.

1.2.3 Problems of PCB-based Ferrite Circulator Integration in Millimeter-wave Range:

Microwave Circulators are essential components for full-duplex communications. Much work has been done with circulators supporting various applications such as radars, satellites, and defense systems [29]-[31]. Most circulator designs based on PCB technologies have substantial losses due to high dielectric materials [32], [33]. In addition, the losses could be due to both the ferrite disk (both dielectric and magnetic loss) and the feed (conductor losses). Using high dielectric enhances the circulators matching bandwidth and isolation level. However, higher losses are anticipated at the mm-wave bands, and surface waves and leakages deteriorate the system's overall performance. Air-filled rectangular waveguides could be an option to solve this problem. However, the fabrication of rectangular waveguides becomes more complex and expensive in the mm-wave bands and might only be suitable for some applications. Therefore, a solution is required with a printed structure that can support wideband communication in mm-wave without having high

dielectric materials to achieve better matching & isolation. In addition, the PCB technology has to suppress surface waves and leakages in the mm-wave band.

1.2.4 Integration of Custom-made Ferrite disks in Nonreciprocal Microwave Circuits:

Ferrites are common in the commercial industry for aerospace, automotive, biomedical instrumentation, communication, defense, radars, and satellites. The maximum available ferrites in the industry have a magnetization saturation of approximately 5300(G). It is possible to determine the proper frequency band for the ferrite based on saturation magnetization. High saturation magnetization supports high-frequency applications [33], [34]. Therefore, to cover a wide frequency range in the mm-wave spectrum, high-magnetization disks will be essential to build the microwave devices such as isolators, circulators, and differential phase shifters. Another problem associated with ferrite disks from the industrial point of view is the limited available sizes. Only some standard diameters and thicknesses are available. Fabricating custom-made disks takes a long time and has a high cost. Therefore, a productive technique should be employed to solve this problem with a straightforward approach highlighting the co-precipitation method to fabricate the powder and then use the powder to form a disk suitable for high-frequency microwave components. In most cases, only the chemical process is highlighted; however, the overall ferrite powder-to-disk fabrication steps are somehow not covered. Fabricating a ferrite disk goes through some significant steps, which must be clearly stated.

1.3 Motivation and Objectives

In 2009, Kildal proposed the Gap waveguide technology that uses PEC-PMC parallel plate configuration where the distance between the two plates is kept less than a quarter wavelength so that there is no wave propagation around the guiding structure within a specific bandgap [35], [36]. The wave is directed to propagate inside an air gap surrounded by periodic cells to realize the structure, which works like a high-impedance surface [37]. These periodic unit cells prevent leakage and ensure a quasi-TEM mode inside this air gap. A gap waveguide as a guiding structure exhibits superior characteristics to other guiding structures, such as microstrip lines and substrate-integrated waveguides [16]. A detailed analysis is discussed in [16], highlighting the attenuation, radiation, and conduction losses. Although the implementation of mm-wave components using

gap waveguide technology has been introduced, more developments are required to support future technology requirements. Here, we are particularly interested in a packaged PCB-based guiding structure, substrate integrated gap waveguide (SIGW), that uses periodic cells to control the structure's bandgap without signal dispersion. For a SIGW, a dielectric-filled gap is realized.

The objectives of this work are divided into three tracks.

- The first track focuses on designing an integrated horn of stacked layers of PCB substrates for the ka-band. The leakage problem between the stacked conducting surfaces is analyzed. At mm-wave frequencies, surface roughness or imperfect flat surfaces present possible gaps that cause severe unexpected leakage. This problem is almost overlooked by engineers designing mm-wave devices made of stacked layers of dielectric cladding substrates for cost reduction. Here, the problem is demonstrated for the first time. One of the PEC-PECs is replaced by PMC to have PEC-PMC parallel plates to prevent leakage. We propose transforming one of the PEC-PEC surfaces into artificially magnetic conductors (AMC), creating a PEC-AMC layer that suppresses any leakage with no contact between the surfaces; the gap is less than a quarter wavelength. In each layer of the horn, the opening is surrounded by periodic cells to suppress leakage and surface waves. In addition, the upper surface surrounding the horn's opening is covered by EBG mushroom cells to act as a soft surface that suppresses the surface waves and reduces the edge diffraction, which improves the radiation characteristics of the horn antenna.
- The second track focuses on a low-cost, wideband circulator design based on substrate-integrated gap waveguide (SIGW) technology. The circulator key design equations have been derived and tailored for SIGW technology. Most PCB-based circulators have massive dielectric losses at the mm-wave range, leading to spurious radiation, leakages, and surface waves, degrading the overall system performance. To improve the matching level, a two-section Chebyshev transformer is added to the ridge, and a low-dielectric filling has been considered to provide mechanical support to the ferrite disk. The reflection between the feeding lines and the center ferrite disks has been reduced. The filling dielectric materials have added insertion loss, but the mode has kept its Quasi-TEM type, resulting in a non-

dispersive operation. The proposed circulator is fabricated and tested for the first time based on SIGW in the mm-wave spectrum, where an acceptable agreement between the measured and simulated results is obtained. Moreover, an integration technique is demonstrated for the first time based on SIGW technology, where the circulator and the antenna are integrated to form a full-duplex system.

- The third task highlights a fabrication technique of an mm-wave high-magnetization ferrite disk with nickel-zinc ferrite (NZF) composition heated at different atmospheres. At first, using the chemical co-precipitation method, a nickel-zinc ferrite powder was fabricated and later baked at different temperatures. The magnetic properties such as X-ray diffraction, scanning electron microscope (SEM), and magnetization saturation using a vibration sample magnetometer (VSM) were verified at room temperature. Later, the ferrite powder was pressed with a hydraulic press machine to form the powder into a disk-shaped, which can be incorporated directly with a microwave circulator design. The fabricated ferrite disk magnetization is 1.8 times higher than the maximum magnetization in the microwave and space industries.

1.4 Contributions

The major contributions of this work are shown below, where several prototypes of mm-wave components and antenna subsystems are deployed.

- **Microstrip to SIGW Transition Design:** The SIGW is a packaged multilayer structure. To do the measurements, we have proposed and designed a wideband microstrip-SIGW transition with an excellent matching bandwidth with S_{11} below -28.5 dB over the operating bandwidth from 28-35 GHz. The transmission coefficient S_{21} is around -0.5 ± 0.1 dB over the whole operating bandwidth of the waveguide. This transition will be used to feed the SIGW horn antenna and the SIGW wideband circulator design.
- **SIGW Horn Antenna:** An integrated multilayer horn antenna based on SIGW technology is demonstrated for the first time to prevent unexpected leakages due to surface roughness

of imperfect flat surfaces from radiating structures in the mm-wave spectrum [117]. Many engineers overlooked this problem. The proposed horn antenna achieved 11 dBi gain and 20.5 % impedance bandwidth, with better than -26.5 dB cross-polarization.

- **SIGW Circulator Design:** A simplified analysis with a low dielectric-filled Ka-band Y-junction circulator is designed and fabricated for the first time based on SIGW technology [139]. A new design equation is tailored based on a low dielectric filling considering the effect of fringing fields around the ferrite disk. In addition, a new design equation to predict the coupling angle based on the relative permittivity of the material is proposed, which can give an excellent prediction to start the design work of the circulator. The proposed circulator covers a wide frequency range with a good return loss and isolation at the center frequency. It can support full-duplex communication and can be incorporated with Ka-band satellites and radars in the mm-wave range.
- **High Magnetization Ferrite Powder and Disk:** Another contribution of the present work is the invention of nickel-zinc ferrite (NZF) powder using co-precipitation measurement. Higher magnetization is critical and requires different compositions, sintering processes, and heat treatments. Many powders were processed, validated, and the measurement & proposed fabrication techniques are very effective in terms of performance, cost, and efficiency. A higher magnetization will allow microwave devices to operate at higher frequency bands. The proposed work covers different ferrite disks with a high magnetization suitable for mm-wave communication devices. The invented ferrite has a significantly higher magnetization than the available ferrite disks in the market. Different heat treatment atmospheres were considered to verify the saturation magnetization heating for 4 h. The proposed ferrite disk fabrication technique provided a magnetization $4\pi M_s$ of 9500 (G), 1.8 times more than the magnetization commercially available in the microwave and space industry. This will open a new doorway for the microwave and space industry supporting various future applications in the mm-wave spectrum. In the mm-wave range, the invented ferrite disk can be used with plenty of microwave devices, such as circulators, duplexers, isolators, differential phase shifters, etc. A US patent is filed for this innovative work [140].

- **Circulator Design Based on the Fabricated Ferrite Disk:** A prototype is manufactured to validate a circulator design with the fabricated ferrite disk at the mm-wave range. The circulator provides excellent measured isolation and return loss below -20 dB at the center frequency of 28 GHz. The proposed high-magnetization ferrites can be deployed with various other microwave devices, such as differential phase shifters, ferrite switches, and ferrite-based isolators. For validating our concept with high-magnetization ferrite disks, another example is given to design a wideband circulator operating at V-band from 50-70 GHz, with a matching level below -18 dB.

1.5 Dissertation Organization

The dissertation comprises six chapters with abstracts and references: The literature review of the guiding structures, SIGW-microstrip transition design, research methodology, fabrication limitations, and guidelines are covered in **Chapter 2**. **Chapter 3** illustrates an integrated multilayer horn antenna design based on a substrate-integrated gap waveguide covering a 28-34 GHz range suitable for mm-wave satellite applications. The multilayer horn antenna is compared with the PEC-PEC horn and metal horn antenna and provides exceptional performance in the mm-wave range. **Chapter 4** covers the ferrite circulator design based on SIGW technology. The Y-junction circulator was analyzed and simulated where excellent return loss, isolation, and insertion loss were obtained for the three-port nonreciprocal device. The ferrite was surrounded by a low-loss dielectric filling, 85 % below the ferrite materials permittivity, so the PMC boundary condition remains valid. **Chapter 5** describes the structural and magnetic properties of the Nickel-Zinc ferrite powder using a chemical co-precipitation process. The fabricated ferrite powder is heated at different atmospheres to enhance saturation magnetization. The highly magnetic powder is pressed with a hydraulic machine to form a disk supporting mm-wave spectrum RF devices such as circulators, isolators, and differential phase shifters. Finally, **Chapter 6** covers the outcomes and suggests valuable extensions for future work. The standard operating procedure (SOP) highlighting the synthesis of Nickel-Zinc Ferrite (NZF) nanoparticles is covered in the appendix section.

Gap Waveguide Literature Review and Design

2.1 Overview:

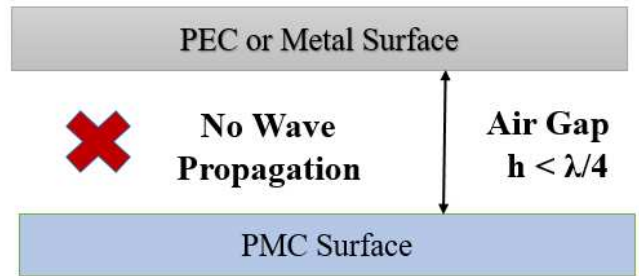
The design challenge for wireless communication in mm-wave frequencies is to simultaneously realize an overall system with low loss, compact size, fabrication feasibility, and cost-effectiveness. In 2009, Kildal proposed the Gap waveguide technology that uses PEC-PMC parallel plate configuration where the distance between the two plates is kept less than a quarter wavelength so that there is no wave propagation around the guiding structure within a specific bandgap [35], [36]. To realize this structure, the wave is directed to propagate inside an air gap surrounded by periodic cells, which works like a high-impedance surface [37]. These periodic unit cells prevent leakage and ensure a quasi-TEM mode inside this air gap.

2.2 Different Guiding Structures Based on Gap Waveguide:

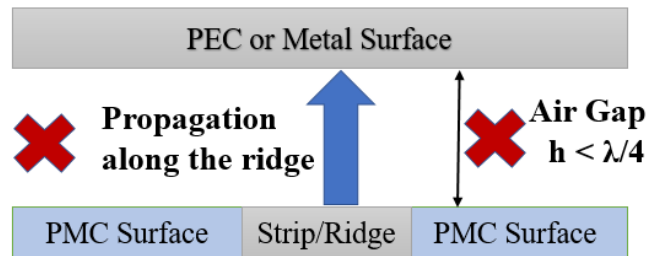
A gap waveguide as a guiding structure exhibits superior characteristics to other guiding systems, such as microstrip lines and substrate-integrated waveguides [16]. A detailed comparison is highlighted in [16], showing different PCB guiding structures' conductors, radiation, and attenuation losses. A gap waveguide consists of two parallel plates, one is a Perfect electric conductor (PEC), and the other is a perfect magnetic conductor (PMC). A perfect magnetic conductor does not exist in nature. However, it can be realized with a periodic structure such as a metal bed of nails or mushrooms. Fig. 2.1 illustrates the basic operating principle of a gap waveguide technology.

As shown in Fig. 2.1 (b), incorporating a ridge in the middle surrounding the PMC surface will create a PEC-PEC configuration that will allow wave propagation and support a Q-TEM mode, which is indicated with the blue arrow. On the other hand, the PEC-PMC configuration will block any wave propagation transverse to the ridge direction, displayed with the red cross-shaped mark. The gap waveguide can be considered an extension of the hard and soft surfaces. Soft surfaces block any polarization wave propagation, whereas hard surfaces support wave propagation [38].

This concept is mainly used to improve the horn antennas' radiation characteristics by adding corrugated surfaces [39]. The realization of soft and hard surfaces is highlighted in Fig. 2.2.



(a)



(b)

Fig. 2.1: (a) PEC-PMC parallel plate configuration, (b) Ridge surrounded by PEC/PMC surfaces.

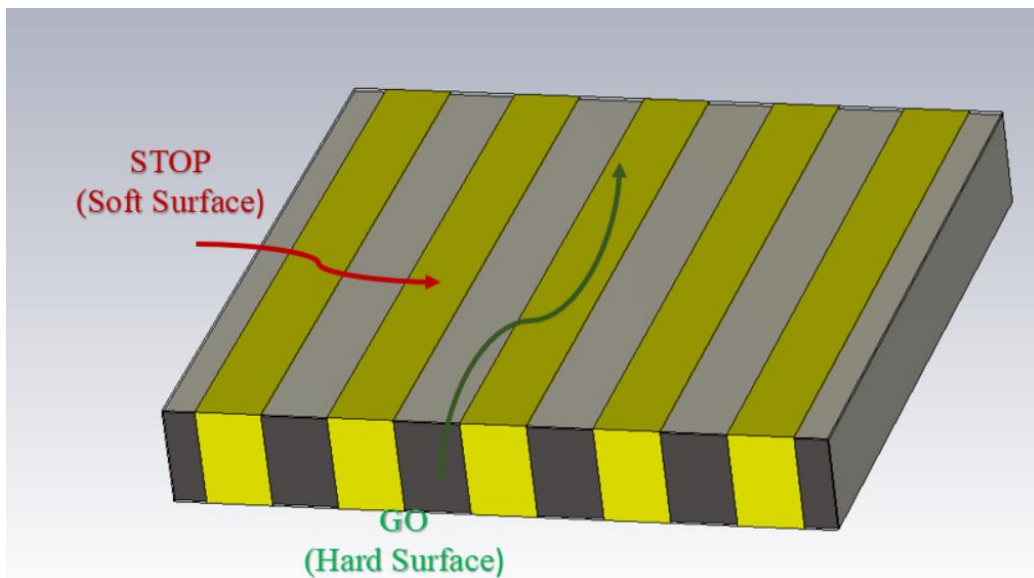


Fig. 2.2: Illustration of soft and hard surfaces re-plotted from [41].

The use of the soft surfaces and electromagnetic bandgap (EBG) in a wireless inter-chip communication concept is studied, which had a significant advantage in focusing the energy toward the receiving antenna eliminating the spherical spreading losses from the radiated spherical wave nature [40]. Further explanation of the mechanism by which soft surfaces function is provided in [41], [42].

Electromagnetic bandgap (EBG) structures can stop the wave propagation in two dimensions (2-D) of all polarization and directions within a certain stopband, defined by the unit cell dimensions. EBG surfaces can be realized with joints made of metal pins periodically in 2-D surfaces, known as the 'bed of nails' [43]. These beds of periodic nails can also be realized with PCB structure, where the metallic pins are replaced by conducting plated vias and covered with a circular or square-shaped patch [44], [45]. The periodic bed of nails is highlighted for both metal and PCB structures in Fig. 2.3.

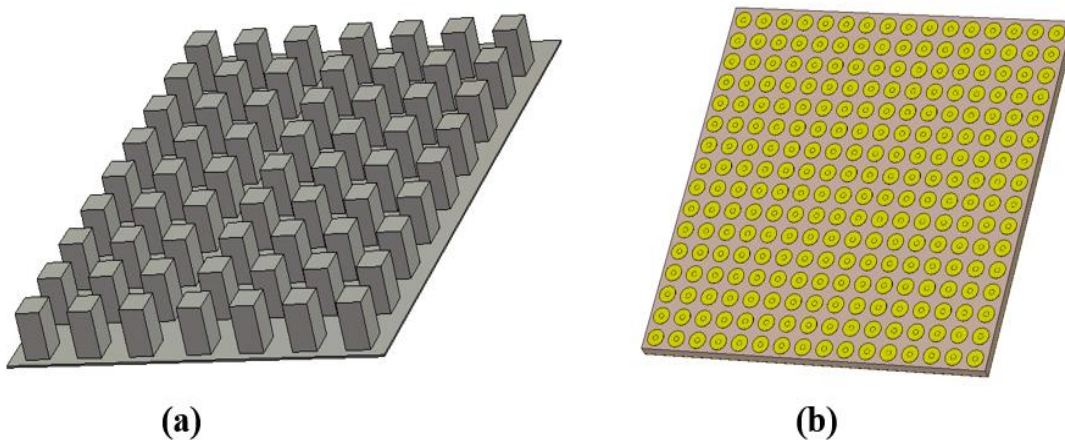


Fig. 2.3: Electromagnetic bandgap structures, (a) periodic bed of nails, and (b) bed of mushrooms, re-plotted from [37].

The mushroom patches are also known as Sievenpipers mushroom cells [37]. Each cell is a square patch on a grounded dielectric substrate connected to the ground by a thin wire. The wire is realized by metalized via holes between the patch and the ground plane. These periodic EBG structures generate a high-impedance surface without wave propagation within the bandgap. It is

worth mentioning that the height of the substrate should be one-tenth of a wavelength, where the vias are essential to suppress the surface waves within the substrate.

In 2009, Kildal *et al.* [35] proposed the gap waveguide technology, where the necessary cut-off of parallel plates of a perfect electric conductor (PEC) and perfect magnetic conductor (PMC) configuration was used to control the electromagnetic wave propagation between the PEC-PMC parallel plates. The PEC-PMC parallel surfaces suppress the wave propagation for any polarization if separated by a distance less than $\lambda/4$. However, if a PEC strip is placed on top of the PMC surface (representing the ridge), a parallel-plate waveguide mode (PEC-PEC separated by a distance less than $\lambda/4$) is supported for the vertically polarized wave propagation. Thus, PEC-PEC is surrounded from both sides by PEC-PMC, suppressing wave propagation between them and only allowing propagation between PEC-PEC parallel plates. As naturally, there is no PMC, it is realized artificially by a periodic bed of nails where the surface acts as an artificial magnetic conductor (AMC) surface [36], [37]. In addition, to suppress the waves, the air gap separation between the parallel surfaces must be less than a quarter of a wavelength within the frequency band that satisfies the AMC condition. The basic geometry of a ridge gap waveguide (RGW) is shown in Fig. 2.4(a).

The RGW supports Quasi-Transverse Electromagnetic (Q-TEM) mode approximation and is not subjected to any signal dispersion, which mitigates the signal distortion. Various microwave components supporting multiple applications at mm-wave had already been deployed based on this technology. Antenna arrays and large feeding structures have been demonstrated based on ridge gap waveguides in the literature [47]-[51]. In addition, microwave components for various applications, such as power dividers, couplers, resonators, filters, diplexers, etc., were already fabricated based on this technology [52]-[57]. Instead of an air-filled RGW, a dielectric-filled RGW can also be used for a matching purpose, as illustrated in Fig. 2.4(b), providing a Q-TEM mode propagation. Adding a dielectric-filled gap waveguide will add losses associated with the high dielectric material [31]. Other types of gap waveguides were proposed based on the RGW principle, such as groove gap waveguides, as highlighted in Fig 2.4(c).

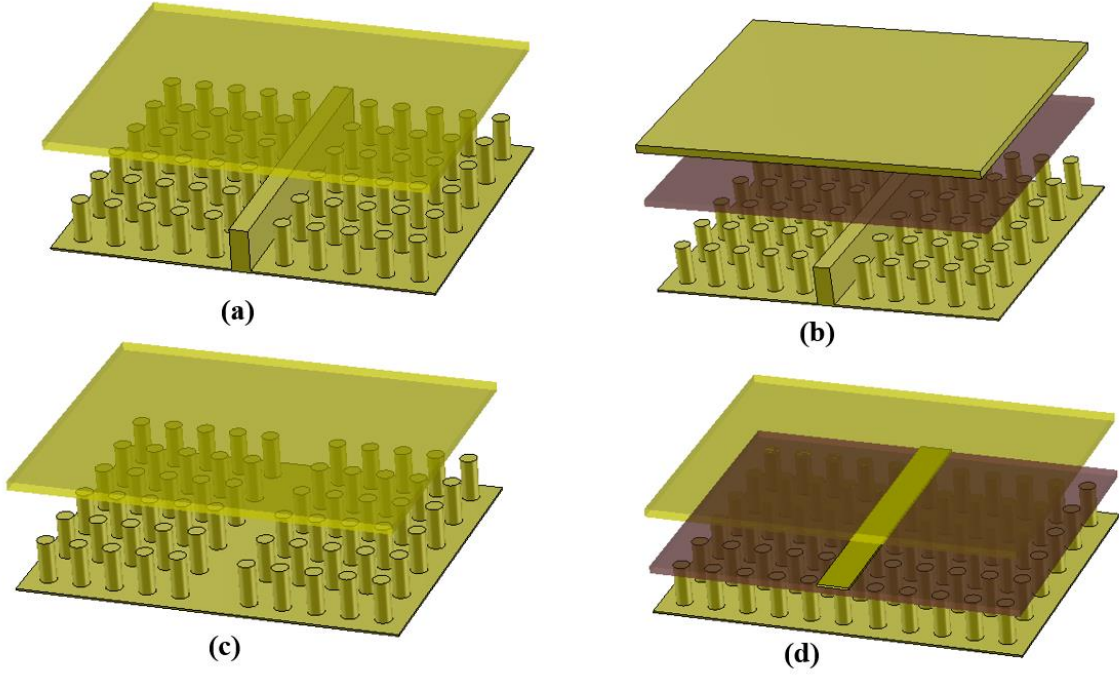


Fig. 2.4: Metal Gap Waveguide structures, (a) Ridge gap waveguide, (b) Dielectric-filled gap waveguide, (c) Groove gap waveguide, (d) Inverted microstrip gap waveguide, re-plotted from [16].

In terms of losses and performance, the groove gap waveguide (GGW) has various advantages over RGW, such as it supports TE mode propagation. The ridge is removed while a groove is embedded with a periodic bed of nails on both sides [55]. The mode propagation of GGW is similar to a rectangular waveguide, and it can handle high power. Several microwave components in the mm-wave range are already deployed based on GGW technology [57]-[60]. Moreover, microwave monolithic integrated circuit (MMIC) implementations were also developed based on this technology [61], [62]. Inverted Microstrip Gap Waveguide (IMGW) has the same mode propagation as the RGW, where the ridge is removed, and a substrate is loaded on top of the periodic bed of nails [63], [64]. The IMGW can facilitate the design process since arranging a metal bed of nails around the resonators and lines based on RGW can be complicated. However, the additional substrate on the top will increase the overall size, and the substrate introduces dielectric losses. In addition, the bandgap will be reduced for this type of gap waveguide because of the additional substrate, which will increase the gap from the bed of nails to the top metal conductor [64], [65].

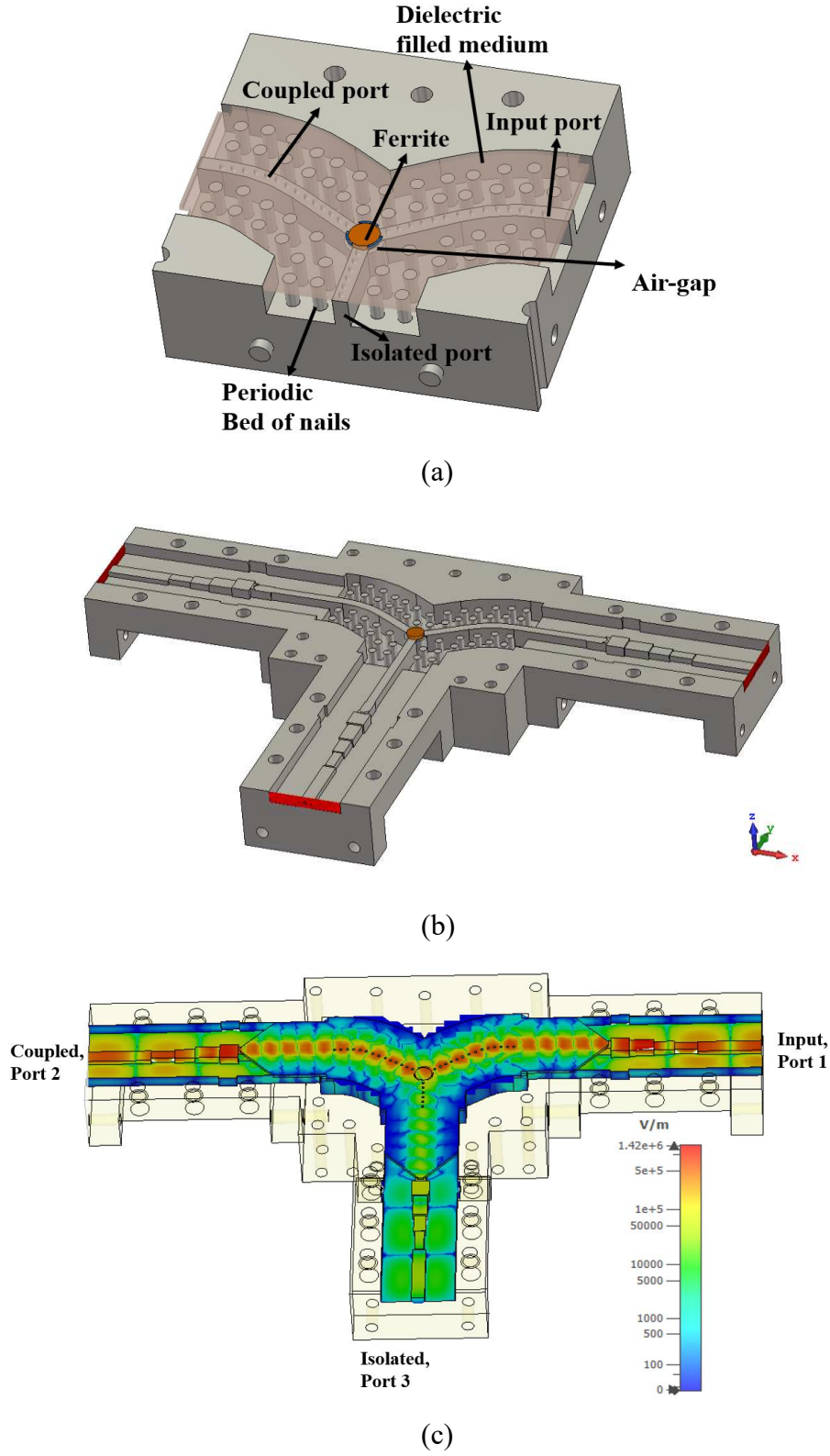


Fig. 2.5: (a) 3D view of a Y-junction ferrite circulator based on RGW, (b) Y-junction circulator with proper transition, (c) Electric field distribution at 15 GHz with an input power of 3 KW.

The gap waveguide has a high-quality factor and low attenuation. It can handle high power and does not require any electrical contact like rectangular waveguides, which facilitate the deployment in the mm-wave range. Fig. 2.5 (a) and Fig. 2.5 (b) show a high-power ridge gap waveguide circulator design operating from 12-18 GHz, where the upper ground is hidden for a clear illustration. Fig. 2.6(c) shows the power flow figure where the injected power is 3 KW and the E-field strength is 1.425 MV/m, almost half of the breakdown voltage of 3 MV/m. Generally, if the E-field strength inside an air gap exceeds 3 MV/m, there will be a spark, and the component will burn.

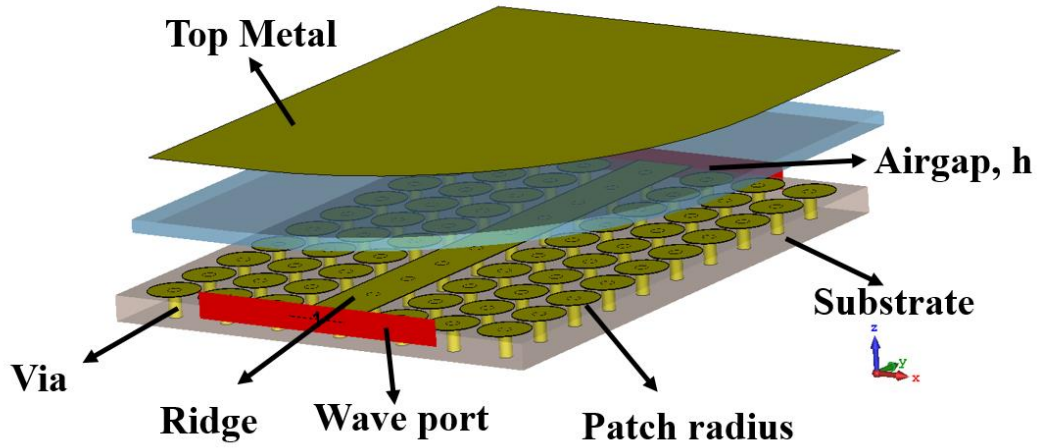


Fig. 2.6: 3D-view of printed ridge gap waveguide.

Although metal RGW structures show excellent performance in power handling, low loss suppresses surface waves within a specified bandgap. It will require high-precision CNC milling, which is expensive. In addition, most CNC milling companies have a fabrication tolerance of 0.005" or 0.13-mm precision [66], which can significantly affect the performance of the microwave components at the mm-wave frequency band. Although the RGW provides a packaged solution, it might not be a good solution for many applications. A printed ridge gap waveguide (PRGW) can be employed by replacing the bed of nails with a bed of mushrooms to solve this problem, as shown in Fig. 2.6.

A PRGW can be suitable for replacing the standard PCB guiding structures such as substrate-

integrated waveguides (SIW), microstrip lines, strip lines, and coplanar waveguides (CPW). At higher frequencies, all the PCB-based guiding structures will have significant dielectric losses and severe leakages due to bending and surface waves, and it will excite cavity modes [13], [16]. Some of the critical benefits of the PRGW structure are given below,

- ❖ Contactless, it can be connected with plastic screws,
- ❖ It can suppress surface waves and leakages within a specified bandgap,
- ❖ Planar, less fabrication complexity,
- ❖ Lower loss at the mm-wave range,
- ❖ Suitable for packaged MMIC integration, and
- ❖ Supports Q-TEM, TE, and TM mode propagation.

Multiple antennas and antenna feeding structures were deployed using this PCB guiding structure, and many techniques were implemented to enhance the system's bandwidth. A 4 x 4 Printed ridge gap waveguide antenna array with magneto-electric (ME) dipole was used for the high gain [68]. A high gain bow-tie antenna array with grooves was proposed in [70], which had high edge diffractions from the slot substrate and the top metallic groove. In addition, the structure became extremely bulky after adding the three-layered grooves with brass material limiting its applications. A dual-polarized printed ridge gap waveguide antenna was utilized to obtain high isolation; however, the feeding structure became very complicated for using five substrates, where two were for excitation purposes only [71]. In addition, a 3D printing dielectric polarizer was fed by a PRGW ME dipole antenna with dielectric slabs to provide 20 dBi gain and 6.5 % axial ratio bandwidth [72]. A planar SIW, cavity antenna array, was excited with PRGW technology to provide high gain and wide bandwidth; however, the sidelobe level is less than -7 dB at high frequency, which limits its applications [73]. Besides, beamforming network components, such as couplers, crossovers, and butler matrixes, are designed based on this technology. In [74], a 3-dB coupler with PRGW technology was used to support the mm-wave applications. In addition, a compact crossover was demonstrated at 30 GHz for beamforming applications [75]. In [76], a 0-dB backward coupler with PRGW technology was used to support the mm-wave applications. A 4 x 4 butler matrix using couplers, cross-overs, phase shifter, and the semi-log periodic antenna is deployed using Printed RGW from 27-33 GHz with ± 1.5 dB output amplitude imbalance and $\pm$

10° phase errors [77]. In [78], a PMC-packaged single substrate 4 x 4 butler matrix is designed and integrated with a double ridge horn antenna for multi-beam purposes at the mm-wave range. Moreover, PRGW has been utilized to develop microwave components for mm-wave and sub-mm-wave, such as diplexers and power dividers [80], [82]. In [79], a low-loss gap-coupled bandpass filter is designed with five-section Chebychev transformers to improve the matching level. In addition, a wideband Shiffman 45° phase shifter was proposed with an output phase difference of $45^\circ \pm 3.5^\circ$ [81]. In addition, reconfigurable PRGW structures were deployed in the mm-wave band to support strong and compliant communication systems [120], [121]. Moreover, some articles in the mm-wave band discuss an integration technique PRGW with an active amplifier module [122], [123].

RGW is not a standard technology that can be launched using standard measurement equipment. Hence, proper transitions are required to connect the RGW to standard connectors for measurements such as the waveguide, coaxial, and microstrip line [83]-[85]. Instead of having an air-filled PRGW, it is also possible to have a substrate-integrated gap waveguide (SIGW) configuration, where the wave propagates inside a dielectric material. The following section will highlight the unit cell structure and the SIGW-microstrip transition design.

2.3 Substrate Integrated Gap Waveguide:

The substrate-integrated gap waveguide (SIGW) can create a stopband using a periodic structure that suppresses the leakage around the ridge. The fields are confined within the ridge region. The unit cell design is visited in many articles, where both the cell dimensions and the response are illustrated [70], [74], [85]. The unit cell design is conducted using the EIGEN MODE SOLVER of CST Microwave Studio. From this solver, the dispersion diagram can be obtained, which will provide the EBG behaviour of the unit cell. Some of the essential parameters that control the bandgaps are: airgap, via diameter, spacing between via to via, and height of the vias are varied to obtain the objective bandgap.

The SIGW is a packaged multilayer structure. To do the measurements, microstrip-SIGW transition is used, as highlighted in Fig. 2.7(a). The first layer contains periodic cells along with the ridge, and the second layer includes the dielectric filling extended on both sides to have a proper microstrip-SIGW transition. The S-Parameter of the transition is illustrated in Fig. 2.7(b).

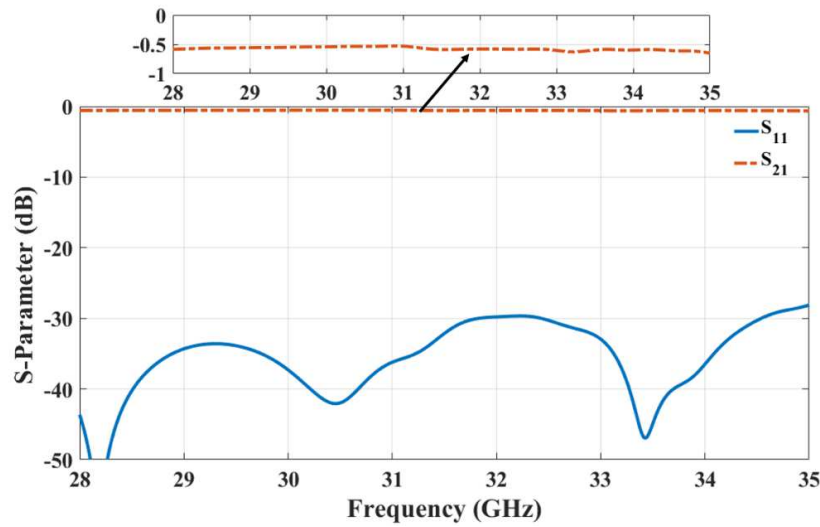
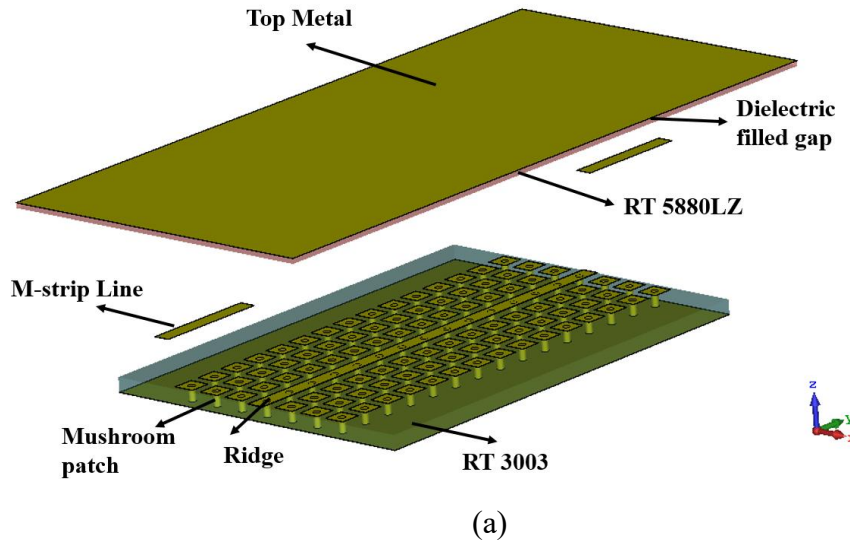


Fig. 2.7: Microstrip-SIGW transition, (a) Geometry, (b) Simulated S-Parameter response.

The matching bandwidth of the waveguide shows an exceptional result from 28-35 GHz, with S_{11}

below -28.5 dB over the operating bandwidth. The transmission coefficient S_{21} is around -0.5 ± 0.1 dB over the whole operating bandwidth of the waveguide. The feeding line width of a 50 Ω microstrip line is $W_m = 0.83$ mm different from the ridgeline width of $W_r = 0.9$ mm. Therefore, the same ridgeline was added to the dielectric-filled line again and connected to the standard 50 Ω microstrip line. Here there is no need for a stripline since the used gap considered is a dielectric-filled medium, the same as the substrate of the microstrip line. For clarification, the transition step would require three different transitions instead of a dielectric filling if it were an air-filled structure. The first one will be the 50- Ω microstrip line; the second step will be a strip line since two different filling mediums exist, and the air-filled structure will have a different line width. Usually, the feeding microstrip line is extended up to 2-3 periodic cells, similar to the stripline configuration [70], [85]. Usually, three mushroom cells on both sides of the feed line are sufficient to control the bandgap of the structure without having a leakage. Using more periodic cells beyond that does not improve the performance in terms of the transmission or matching level. In other words, using more cells will increase the computational time and cost with similar performance with three periodic cells [14], [16], [65].

2.4 Circulators: Topology, Applications & Review

This work focuses on designing a Y-junction ferrite circulator, an essential component in the RF frontends. The microwave circulator is a three-port device where power can be transferred from one port to another, whereas the third port is isolated. Microwave circulators were designed to support radar applications in the 1950s [86], [87]. For decades, significant effort has been directed to this type of component, providing various techniques to enhance the performance of the circulators. The first circulator design was proposed using Faraday's rotation techniques and was limited to low-power applications [87]. Phase shift circulators were utilized for a more significant gap size to ensure high power handling capability [88], [89]. The Y-Junction circulator is widely used where the ferrite disk is placed in the middle of the circular junction [90], [91]. In addition, the middle ferrite disk was implemented through many configurations, such as triangular or hexagonal-shaped posts, which are responsible for the non-reciprocal behaviour of the circulator [92], [93].

Microwave circulators were deployed in many commercial applications, such as high-power air traffic surveillance and airborne weather sensing radars [29], [30]. A ridge gap waveguide of ferrite circulator was proposed, covering a whole Ku-Band, with excellent return loss and isolation level [31]. However, using a metal ridge gap waveguide requires higher accuracy CNC milling, which will be expensive, and the structure is bulky, which will not be a suitable option in the mm-wave range. In addition, an X-band circulator and antenna as a single integrated system was proposed using microstrip technology that provided a return loss above 14 dB, with a high insertion loss and narrowband [32]. A similar approach was made to integrate a circulator and antenna in a single layer at the Ku-band. The insertion loss is improved using an impedance equalizer to balance the circuit [33]. In addition, a stripline ferrite circulator was designed at K-band, where stripline modes were considered to solve electric field expression [34].

A self-biased Y-junction narrowband ferrite circulator operating at 13.65 GHz was proposed, where the insertion loss is around 1.52 dB [94]. In addition, a ferrite LTCC multifunctional circulator with integrated winding was designed at Ku-band, where both external magnets and external 200 mA current were applied to achieve a 1.6 dB insertion loss [95]. Moreover, a Y-junction circulator based on ESICL has been designed to cover 33% impedance bandwidth with a measured insertion loss of 1 dB [96]. In addition, substrate integrated waveguide technology was also deployed to build microwave circulators using a complex gyrator circuit at 24 GHz [97]. Various circulators were also deployed and incorporated with the antennas to form full-duplex communication.

An integrated microwave circulator and antenna assembly were proposed using a complex port impedance to have a maximum power transfer to cover 4 GHz bandwidth from 12-16 GHz [98]. A SIW-based ferrite-circulator-based antenna module was designed at Ka-band that provided 5% bandwidth, and a measured transmission coefficient of 4 dB was attributed to the dielectric loss and discontinuities between the circulator and the ferrite surface [99]. Moreover, a self-biased, wideband microstrip circulator for an integrated antenna system was proposed with a high insertion loss of 2.7 dB with 10.7% impedance bandwidth (covering 32-35.6 GHz) [100]. Most of the previously published circulators are designed with microstrip line technology, which will have a massive loss at the mm-wave range and encounter surface waves and leakage issues. The packaged

SIGW circulator will not encounter any leakages within a specified bandgap and will provide strong mechanical support compared to the other published designs.

2.5 Research Methodology:

Although much work is published with the printed RGW technology, there is room for more development in the mm-wave range. Printed RGW has featured performance compared to other PCB guiding structures working at mm-wave bands. In the following chapters, a more detailed analysis of the components will be demonstrated from an analytical point of view to simulation and later fabrication & testing of the design component. Before that, a design methodology will be highlighted here, starting with the design specifications and requirements. Later the components will be verified using the 3-D electromagnetic (EM) solver; afterward, the components will be fabricated and measured.

2.5.1 Design Specification and Requirements:

The most crucial step in the design is identifying the specifications supporting a specific application. This work's objective frequency band is 30 GHz, suitable for Ka-band satellite applications supporting full-duplex communication. The present work is at the mm-wave band with printed technology, and it is essential to realize what type of guiding structure will be suitable to operate at these frequency bands with lower losses. Besides, the oxygen absorption losses are relatively higher than the lower frequency bands in the mm-wave range, so high gain antennas are required to compensate for the losses. This work primarily focuses on integrating an antenna and circulator to form a full-duplex system. So each component needs to be separately designed with its specifications. For instance, we consider -10 dB as a sufficient matching level while designing an antenna for RF frontends. However, considering the integration between the antenna and the circulator, it is better to have an antenna with a deep matching characteristic. Because due to the loading effect, the overall performance will change. We have considered a -15 dB as a standard matching for this work while designing the circulator and the antenna within the objective frequency bands.

2.5.2 Design & Optimization:

The design and optimization are done using Computer System Technology (CST) Microwave Studio, a 3D Electromagnetic Solver. Unit cell waveguide design and optimization will be discussed in this section, along with some limitations of the fabrication process.

- ❖ **SIGW Unit Cell Design:** The unit cell design is conducted using the EIGEN MODE SOLVER of CST Microwave Studio. From this solver, the dispersion diagram can be obtained, which will provide the EBG behavior of the unit cell. For the designed SIGW unit cell, the bandgap is from 20-47 GHz, which is already shown in Fig. 2.7(b). Some of the essential parameters that control the bandgaps are: airgap, via diameter, s between via to via, and height of the vias are varied to obtain the objective bandgap.
- ❖ **Waveguide Design & Optimization:** The waveguide is designed using the time domain solver (transient solver) using CST Microwave Studio. The time-domain solver uses the finite integration technique, where Maxwell's equations are solved numerically in the integral form. On the other hand, the frequency domain solver of CST uses the differential of Maxwell equations numerically and is based on the finite element method (FEM) [119]. The operating frequency band of the waveguide will be pretty similar to the dispersion diagram of the unit cell.

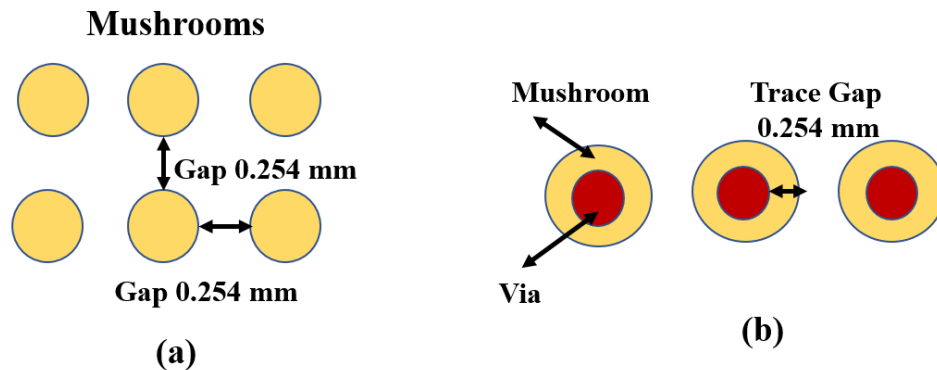
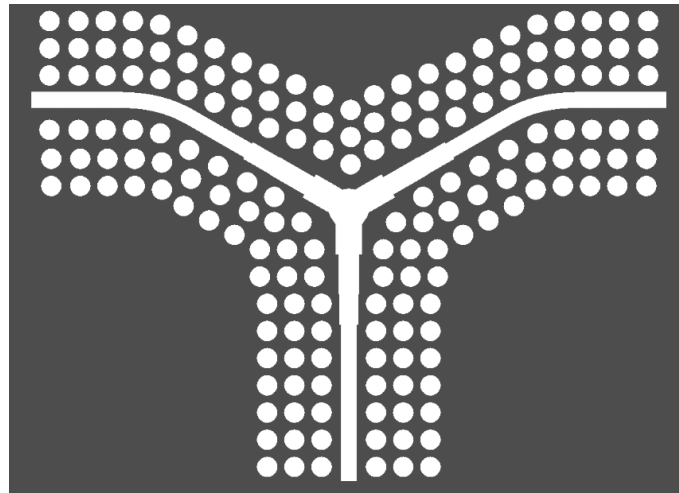


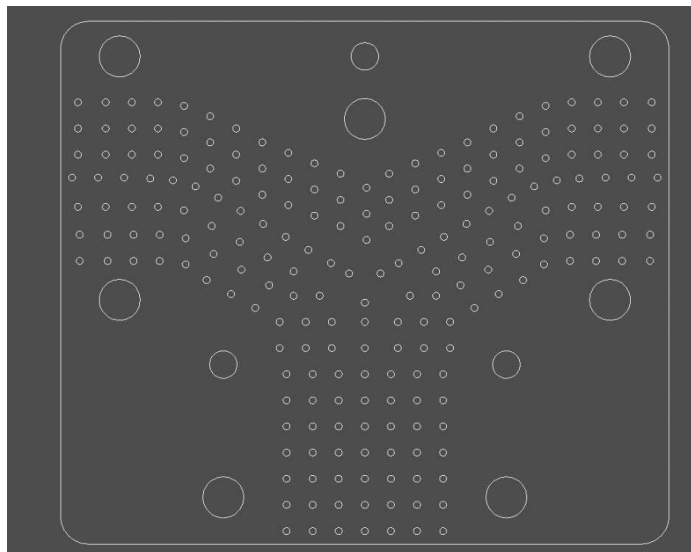
Fig. 2.8: Fabrication guidelines of plated vias, (a) mushroom to mushroom distance, (b) via edge to mushroom edge distance.

2.5.3 Fabrication Guidelines:

After finalizing the simulation, the next step is to prepare the fabrication files of the PCB structures. In practice, the simulator uses waveguide ports, considering the ideal scenarios. However, while doing a practical measurement, a connector will be required. In our case, a 2.92 mm female end-launch connector is used from Southwest Microwaves. 2.92 mm end launch connectors allow the connection between the device under test (DUT) and the measurement equipment interface.



(a)



(b)

Fig. 2.9: Fabrication files, (a) Gerber format, (b) Dxf format.

Adding a connector will add additional losses (insertion losses) in the structure, highlighted in the datasheet from the southwest microwave's website [101]. The SIGW is a multilayer PCB structure that can be connected using thermal pressing or with some plastic screws. The fabricated layers are assembled using high temperature and pressure, which uses adhesives at the layers' corners to provide good mechanical stability [102]. The adhesive that connects the layers is epoxy glue with a dielectric constant of 3.5, which requires high temperature and pressure to combine the layers [103]. Some fabrication tolerances and limitations for the plated vias design need to be followed. Firstly, the minimum via diameter must be half of the substrate height. Secondly, for any mushroom cells to other mushroom cells, the minimum gap has to be 0.254 mm or 10 mils (0.01"). Finally, the distance from the via to the mushroom trace must be 0.254 mm or 10 mils (0.01"). Fig. 2.8 highlights the fabrication guidelines of the plated vias and mushroom cell placements.

The 2-D Gerber and Dxf files are extracted from CST to prepare the PCB boards using the LPKF PCB prototype technology and laser material processing machine. The Dxf files are required for making the drill files, and the Gerber files are for etching the conductive layers. Fig. 2.9 highlights a sample Gerber and Dxf files, where the Gerber files indicate the conductive part, and Dxf indicates the drill formats.

2.5.4 Testing and Experimental Validation:

The Scattering-parameter is measured using an N52271A Vector network analyzer, where the measurement setup is Fig. 2.10. The vector network analyzer can measure up to 67 GHz at Concordia University. The gain and radiation patterns are measured inside an anechoic chamber, as shown in Fig. 2.11.

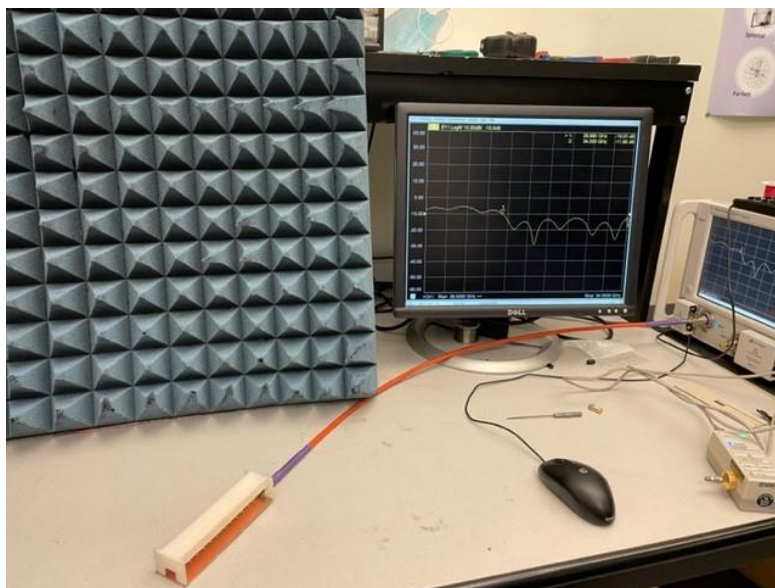


Fig. 2.10: Measurement setup of N52271A vector network analyzer.

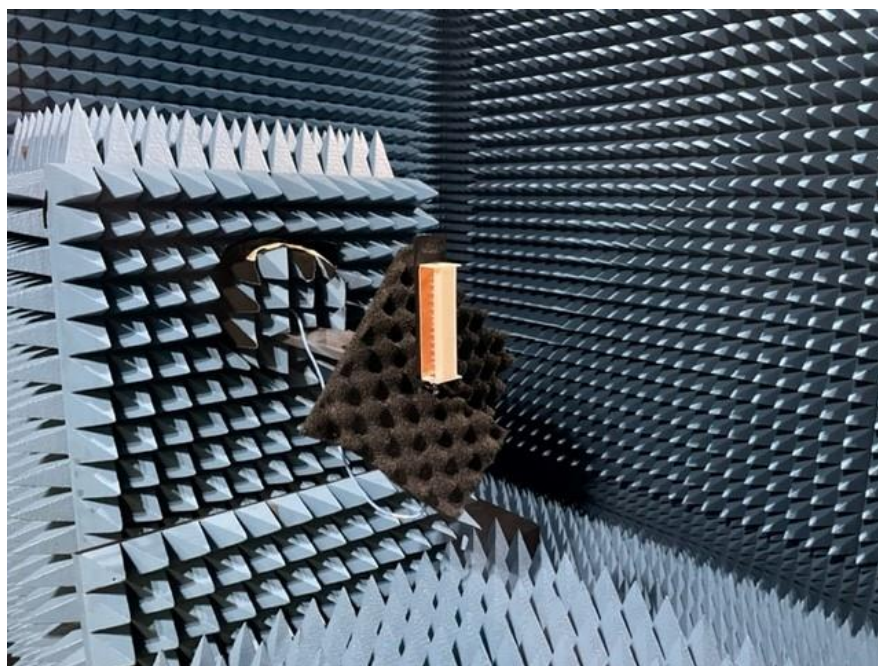


Fig. 2.11: Measurement setup of an antenna inside the anechoic chamber.

Ka-Band Integrated Multilayer Pyramidal Horn Antenna Excited by Substrate Integrated Gap Waveguide

3.1 Introduction

Pyramidal horn antenna is one of the simple popular aperture antennas for medium-range gain. For the last 70 years or beyond, it has been considered one of the most exceptional antennas with excellent performance in terms of gain, bandwidth, and radiation pattern [104], [105]. Conventional horn antennas are usually fed by a waveguide, traditionally made of a perfect electric conductor (PEC). The pyramidal horn antenna consists of flared conducting walls in E- and H-plane to extend the waveguide walls. Flaring angles and horn length are designed to achieve certain radiation characteristics. Integrating the horn antenna at mm-wave frequencies is difficult without using a transition between the waveguide and the printed circuit [105],[106]. Here, to overcome these difficulties, the conventional rectangular waveguide is replaced by a printed wideband slot fed by a substrate-integrated gap waveguide (SIGW) to ensure unidirectional radiation and no direct back radiation from the slot.

3.2 Multilayer Horn Antenna Design Procedure:

A wideband slot antenna is excited by a substrate integrated gap waveguide (SIGW) to provide unidirectional radiation. A multilayer pyramidal stepped horn is placed above the slot to enhance the antenna's directivity. The horn walls are formed as stepped conducting walls. The horn length is chosen to be short to achieve a certain beamwidth. The walls are realized by four thin dielectric substrate layers of double cladding with rectangular cuts surrounded by conducting vias to form the conducting surface walls. The substrate layers are stacked above the slot. It should be stated that vias on the H-plane side could be removed for a linearly polarized horn. The edges of the conductor cuts would be sufficient to act as a conducting wall. The two parallel conducting surfaces are parallel to the electric field that can not be propagating between them, as the gap is much less than a half wavelength that should allow this polarization to propagate between them. As the aperture size increases, the gain should increase; however, aperture phase errors would deteriorate the gain and the radiation characteristics. Therefore, adjusting each layer's opening size

is essential to control the horn's flare angles and reduce the aperture phase error. Since the proposed pyramidal horn antenna is based on PCB multilayer substrates, there could be some undesired surface roughness or unflattened surface of the substrates. The surface roughness causes invisible air gaps that create PEC-PEC parallel plate waveguides supporting substantial electromagnetic signal leakage regardless of the air gap height, as shown in Fig. 3.1(a). It is essential to control the layers' leakage by assuring complete electrical contact between them, as the physical electrical connection would not be guaranteed.

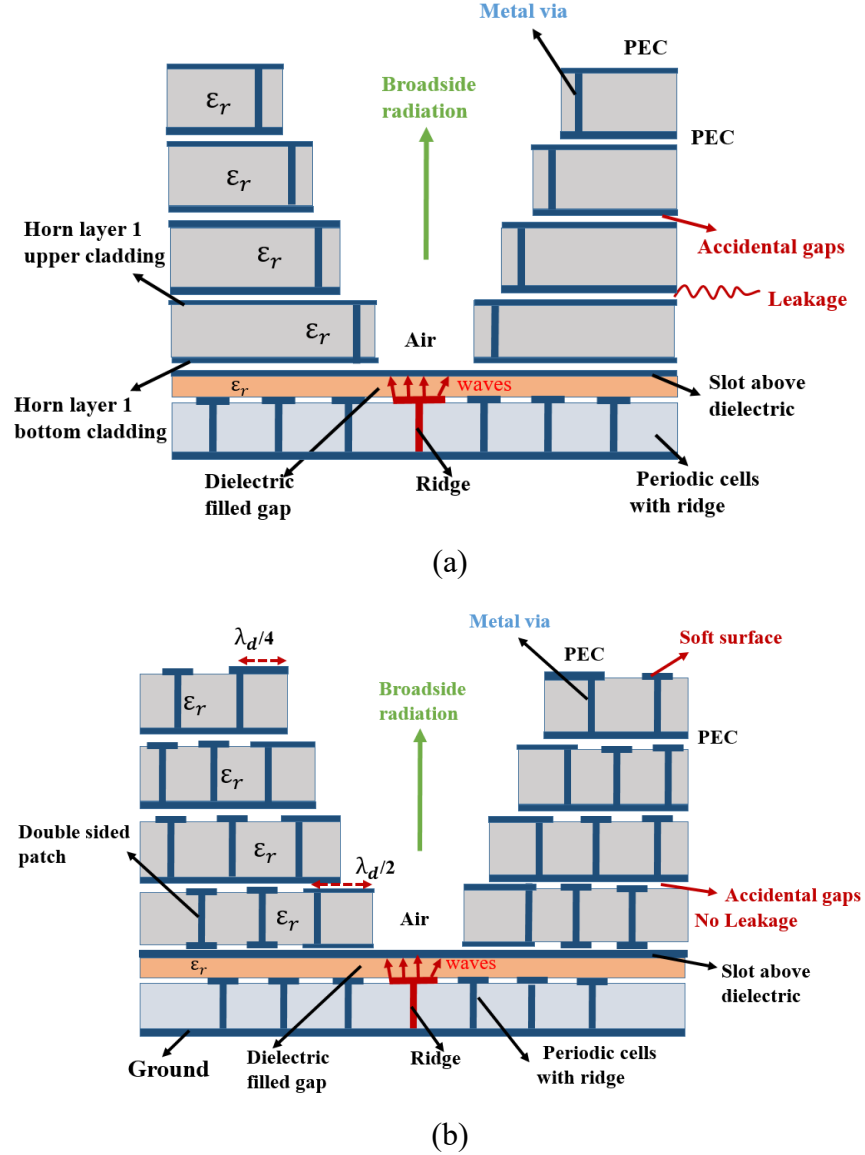


Fig. 3.1: Cross-sectional view of the proposed antenna, (a) PEC-PEC configuration, (b) PEC-AMC between layers.

To prevent leakage, even if an air gap exists, one of the PEC surfaces must be converted to a perfect magnetic conductor (PMC) to have two parallel plates of PEC-PMC. As such, no waves propagate between PEC-PMC surfaces as far as the gap between them is less than a quarter wavelength. However, PMC does not physically exist. A periodic structure with high impedance can realize the PMC surface surfaces, creating an artificial magnetic conductor (AMC) surface that acts as a PMC within a specified bandwidth, as illustrated in Fig. 3.1(b).

The periodic surface must be designed for the desired band, including the antenna's intended operating bandwidth. One possible AMC can be realized by an array of cells of mushroom patches. The mushroom patches are also known as Sievenpipers mushroom cells [37]. Each cell is a square patch on a grounded dielectric substrate and connected to the ground by a conducting thin wire. The wire is realized by metalized via holes between the patch and the ground plane. The top surface of the last layer that forms the horn aperture is surrounded by the conducting surface. This surface support surface electric currents that radiate, causing deterioration of the horn radiation characteristics. To improve that, the surface is converted from a hard surface (PEC) to a soft surface (AMC) by surrounding the aperture with mushroom cells. Therefore, the horn design requires three different types of mushroom cells that are supposed to be appropriately designed to support the required operating frequency band. The first one is the cell surrounding the printed SIGW line that excites the slot. The SIGW width and the dielectric-filled gap height are designed to match the input port and couple efficiently with the slot. The second one is the cell between the layers, which has the smallest possible air gap as they represent a likely accidental gap; the last one is the top cell, which should act as a soft surface surrounded by the free space.

In the next two sections, this concept is discussed in more detail. For the proposed horn antenna, the outer aperture length and width are designed based on the following equation [105],

$$A = \sqrt{3\lambda\rho_2} \quad \text{and} \quad B = \sqrt{2\lambda\rho_1} \quad (3.1)$$

where A and B are aperture length and width, λ is the wavelength, ρ_1 and ρ_2 , phase center in E- and H-plane, respectively. Here, four stacked dielectric substrates provide the horn antenna length where each layer's thickness is 1 mm. The bottom substrate is printed on Rogers 3003 material

with a thickness of 0.75 mm. The dielectric-filled gap is chosen to be 0.254 mm. Adding all these values gives the distance from the phase center to the last aperture. In both planes, the phase center is considered the same, which is 6 mm or 0.6λ , a very short horn operating at the central frequency of 30 GHz.

Substituting the following values in Equation. (3.1) provides the outer aperture dimension $A = 13.4$ mm and $B = 10.4$ mm, respectively. The horn antenna is designed by selecting the optimum flaring angle of the pyramidal horn antenna and realized by the proposed stepped horn structure [104], [105]. Modifications have to be made to the outer aperture size so that the flaring in both planes becomes less than 90° . Usually, for a traditional horn antenna, ρ_1 and ρ_2 are comparatively larger than our proposed antenna. In the proposed work, it is $\rho_2 = 0.6 \lambda$ which is larger than $A/2 = 0.67\lambda$. To overcome this issue, the following modifications are highlighted in the following proposed equations.

$$A = \sqrt{3\lambda\rho_2} - \delta_a \quad \text{and} \quad B = \sqrt{2\lambda\rho_1} - \delta_b \quad (3.2)$$

where, $\delta_a = 2$ and $\delta_b = 1.4$ are the subtracted length and width to fix the flaring in both H- and E-plane, respectively. The flare angle in both E- and H-plane can be calculated from the following equations,

$$\theta_e = \tan^{-1} \left(\frac{\frac{B}{2}}{\rho_1} \right) \quad \text{and} \quad \theta_h = \tan^{-1} \left(\frac{\frac{A}{2}}{\rho_2} \right) \quad (3.3)$$

From Equation (3.3), the flare angle values in both planes are obtained, where $2\theta_e = 73.4^\circ$, and $2\theta_h = 83.4^\circ$, respectively. It is worth mentioning that a wideband slot feeds the proposed horn antenna, whereas the regular horn antenna is excited by a rectangular waveguide. Therefore, the design procedure is based on optimization so that the maximum radiation is obtained in the broadside direction. The slot is excited by a dielectric-filled ridge gap waveguide (RGW).

3.3 SIGW Multilayer Horn Antenna Using PEC-PEC Walls

In this section, we cover the design of the SIGW that feeds the slot multilayer horn antenna. This section is divided into four subsections. Subsection 3.3.1 covers the SIGW unit cell design using a periodic boundary condition. Then the wideband slot design using a single-section Chebyshev transformer is given in Subsection 3.3.2. Subsection 3.3.3 represents the SIGW multilayer horn antenna design, and finally, Subsection 3.3.4 includes the leakage analysis in PEC-PEC metal walls of the SIGW multilayer horn antenna.

3.3.1. SIGW Unit Cell Design Analysis

The proposed work is based on a substrate integrated gap waveguide that can create a stopband using a periodic structure. The periodic boundary suppresses the leakage around the ridge. In other words, the fields are confined above the ridge region. Unit cell design is presented in many articles, where both the cell dimensions and response were illustrated [70], [74], [85]. Thus, these analyses are removed for brevity. Fig. 3.2(a) shows the designed SIGW unit cell as a row of three mushrooms from both sides of the ridge truncating the periodicity. The periodic boundary condition is forced on the transverse planes surrounding the mushroom rows and touching the ridge from both ends to form an infinite-long SIGW. Fig. 3.2(b) provides the dispersion diagram of the SIGW unit cell in Fig. 3.2(a) using the CST Microwave studios Eigen Mode Solver. RO3003 substrate is used with ϵ_r of 3 and a thickness of 0.75 mm.

The one mushroom unit cell analysis, which is removed, indicates a bandgap indicated by the shaded area with no mode existing within it, and the number of modes under the shaded area is only one that propagates. However, when we use the cell in Fig. 3.2(a), the propagating mode due to the ridge appears in the bandgap region, and more modes exist below the shaded area. These extra modes are due to the truncation of the periodic structure around the ridge. It can be seen that the SIGW bandwidth is actually within the frequency range of the shaded area that the bandgap of the unit cell covers. The wave propagates along the ridge and supports a Q-TEM mode. Since RGW supports Q-TEM mode, no signal dispersion is expected. Table 3.1 summarizes the unit cell design with all the required parameters.

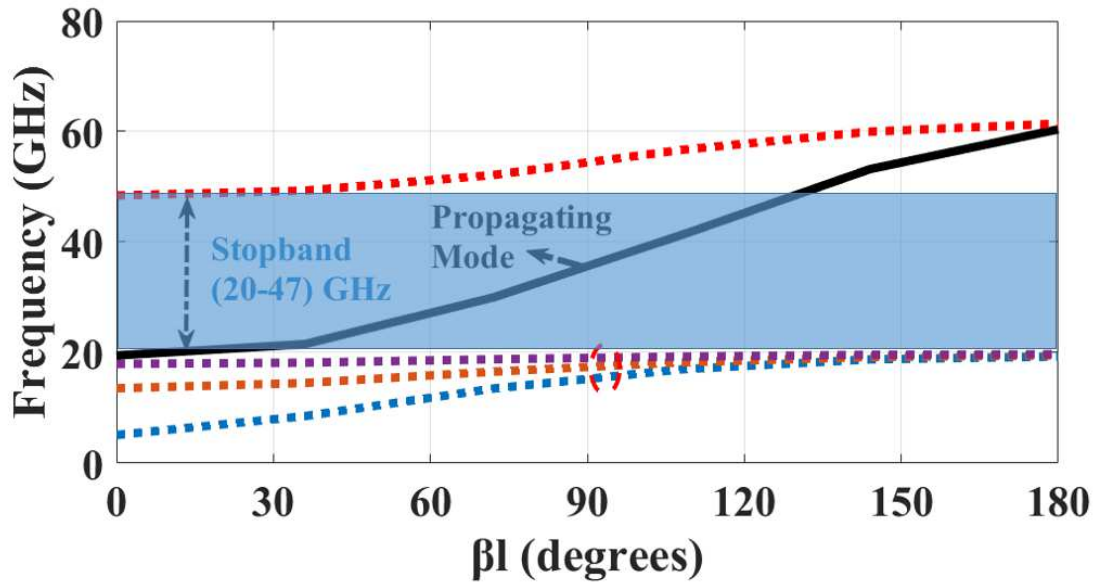
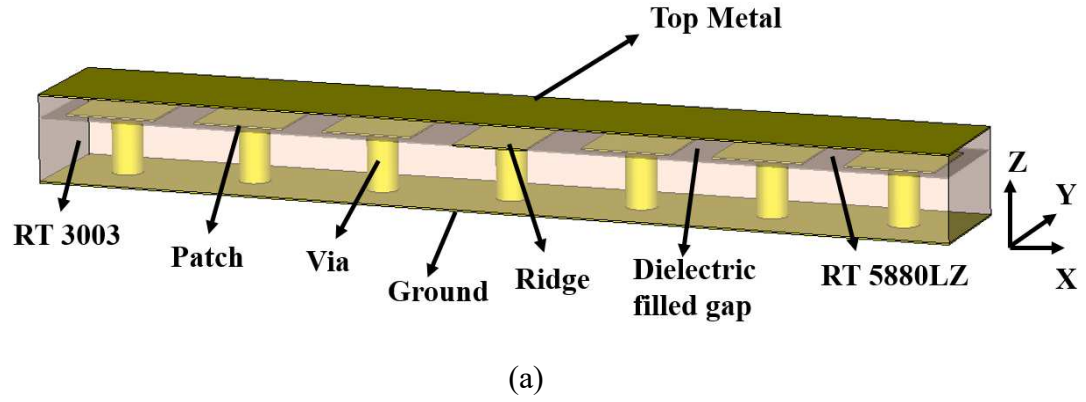


Fig. 3.2: SIGW one-row unit cell analysis. (a) Geometry, (b) Dispersion diagram.

Table 3.1: Dimensions of Unit Cell

Parameters	Value in (mm)
Height of pin, d	0.75
Patch width, W_p	1.1
Via radius, R_o	0.1875
Air-gap, h	0.254
Ridge width, W_r	0.9
Via-Via distance, p	1.6

3.3.2. SIGW Slot Design

Since a slot is a resonant narrowband antenna, to increase the bandwidth of the antenna, a wideband Bowtie-shaped slot is used and excited by the dielectric-filled ridge with a T-shaped termination. In addition, a single-section Chebyshev transformer is used for the SIGW feeding line to match it with a T-shaped ridge under the slot to enhance the antenna's bandwidth, as shown in Fig. 3.3(a).

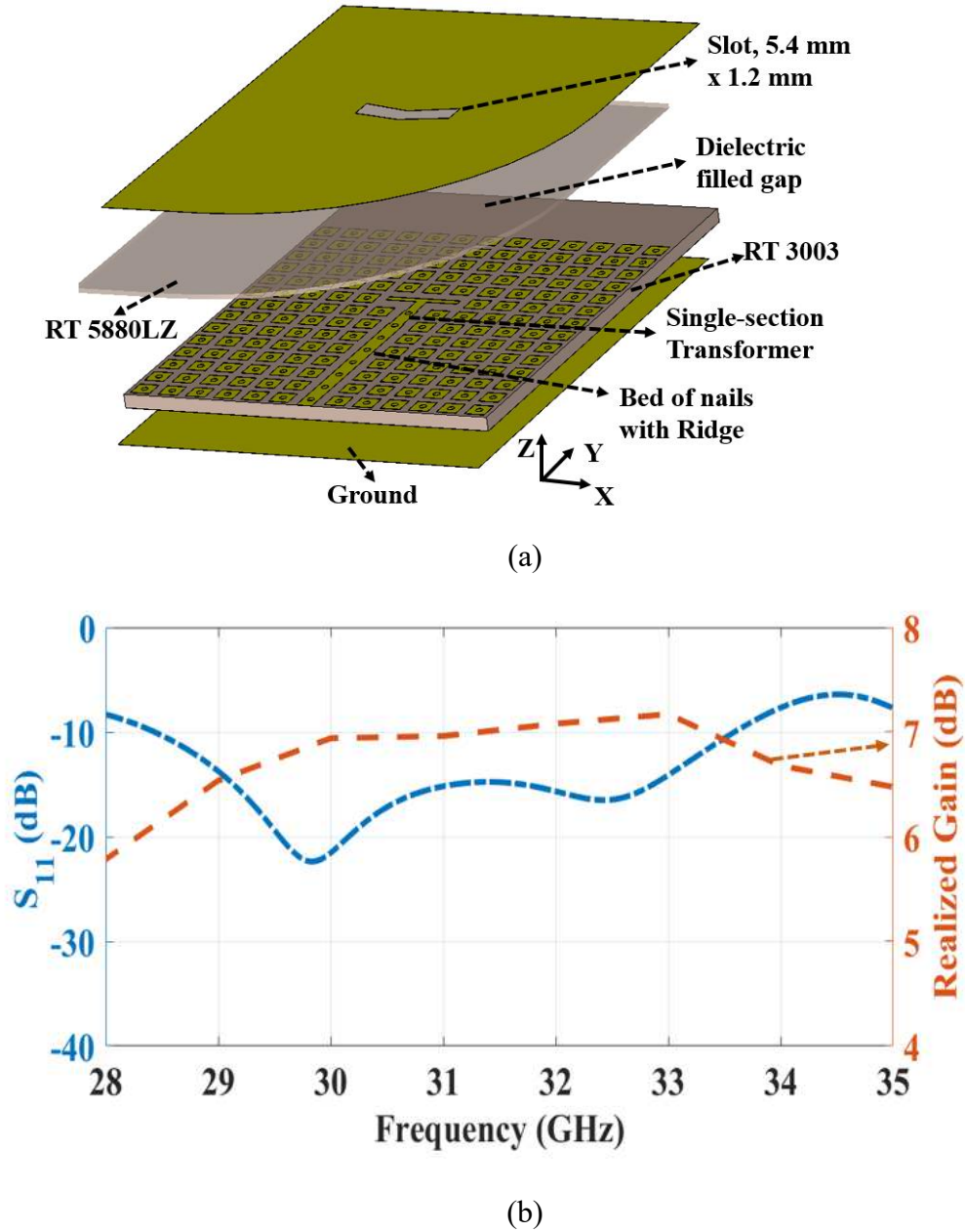


Fig. 3.3: (a) Geometry of wideband SIGW slot antenna, (b) Simulated S_{11} & Gain.

The length and width of the single-section transformers are $L1 = 1.8$ mm, and $W1 = 0.7$ mm, respectively. The dimension of the slot is (5.4 mm x 1.2 mm). This led to an overall impedance bandwidth of 16.2 % and 7 dB gain, as highlighted in Fig. 3.3(b). It should be stated that using SIGW as a feed line prevents any direct back radiation from the slot, unlike the case of using a microstrip line for excitation that allows for direct back radiation. Usually, to suppress the direct back radiation, a reflector is placed on the back at a $\lambda/4$ distance from the slot, where $\lambda = 10$ mm centered at 30 GHz.

It is important to point out that instead of using a dielectric-filled ridge, it is also possible to use an air-filled ridge. Since this work is based on the multilayer horn antenna, maintaining a proper air-gap thickness would be difficult when an array and an extensive feeding network are needed, as the thin substrate flatness is not assured. The dielectric-filled ridge gap waveguide slot excites the multilayer horn antenna. A dielectric-filled gap ensures strong mechanical stability for the best possible performance.

3.3.3. SIGW multilayer horn antenna using PEC-PEC walls

To increase the gain furthermore, a four-layer horn antenna on top of the slot is designed, where all layers have a total thickness of 4 mm. The horn antenna is designed by selecting the optimum flaring angle of the pyramidal horn antenna and realized with the proposed stepped horn structure [104]. Based on the equation described in [104], the outer aperture length and width of the horn were calculated and later optimized using the Transient Solver of CST Microwave Studio. To control the leakage from the horn substrate, metallic vias are used to surround the horn opening at each layer. The overall structure of the designed antenna is shown in Fig. 3.4(a). The proposed antenna achieves 18.5 % impedance bandwidth from 28.7-34.3 GHz and 10.2 dB gain. The reflection coefficient and the gain comparison are shown in Fig. 3.4(b) for slot and PEC wall horn antennas. Fig. 3.5 represents the radiation pattern comparison for both antennas. In the simulator, all layers of conducting surfaces are electrically connected, assuring no leakage as an ideal scenario with no potential gaps between the layers. However, there is always a possibility of having some accidental gaps, which can deteriorate the antenna's performance and allows for leakage. Therefore, in this work, an accidental gap of 15 μ m at each layer is considered while simulating

the horn antenna with PEC-PEC walls. The gain of the PEC horn is enhanced by 3 dB throughout the whole operating bandwidth. It is important to point out that metallic vias are used at each layer of the horn, which acts like a PEC wall. The vias control any possible leakages to the dielectric substrate. The gain of the PEC horn is enhanced by 3 dB throughout the whole operating bandwidth. Instead of the horn antenna with 4 layers, more layers can be added to improve the gain and by minimizing the flaring angle.

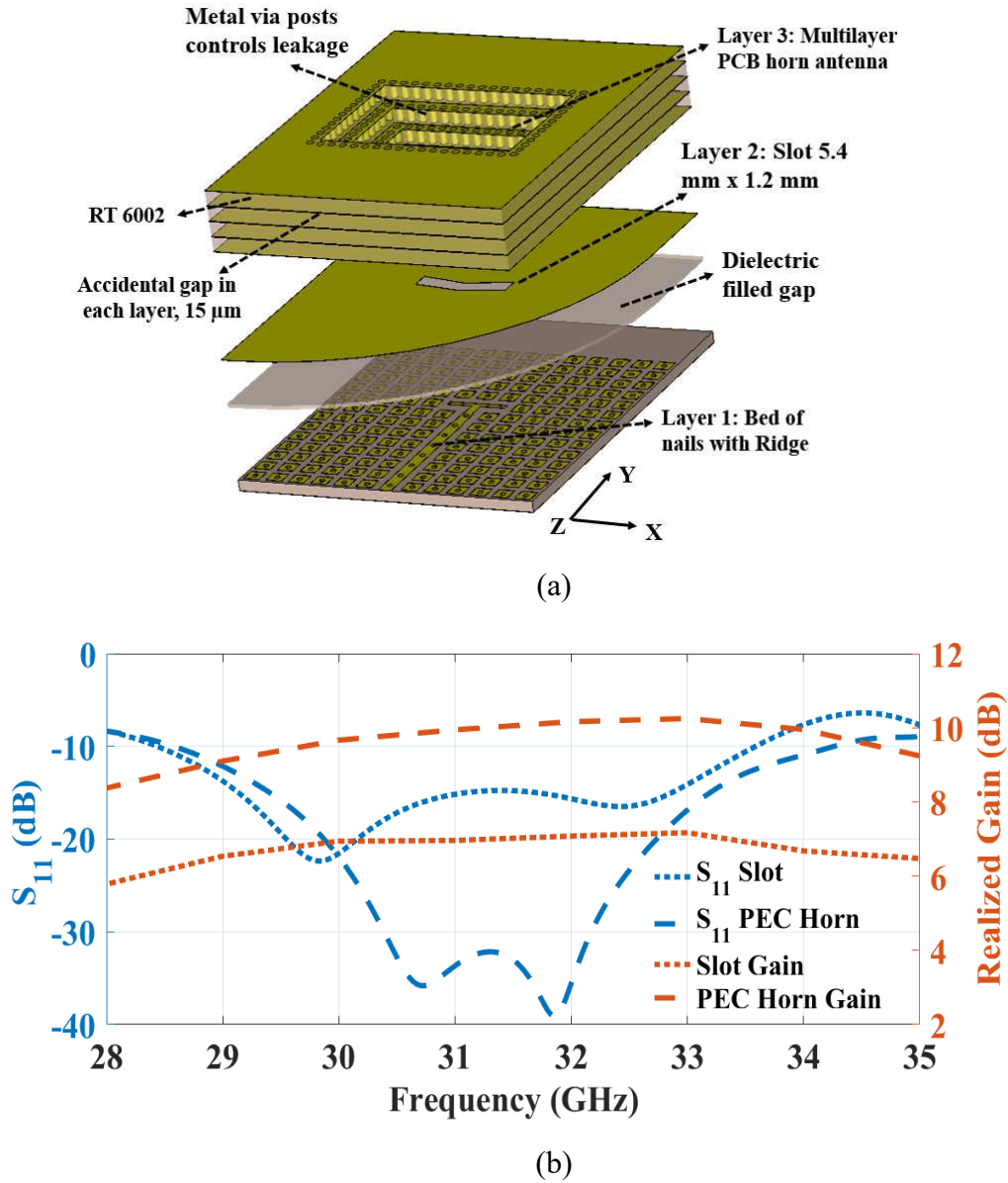


Fig. 3.4: Slot and PEC walls horn characteristics. (a) Geometry of PEC walls horn, (b) Simulated S_{11} & Gain of the SIGW slot and PEC walls horn antennas.

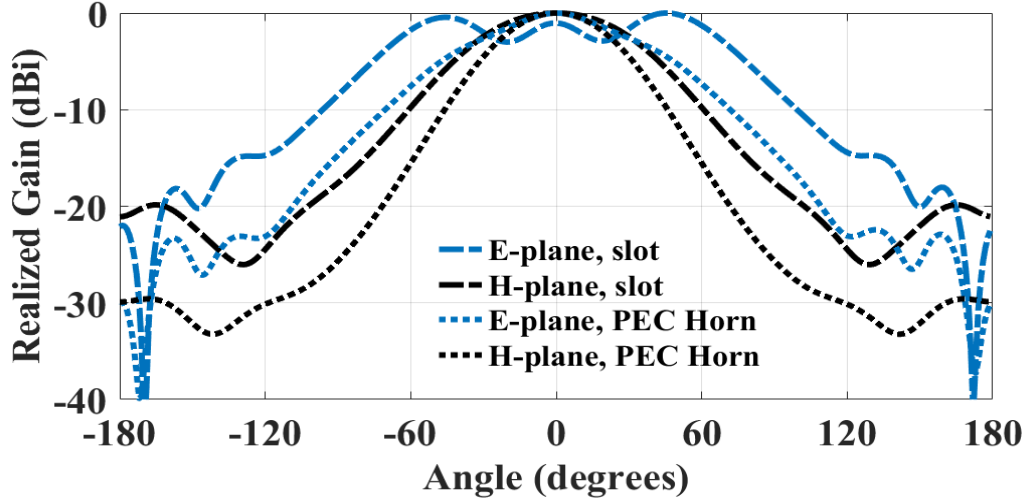


Fig. 3.5: E- and H-plane radiation patterns comparison of the slot and the PEC horn antennas at 30 GHz.

3.2.4. Leakage from PEC-PEC walls with accidental gaps

At the mm-wave, the contribution of copper cladding to the performance of PCB becomes more substantial, which mostly comes from the surface irregularities of the copper foils. Therefore, adding multiple substrates makes it possible to get some air gap due to surface roughness, and the imperfect flatness of the substrate is a big issue [25], [26]. For different Rogers laminates, the copper cladding varies between $0.3 \mu\text{m}$ to $1.3 \mu\text{m}$. In [27], a contactless air-filled substrate integrated waveguide (CLAF-SIW) structure was designed to measure the effect of the gaps. It is noticed after the measurement with the vernier calipers that there is a gap between the possible stacked substrates. The measurements indicated a likely gap of $10\text{-}20 \mu\text{m}$ between the PEC-PEC layers. At the mm-wave range, this gap can cause a detrimental effect because the PEC-PEC configurations can cause possible leakages [28]. To validate this point, we have considered a $15 \mu\text{m}$ gap between the horn layers to study the effect of the leakages. Fig. 3.6 illustrates the E-field distribution of the proposed SIGW multilayer horn antenna, where the gap between the two layers is $15 \mu\text{m}$. Here, only the field distribution between the first gap is highlighted.

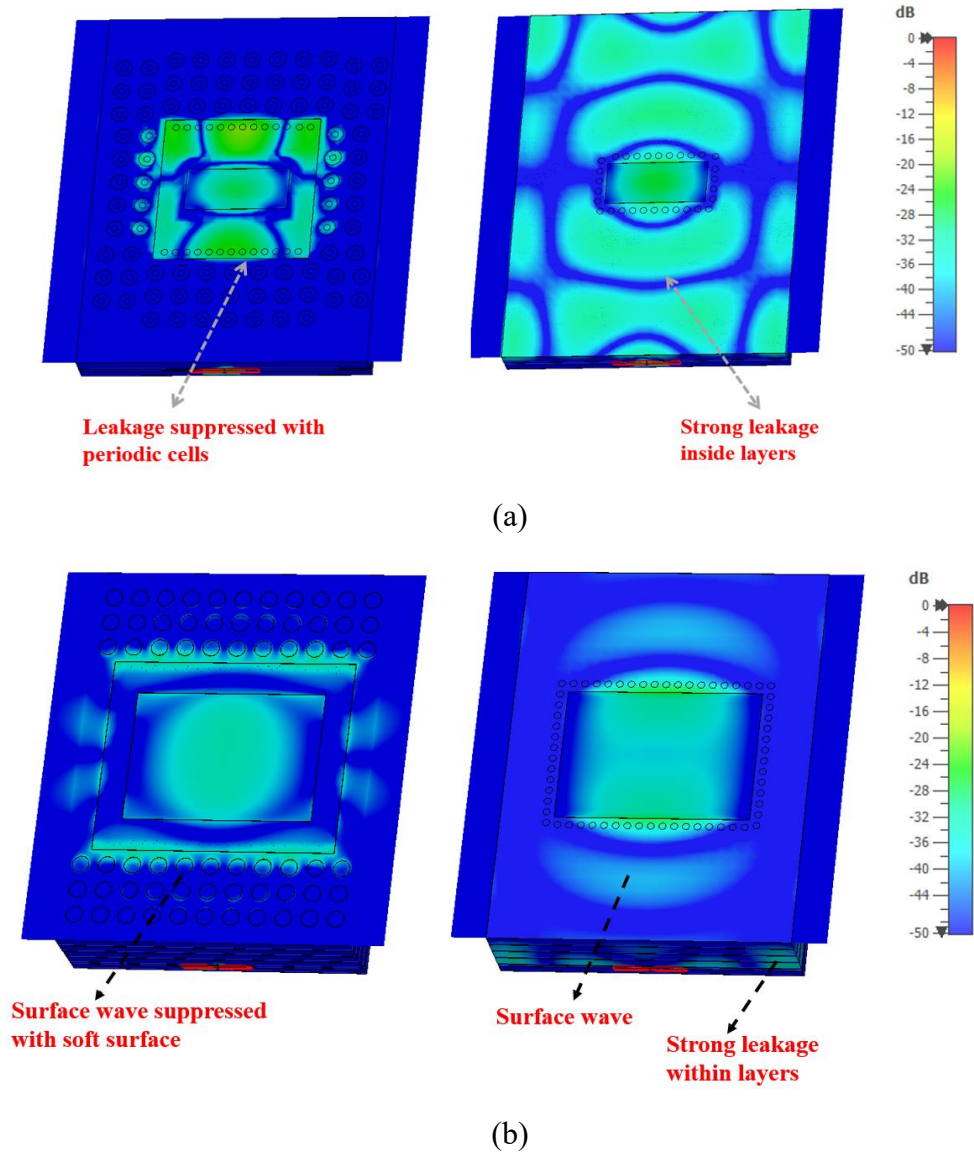


Fig. 3.6: E-field distribution of SIGW horn antenna at 30 GHz, (a) With and Without soft surface inside the first layer with a gap of $15 \mu\text{m}$, (b) With and Without soft surface on the last layer.

It is evident from the field distribution that if there are some accidental gaps within the layer, it results in leakage in the PEC-PEC configuration, which is not desirable. Besides, the top surface of the last layer that forms the horn aperture is surrounded by the conducting surface. This surface support surface electric currents that radiate, causing deterioration of the horn radiation characteristics. In one of the previously published works, a five-layered stacked horn was proposed with SIW technology to provide a cost-effective solution [107]. However, there was a considerable

discrepancy between the measured and simulated radiation patterns caused by the combined effects of the inaccuracy tolerances of the roughness of the horn walls, which are made of metalized via holes. In order to provide a practical solution, a soft surface surrounding the horn opening is proposed so that the leakage can be suppressed even if there are some small gaps. Adding the soft surface reduced the leakage significantly, as highlighted in Fig. 3.6. Therefore, for a multilayer substrate, even though nonflat surfaces or surface roughness, this can be solved by using the PEC-AMC configuration surrounding the radiating element. The next section covers the soft surface analysis in more detail.

3.4. SIGW multilayer horn antenna using soft surface

In the last section, we have seen that possible accidental gaps in the multilayer PCB structure might lead to leakage in a PEC-PEC configuration. However, leakage can be suppressed by modifying the boundary condition to PEC-AMC. The use of the soft surfaces and EBG in a wireless inter-chip communication concept was studied, which had a significant advantage in focusing the energy toward the receiving antenna and eliminating the spherical spreading losses arising from the radiated spherical wave nature [40]. Further explanation of the mechanism by which soft surfaces function is provided in [41], [42]. Three different types of EBG cells are employed. The first one has a double patch with accidental gaps on its top and bottom. The second EBG cells remove the effect of possible accidental gaps on the top. Finally, the upper cells create a soft surface around the horn aperture. Fig. 3.7 shows the cross-sectional view of the three types of EBG cells that are considered for the SIGW multilayer horn antenna design.

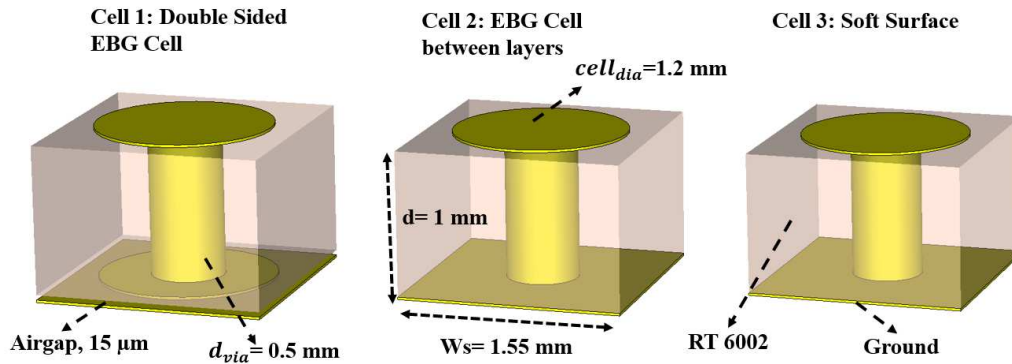
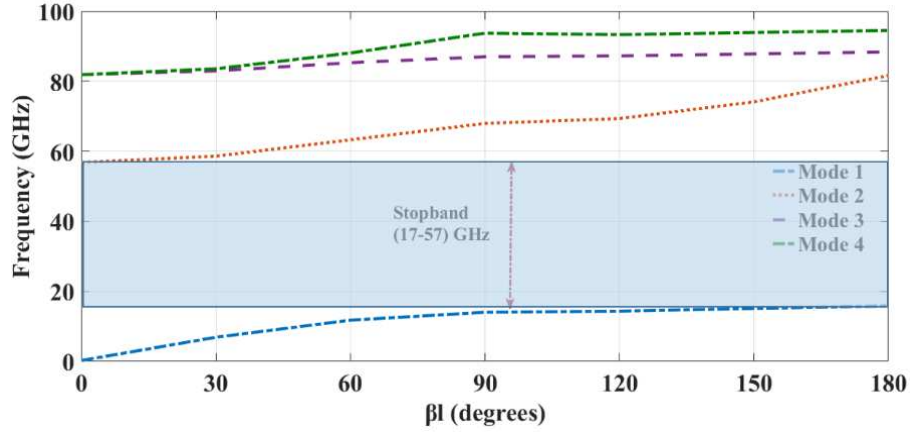
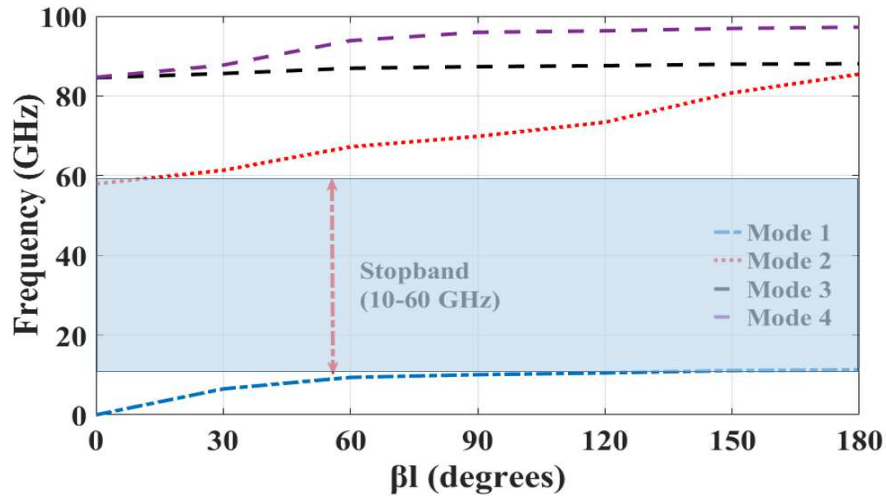


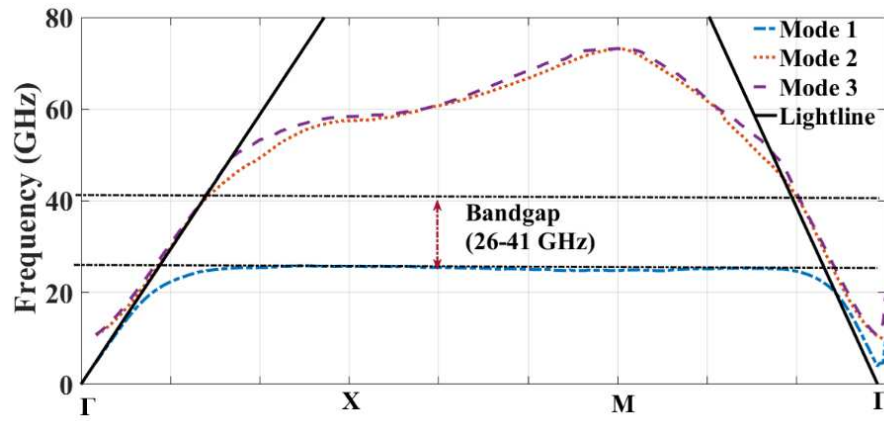
Fig. 3.7: 3D view of the EBG cells of the SIGW horn antenna.



(a)

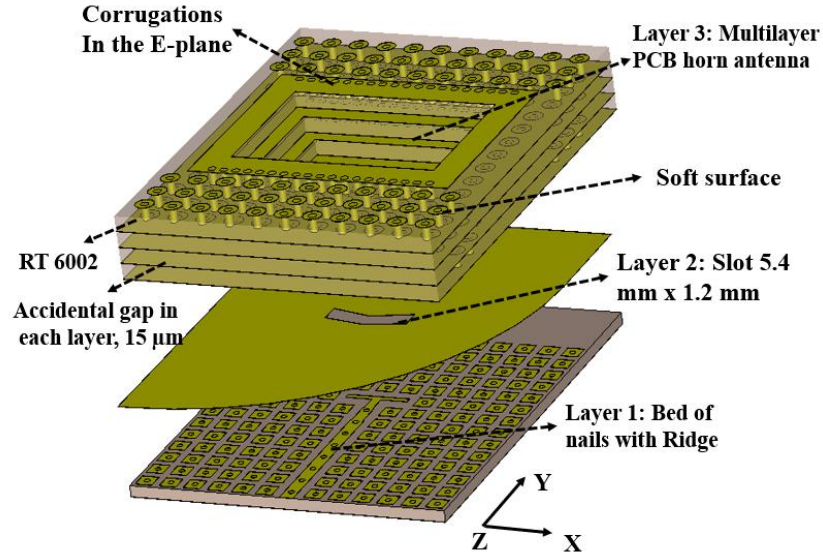


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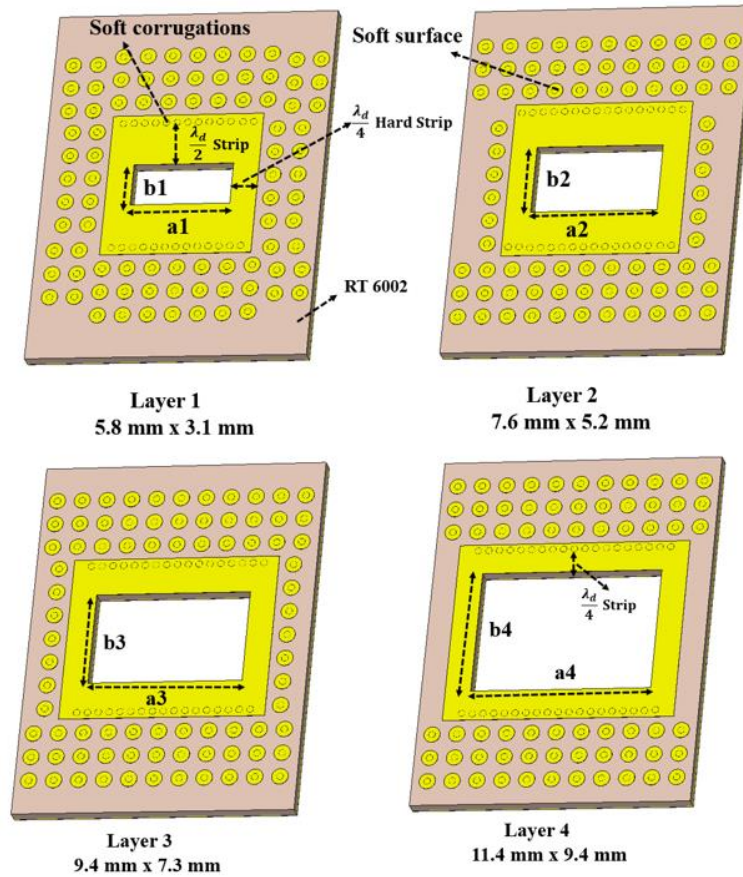


(c)

Fig. 3.8: (a) Dispersion diagram of the double patch unit cell, (b) Dispersion diagram of unit cells between layers, (c) Soft surface on the top layer.



(a)



(b)

Fig. 3.9: E-plane corrugated horn (a) Geometry of SIGW integrated multilayer horn antenna using soft surface, (b) Schematic of layers 1, 2, 3, and 4 of the horn antenna.

The dispersion diagram of different EBG cells employed in the horn antenna is illustrated in Fig. 3.8. The bandgap for periodic structure is determined by plotting the dispersion diagram over the Brillouin zone (Γ -X-M- Γ). The periodic boundary conditions and parametric sweep is used in the Eigenmode Solver to get the dispersion diagram, where Γ -X shows the dispersion in Phase X, X-M shows the dispersion in Phase Y. The periodic cell suppresses the leakages from the horn opening by adding periodic cells on each layer. The bandgap of a periodic cell depends on four essential parameters, such as (i) air gap between the mushroom patch and the top metal (PEC), (ii) patch diameter, (iii) height of via, and (iv) via to via distance. However, the most dominant one is the air-gap; by decreasing the air-gap, the band gap increases. It is worth pointing out that the unit cell size is different from the one used in the feeding layer. Metallic vias surround the horn opening at each layer to control the leakage from the horn substrate. In the E-plane, a soft corrugation is added by placing the vias at a distance of $\lambda_d/2 = 3.2$ mm from the horn opening in the first layer of the horn. As we go further to the final layer, the via is placed at a distance of $\lambda_d/4 = 1.6$ mm from the horn opening. Starting the corrugation from $\lambda_d/2$ in the first layer to $\lambda_d/4$ in the last layer improves the matching bandwidth, as shown in Fig. 3.9. Each of the horn layers with vias had to fabricate individually, and it is not possible to stack all the layers and have vias going through all the layers because of the fabrication limitation that the minimum size of the via's diameter must be half of the substrate height.

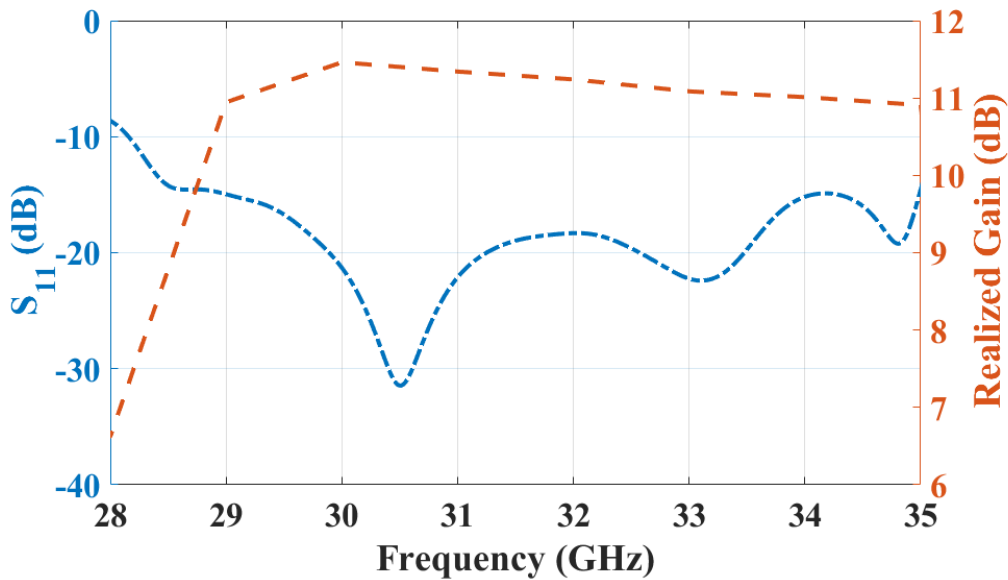
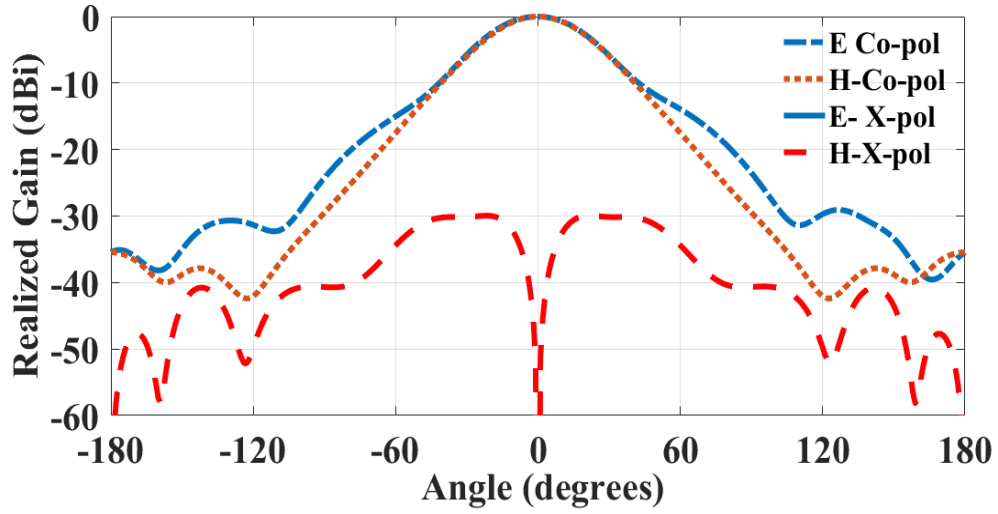


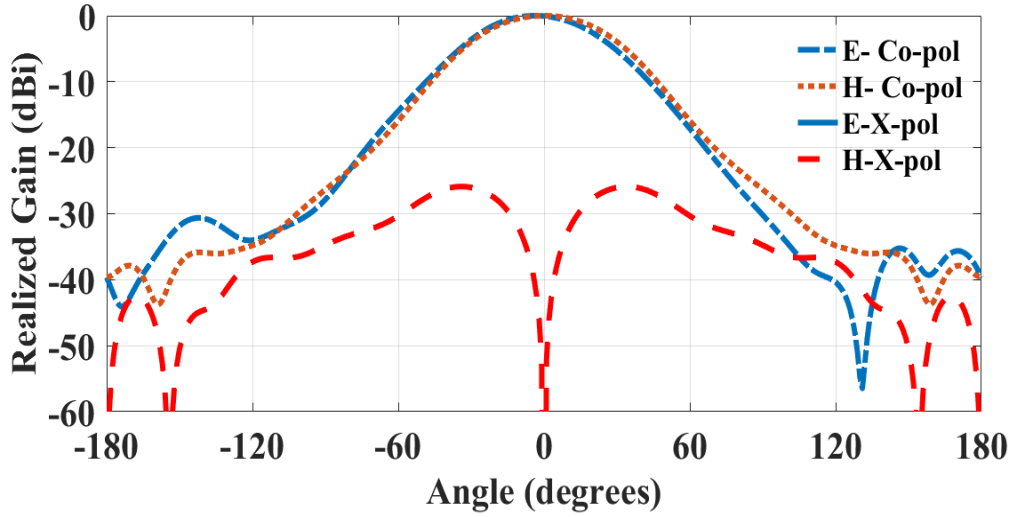
Fig. 3.10: Simulated S_{11} & Gain of SIGW horn antenna with PEC-AMC layers and soft surface.

In addition, three rows of mushroom cells are used as a soft surface around the horn opening to improve the radiation characteristics. The soft surface is added just after the corrugation ring, making the surface a high-impedance surface that can block waves of any polarization. It should also be noticed that the H-plane sides of the horn layers are left open with no vias. The electric field is parallel to these edges, and the conductor cladding forms parallel-plate waveguides between the layers and within the substrates. For this polarization, these waveguides operate below their cutoff frequency. In addition, the conductor cladding was cut at $\lambda_d/4$ to act as an open circuit transmission line to be transformed into a short circuit within the horn for any possible cross-polarized waves that will see this wall as a PEC. The proposed antenna achieves 20.5 % impedance bandwidth from 28.5-35 GHz and exceeds 11 dBi gain. The simulated reflection coefficient and the gain comparison are shown in Fig. 3.8 for an integrated multilayer horn antenna using the soft surface. The soft surface significantly improved the overall radiation characteristics compared to the PEC-PEC configuration horn antenna. The total gain enhancement is 1.5 dBi throughout the entire operating bandwidth. The sole reason for the improvement is controlling the leakage between layers. Fig. 3.11(a) and 3.11(b) illustrate the simulated radiation pattern comparison of both E- and H-plane at 30 and 33 GHz. The radiation patterns in both planes are very stable, with a sidelobe level below -30 dB in both planes. Since the slot is placed horizontally, the antenna's polarization is vertically polarized, so the cross-polarization contributes to the H-plane. In the E-plane, the cross-polarization level is below -60 dB, which is way below the minimum range of the plot curve; thus, the E-plane x-polarization is not shown. In the H-plane, the ratio between co- to x-polarization < -26.5 dB is shown in Fig. 3.11(a) and 3.11(b).

For a fair comparison of our proposed antenna design, one more model is shown where the horn part is built on a 4 mm copper slab, with all the plates being 1 mm in depth. The metal horn part provides solid mechanical support to hold the overall structure. However, since it is built on copper, the whole system is heavy. In terms of bandwidth, the antenna's performance is similar to the proposed antenna with a soft surface; however, the gain is relatively lower than the proposed antenna. Fig. 3.12(a) shows the metal horn antenna fed by SIGW. The simulated reflection coefficient and gain are highlighted in Fig. 3.12(b), where the gain is around 10.4 dBi at the center frequency of 30 GHz.



(a)



(b)

Fig. 3.11: Integrated multilayer horn antenna characteristics with PEC-AMC layers and soft surface, (a) Radiation patterns at 30 GHz, and (b) Radiation patterns at 33 GHz.

Fig. 3.13 highlights the gain versus frequency response for all the antennas based on SIGW technology. It is observed that the proposed antenna with a soft surface has more gain compared to the metal horn antenna. The SIGW multilayer horn with PEC-PEC walls provides a gain of 10 dBi and causes possible leakage due to some accidental air gap. Therefore, it is observed that the radiation characteristics are enhanced by utilizing the soft surface at each layer. In the prototype, it is possible that complete contact between the layers is not assured. Therefore, three rows of

mushrooms were used around the metal vias to form PEC/PMC parallel-plate waveguides that do not allow leakage between them. The measurement results for these cases are discussed in the next section. A comparison is highlighted in Table 3.2 to state the characteristics (advantages/limitations) of various antenna designs using SIGW technology.

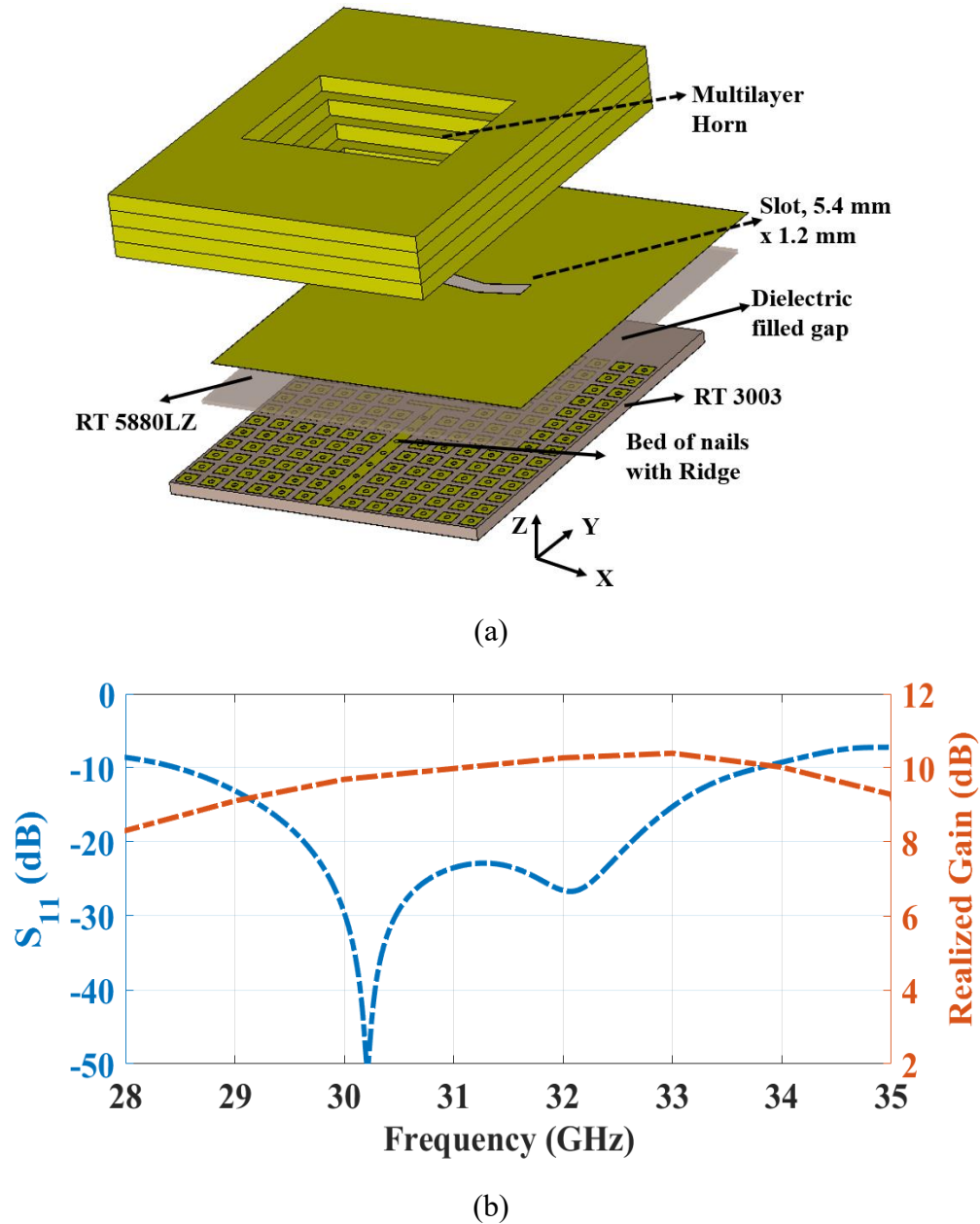


Fig. 3.12: SIGW Multilayer metal horn antenna. (a) Geometry, (b) Simulated S_{11} & Gain.

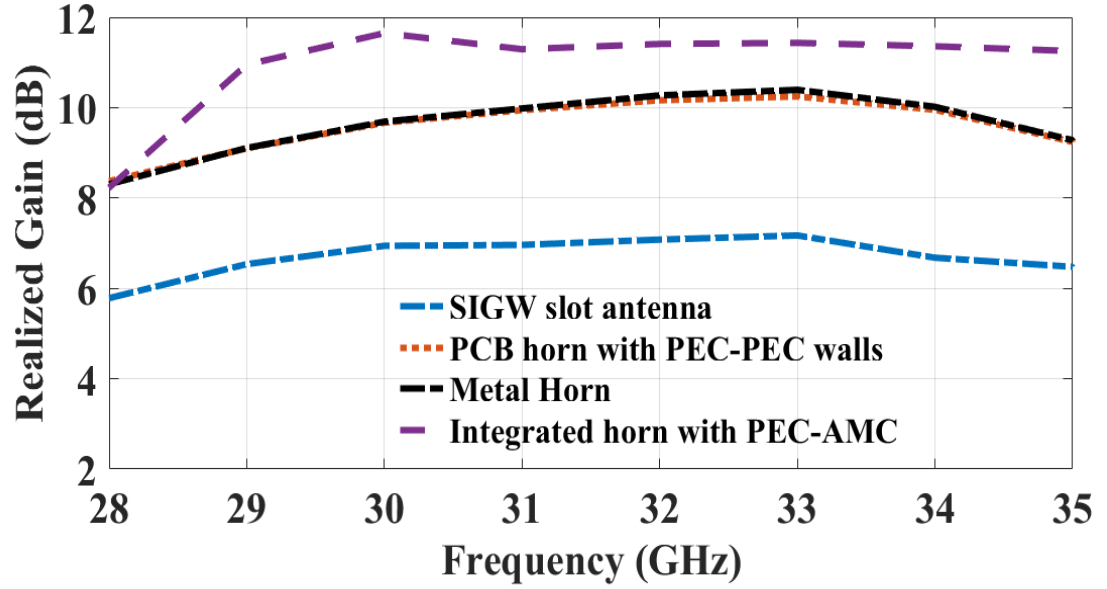


Fig. 3.13: Gain versus frequency comparison of SIGW slot antenna, PCB horn with PEC-PEC walls, metal horn, and integrated multilayer horn with PEC-AMC.

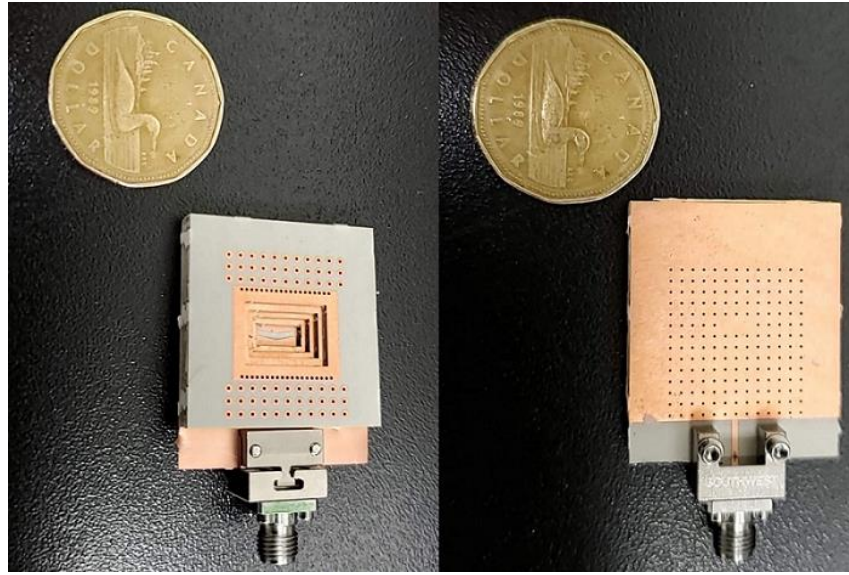
Table 3.2: Performance Comparison between SIGW Horn Antennas

	SIGW PEC-PEC Horn	SIGW Horn with Soft Surface	SIGW Horn with Metal Groove
Advantages	-Wide BW -Self-packaged	-Suppresses leakage. -High BW, High Gain. -Low-loss, self-packaged	-Strong mechanical support -Wide BW
Limitations	-Strong Leakages from accidental gaps. -More losses -Surface waves on horn layers	-Expensive	-Bulky & heavy -Requires CNC Milling -Very Expensive

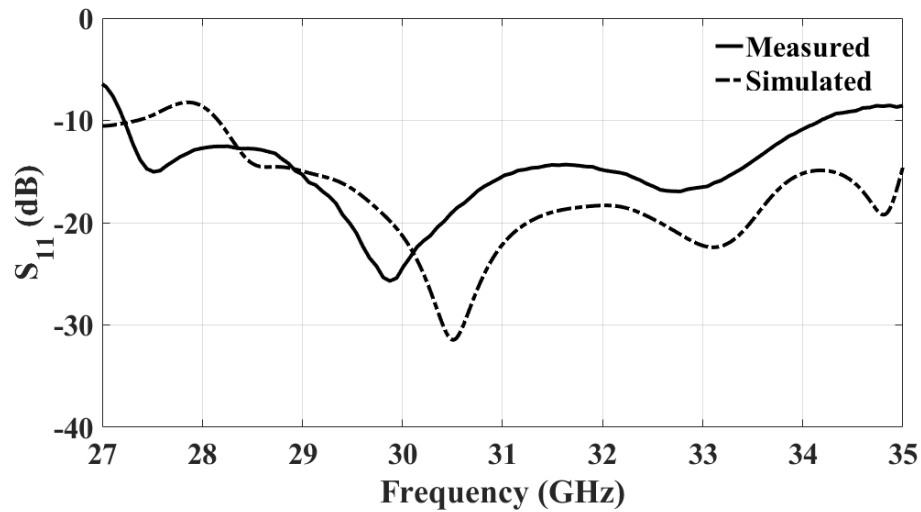
3.5 Experimental and Validation

The proposed antenna is fabricated using the conventional PCB process, where the photos of the fabricated prototype are shown in Fig. 3.14. The fabricated layers are assembled using high temperature and pressure, which uses adhesives at layer corners to provide good mechanical

stability [102]. The S_{11} is measured using an N52271A Vector network analyzer, where the measured and simulated S_{11} is illustrated in Fig. 3.14(b). The measured S_{11} shows a good agreement with the simulated S_{11} covering 22.4 % impedance bandwidth from 27.2-34.2 GHz. It can be observed that there is a shift in the S_{11} between the simulated and measured response, which could be due to the adhesive used in the multilayer horn structure. The size of the antenna is $3\lambda_0 \times 3\lambda_0$ at 30 GHz, which is very compact.

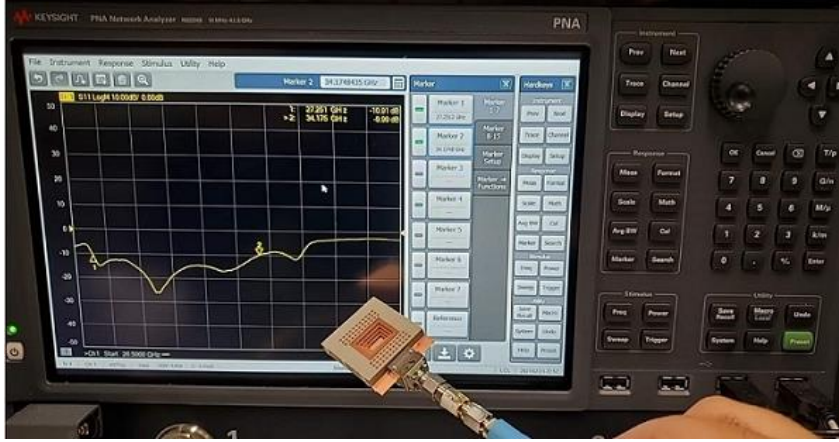


(a)

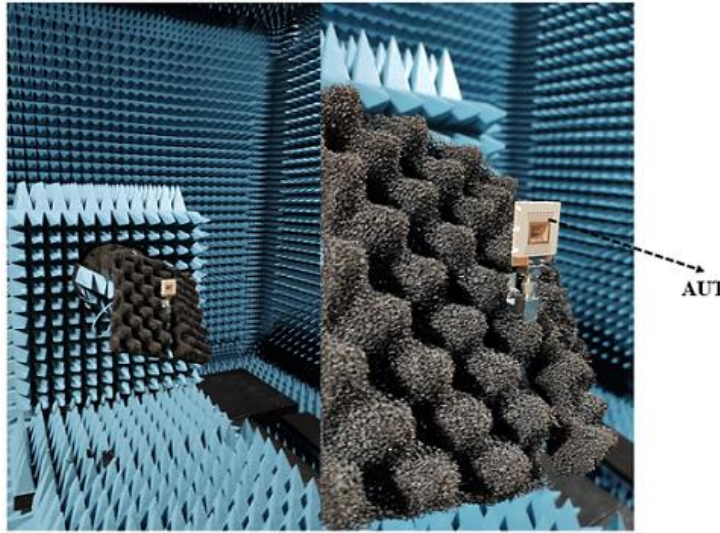


(b)

Fig. 3.14: (a) Photo of the top and bottom, and (b) simulated and measured S_{11} .



(a)

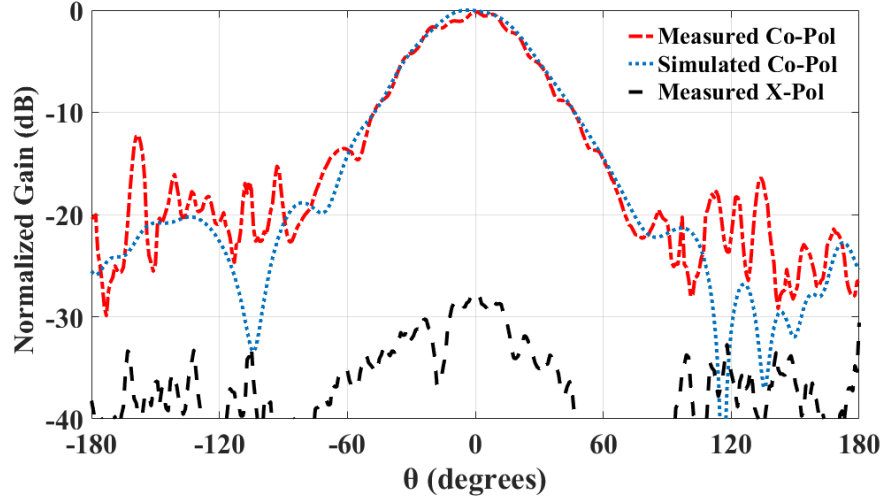


(b)

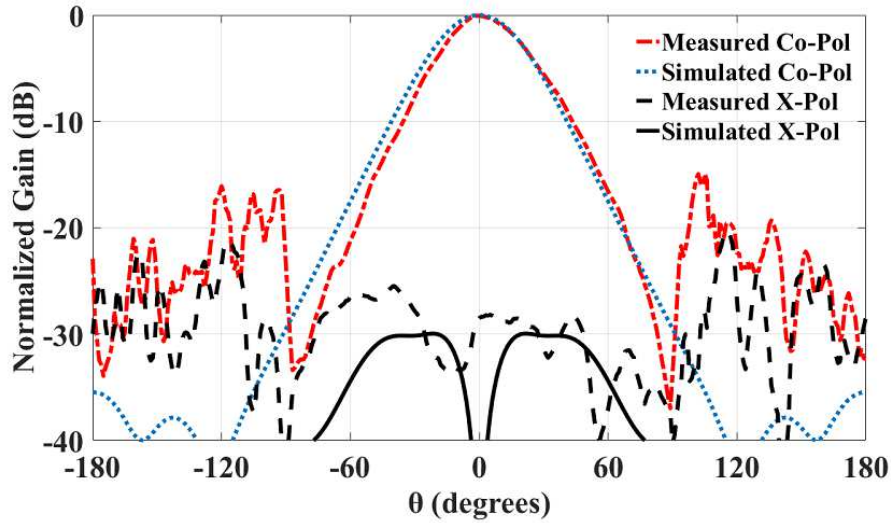
Fig. 3.15: Measurement setup for SIGW Horn Antenna, (a) Measurement using VNA, (b) Radiation pattern measurement inside an anechoic chamber.

The Gain and radiation patterns are measured in the anechoic chamber system. The measurement setup for the assembled horn antenna is shown in Fig. 3.15(a). The Gain and radiation patterns are measured in the anechoic chamber system, as shown in Fig. 3.15(b). The measured E- and H-plane radiation pattern at 30 is highlighted in Fig. 3.16, where an excellent agreement is observed with the simulated response. There is some deviation at 30 GHz in the E-planes due to the connector, and the multilayer substrate adhesives (epoxy glue) may change the effective dielectric constant. The H-plane radiation pattern is very stable at 30 GHz. In both planes, the co- to x-polarization <

-26.5 dB from -90 to 90 degrees range for the proposed antenna. It is worth pointing out that the simulated X-polarization in the E-plane is below the -60 dB level, which is below the curve plot. Fig. 3.16 shows high sidelobe levels, which are from the noisy measurement setup.



(a)

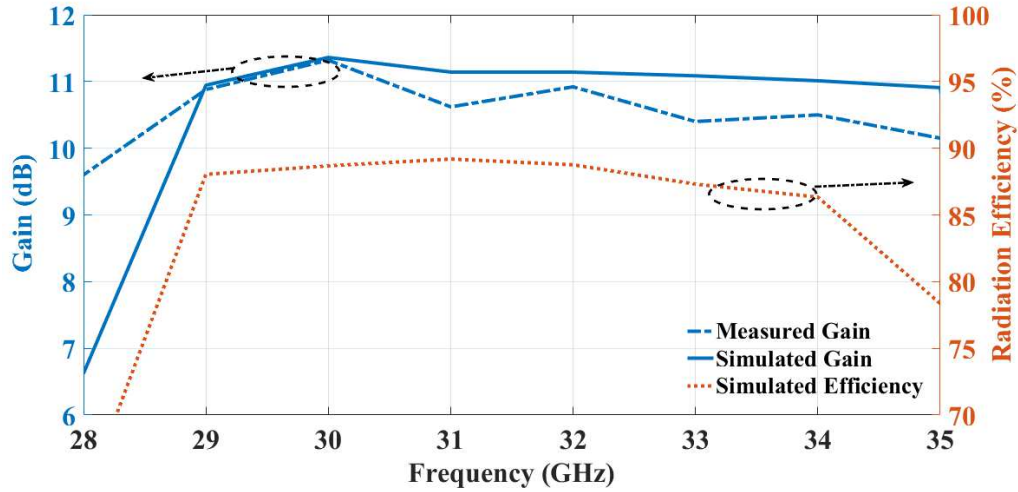


(b)

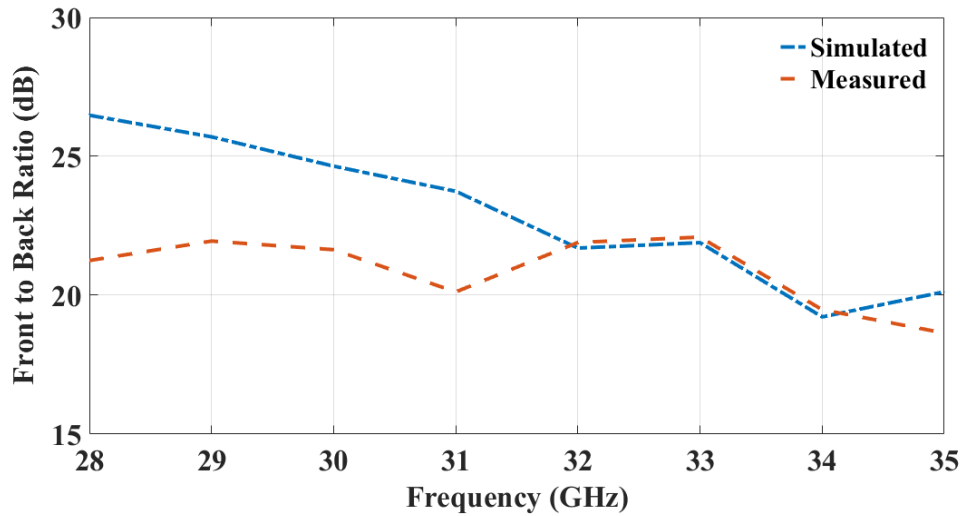
Fig. 3.16: Measured and simulated radiation pattern comparison (a) E-plane at 30 GHz, (b) H-plane at 30 GHz.

The simulated and measured gain versus frequency response is shown in Fig. 3.17(a), which agrees well with the simulated result. The antenna provides a high gain throughout the whole operating frequency. Fig. 3.17(b) shows a comparison between the proposed horn antenna measured and the

simulated front-to-back ratio. The difference between the measured and simulated gain is due to the connector losses of 0.85-1 dB. It is worth mentioning both the measured gain and the front-to-back ratio shows a drop at high-frequency which is due to poor return loss at a higher frequency, Fig. 3.14(b) and low radiation efficiency.



(a)



(b)

Fig. 3.17: (a) Measured and Simulated Gain versus frequency response comparison (b) Measured and Simulated Front-to-Back ratio of SIGW horn.

The aperture efficiency of the antenna is 63%. While calculating the efficiency, only the last opening was not considered; instead, the copper part where the soft corrugations were used with

vias were considered. Table 3.3 compares the proposed work and other related published work. A 94 GHz volumetric integrated 15-layered pyramidal horn antenna with LTCC technology was designed that achieved 8.7 dBi Gain. However, the bandwidth is significantly lower than the present proposed work [106]. Moreover, LTCC fabrication suffers from a number of drawbacks, including a commonly used substrate, the DuPont 9K7 Tape ($\epsilon_r = 7.1$), imposes strict limitations on the fabrication, which can drastically impact the performance of horns and leads to parasitic excitations. Also, the layer-by-layer implementation is done using a laser etched via walls technology that can cause leakage and potentially excite parasitic fields on the dielectric and lead to back radiation and directivity loss. A five-layered stacked horn was proposed with SIW technology to provide a cost-effective solution. However, there was a considerable discrepancy between the measured and simulated radiation patterns caused by the combined effects of the inaccuracy tolerances of the roughness of the horn walls, which are made of metalized via holes [107]. To enhance the Gain, a hybrid antenna was proposed using a surface-mounted conical horn with a circular patch antenna. However, the structure was bulky, which might not suit all applications [113]. Although the performance is enhanced significantly by adding superstrates, the structure becomes bulky, and the antenna efficiency was low [114]. Besides, a differential-fed low cross-polarization pyramidal horn antenna was used, where a capacitive coupling technique was used to enhance the antenna bandwidth [115]. However, the aperture efficiency was low, and the aperture area was huge compared to our proposed work.

Table 3.3: Comparison of proposed SIGW horn with some previously published work

Ref	Freq. (GHz)	Antenna Type	BW (%)	Gain (dBi)	Efficiency (%)
This work	30	SIGW Integrated Horn	20.5	11.5	89(Sim)
[106]	94	LTCC Horn	5 (Sim)	8.7 (Sim)	99 (Sim)
[107]	90	SIW Multilayer Horn	40	9.5	88 (Sim)
[113]	30	Hybrid Surface-Mounted Horn	10	12	89
[114]	12.5	Fabry Perot Resonator Antenna	19	19.1	49
[115]	30	Differential Fed Hybrid Horn	26.7	15	60

Substrate Integrated Gap Waveguide Ferrite Circulator

4.1 Introduction

Microwave circulators are essential components in the RF frontends. It is a three-port device where the signal goes from one port to the next port depending on the biasing, going clockwise or counter-clockwise while the other port remains isolated. Building a full-duplex communication system where the transmitter and receiver work simultaneously is essential. For instance, a typical monostatic radar system consists of a transmitter, antenna, receiver, and circulator. The input power sent from the transmitter goes directly to the antenna, where the antenna captures the signal and sends it directly to the receiver, as shown in Fig. 4.1. It is common to break down a communication system into components designed separately with a specific interfacing specification.

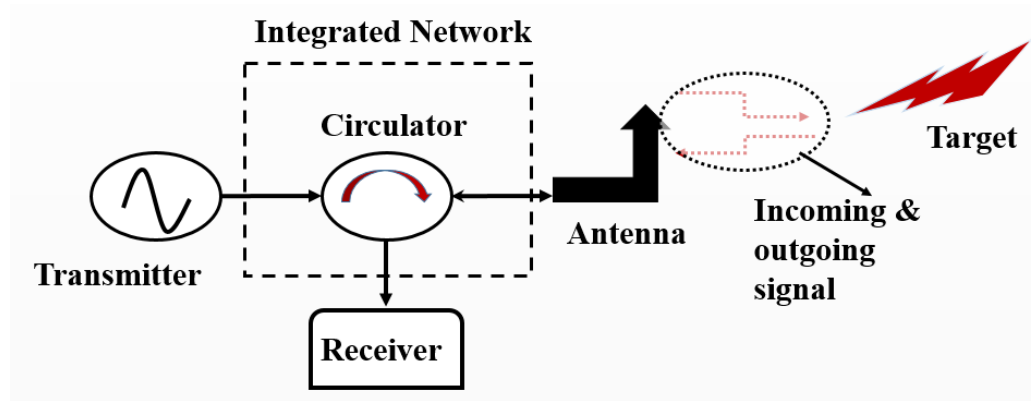


Fig. 4.1: Conventional circulator antenna system.

The Y-Junction circulator is widely used where the ferrite disk is placed in the middle of the circular junction [90], [91]. In addition, the middle ferrite disk was implemented through many configurations, such as triangular or hexagonal-shaped posts, which are responsible for the nonreciprocal behavior of the circulator [92], [93]. Microwave circulators were deployed in many commercial applications, such as high-power air traffic surveillance and airborne weather sensing radars [29], [30].

4.2 SIGW Circulator Design Procedure

A junction circulator is a nonreciprocal three-port network where the power goes from the input port to the output port while the third port is kept isolated. Fig. 4.2 illustrates a schematic of the Y-junction SIGW circulator, where a cylindrical ferrite disk is placed at the center of the circulator. E_z and H_ϕ are the electric and magnetic field components inside the disk. As the input power at Port 1 is equal to the output power at Port 2, this leads to having an $E_{z1} = -E_{z2}$ and $H_{\phi1} = H_{\phi2}$. These two expressions ensure that the power densities at both ports are identical in magnitudes and opposite in directions. On the contrary, Port 3 is isolated, which means zero electric and magnetic field components exist. The above conditions can be described mathematically as follows:

$$E_{zp_1}|_{\phi=0} = -E_{zp_2}|_{\phi=\phi_2} \quad (4.1)$$

$$E_{zp_3}|_{\phi=\frac{4\pi}{3}=-\phi_2} = 0 \quad (4.2)$$

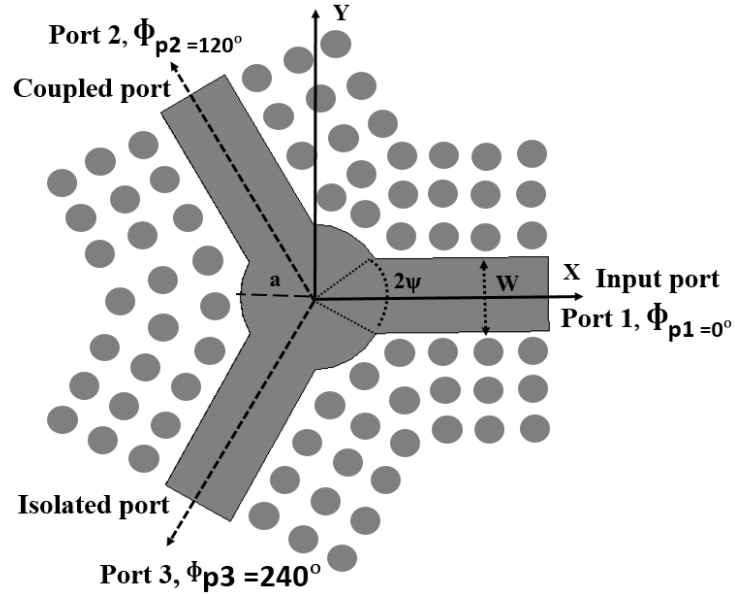


Fig. 4.2: Schematic of the junction circulator with the ridge.

The geometrical parameters of the circulators are the ferrite disk radius a , the port width W , the coupling angle ψ , the port angle ϕ_p , and the disk thickness h . The port width W is related

to the coupling area at each port, where

$$\sin(\psi) = \frac{w}{2a} \quad (4.3)$$

The material properties of the circulator's center disk are the saturation magnetization M_s , the internal biasing magnetic field H_0 , the gyrotropy g_k , and the ferrite dielectric constant ϵ_f . The surrounding medium outside the ferrite material is considered a dielectric medium where $\epsilon_f > \epsilon_d$ so that the PMC boundary assumption is maintained [108]. The dielectric constant used for the filling material is Rogers 5880 LZ, with $\epsilon_d=2$, which is around $0.15 * \epsilon_f$ (the ferrite material ϵ_f is 13.5). The proposed system design is based on an identical interface for both the antenna and circulator to facilitate the integration.

The electric field inside the disk is expressed as the summation of an infinite number of modes [31], [34].

$$E_z = \sum_{n=-\infty}^{\infty} j\eta_{effr} \cdot \eta_0 \frac{\sin(n\psi)}{n\pi} \times \left[\frac{(1+e^{-\frac{j2\pi n}{3}})J_n(x)}{J'_n(x) + \frac{ng_k}{x}J_n(x)} \right] e^{jn\phi} \quad (4.4)$$

where, $x=k_{eff}a$, the effective wavenumber $k_{eff} = \omega\sqrt{\epsilon\mu_{eff}}$, η_0 is the free space intrinsic impedance and η_{eff} is the effective characteristic impedance. The Bessel function of order n and its derivatives are $J_n(x)$ and $J'_n(x)$, respectively. The electric field at the port, E_{zp} can be obtained from the E_z expression in Equation (4.4) in the interval ψ around the port while substituting $\rho=a$. This can be expressed as,

$$E_{zp} = \frac{1}{2\psi} \int_{\phi_p-\psi}^{\phi_p+\psi} E_z d\phi|_{\rho=a} \quad (4.5)$$

where $\phi_p = 0^\circ, 120^\circ$, or 240° for Ports 1, 2, or 3, respectively. The average electric field can be obtained for each port through Equation (4.5).

$$E_{z_{P1}} = \sum_{n=-\infty}^{\infty} j \cdot \frac{\psi}{\pi} \eta_{effr} \cdot \eta_0 \times \left[\frac{1+e^{-j\frac{2n\pi}{3}}}{f_n(x, g_k)} \right] \times \left(\frac{\sin(n\psi)}{n\psi} \right)^2 e^{jn\phi} \quad (4.6)$$

$$E_{z_{P2}} = \sum_{n=-\infty}^{\infty} j \cdot \frac{\psi}{\pi} \eta_{effr} \cdot \eta_0 \times \left[\frac{(1+e^{-j\frac{2n\pi}{3}}) \times e^{j\frac{2n\pi}{3}}}{f_n(x, g_k)} \right] \times \left(\frac{\sin(n\psi)}{n\psi} \right)^2 e^{jn\phi} \quad (4.7)$$

where,

$$f_n(x, g_k) = \frac{J'_n(x)}{J_n(x)} + \frac{ng_k}{x} \quad (4.8)$$

As mentioned before, the circulator conditions are ensured when the power flow in Port 1 is equal to the power flow out from Port 2, while zero fields exist at Port 3, as described in Equations (4.1) and (4.2). Hence, the fundamental circulator design equations are written as follows:

$$\sum_{n=-\infty}^{\infty} \left(\frac{\sin(n\psi)}{n\psi} \right)^2 \times \left[\frac{\cos\left(\frac{2n\pi}{3}\right)}{f_n(x, g_k)} \right] = 0 \quad (4.9)$$

$$\sum_{n=-\infty}^{\infty} \frac{\left(\frac{\sin(n\psi)}{n\psi} \right)^2}{f_n(x, g_k)} = 0 \quad (4.10)$$

A thorough analysis of selecting the ferrite dimension is discussed in detail in [31], [34]. Given the selected material, the values of parameters $x = 1.5727$ and $\psi = 0.5344$ radians are obtained by solving these two fundamental circulator equations. The radius of the ferrite disk $a = 0.83$ mm is obtained based on these two parameters.

Similarly, like the integral electric field equation, the integral magnetic field can be calculated.

$$H_{\phi p} = \frac{1}{2\psi} \int_{\phi_p - \psi}^{\phi_p + \psi} H_{\phi} d\phi|_{\rho=a} \quad (4.11)$$

A closed-form analytical solution was proposed for a stripline circulator providing stripline modes [34]. However, in the present work, we have re-adapted the design equation based on a

single mode to get a Q-TEM mode [31]. Here, we apply the solutions and designs to those based on RGW technology. The electric and magnetic field, along with the intrinsic impedance, can be represented in a matrix form for the 3-port network as shown in Equation (4.12),

$$\begin{bmatrix} E_{zp1} \\ E_{zp2} \\ E_{zp3} \end{bmatrix} = \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{21} & \eta_{22} & \eta_{23} \\ \eta_{31} & \eta_{32} & \eta_{33} \end{bmatrix} \begin{bmatrix} H_{\phi p1} \\ H_{\phi p2} \\ H_{\phi p3} \end{bmatrix} \quad (4.12)$$

Due to the cyclic symmetry of the structure, the following equations can be stated.

$$\eta_{11} = \eta_{22} = \eta_{33} \quad (4.13)$$

$$\eta_{12} = \eta_{31} = \eta_{23} \quad (4.14)$$

$$\eta_{13} = \eta_{21} = \eta_{32} \quad (4.15)$$

Due to the cyclic symmetry, the number of unknowns is reduced, simplifying the equations.

$$\begin{bmatrix} E_{zp1} \\ E_{zp2} \\ E_{zp3} \end{bmatrix} = \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{13} & \eta_{11} & \eta_{12} \\ \eta_{12} & \eta_{13} & \eta_{11} \end{bmatrix} \begin{bmatrix} H_{\phi p1} \\ H_{\phi p2} \\ H_{\phi p3} \end{bmatrix} \quad (4.16)$$

The intrinsic impedance matrix elements can be calculated by,

$$\eta_{11} = \sum_n \left[j \frac{\psi}{\pi} \left(\frac{\sin(n\psi)}{n\psi} \right)^2 \times \frac{\eta_{effr} \cdot \eta_o}{f_n(x, g_k)} \right] \quad (4.17)$$

$$\eta_{12} = \sum_n \left[j \frac{\psi}{\pi} \left(\frac{\sin(n\psi)}{n\psi} \right)^2 \times \frac{\eta_{effr} \cdot \eta_o \times e^{j \frac{2n\pi}{3}}}{f_n(x, g_k)} \right] \quad (4.18)$$

$$\eta_{13} = \sum_n \left[j \frac{\psi}{\pi} \left(\frac{\sin(n\psi)}{n\psi} \right)^2 \times \frac{\eta_{effr} \cdot \eta_o \times e^{j \frac{4n\pi}{3}}}{f_n(x, g_k)} \right] \quad (4.19)$$

After assuming a particular value for g_k , the coupling angle ψ and the value of x can be obtained to satisfy the previous condition. As such, the material and physical dimensions are determined. So, the scattering parameters are calculated from the impedance matrix by:

$$[S] = \left(\frac{Z_r}{\eta_o} [\eta] + [I] \right)^{-1} \left(\frac{Z_r}{\eta_o} [\eta] - [I] \right) \quad (4.20)$$

where Z_r is the line impedance of the dielectric-filled ridge with a surrounding medium having a dielectric constant of, ϵ_d .

The initial dimensions considered from the analysis of [31] lead to a poor approximation in the S-parameter response, as highlighted in Fig. 4.3, where a higher dielectric constant material was used to surround the ferrite disk. The approximation is only valid when the permittivity of the surrounding medium is 60% of the ferrite dielectric constant. In this work, the surrounding dielectric is 85% less than the ferrite relative permittivity. Therefore, the approximation considered in [31] cannot be applied to design the proposed circulator.

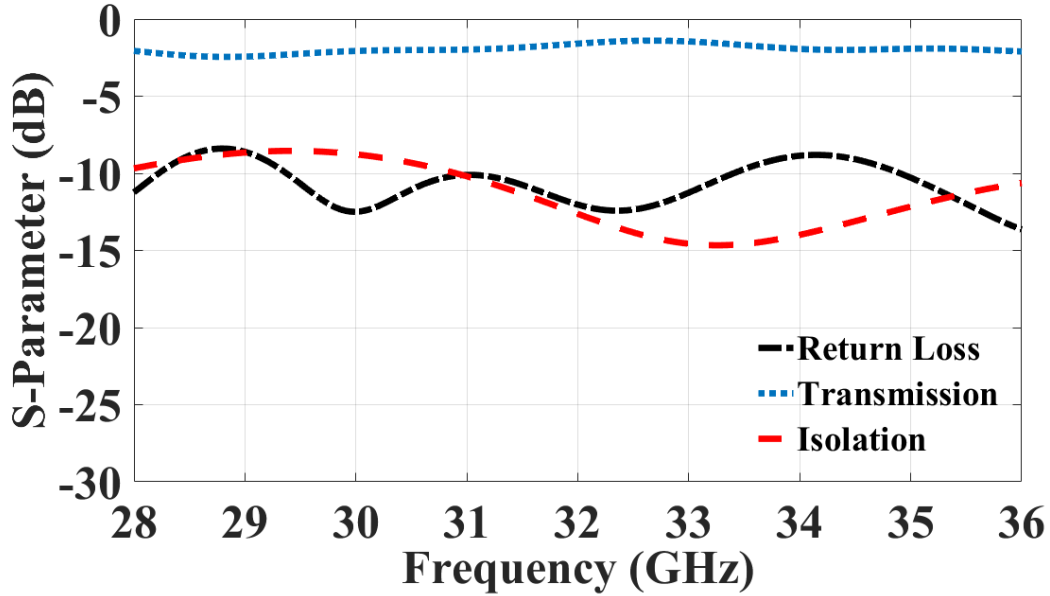


Fig. 4.3: Circulator design with initial coupling angle $\psi = 0.53$ rad.

From the S-parameter response, it is evident that the circulator, based on the initial assumptions from the previous work, cannot be used for design purposes. One of the most critical parameters in the circulator design is identifying the optimum coupling angle, ψ , which controls the trace width, W . In a high dielectric material, the fields will be more confined so that fewer fringing fields will be spreading out; as a result, a lower coupling angle, ψ is sufficient to maintain circulation. However, when the material's dielectric constant is lower, more fringing fields will spread out; as a result, more coupling angles will be required to have a circulation. According to an extensive parametric study, the coupling angle can be related to the relative permittivity by the proposed equation:

$$\psi_{proposed} = \frac{\psi_{initial}}{2} \left(1 + \frac{|\epsilon_f - \epsilon_d|}{0.4 * \epsilon_f} \right) \quad (4.21)$$

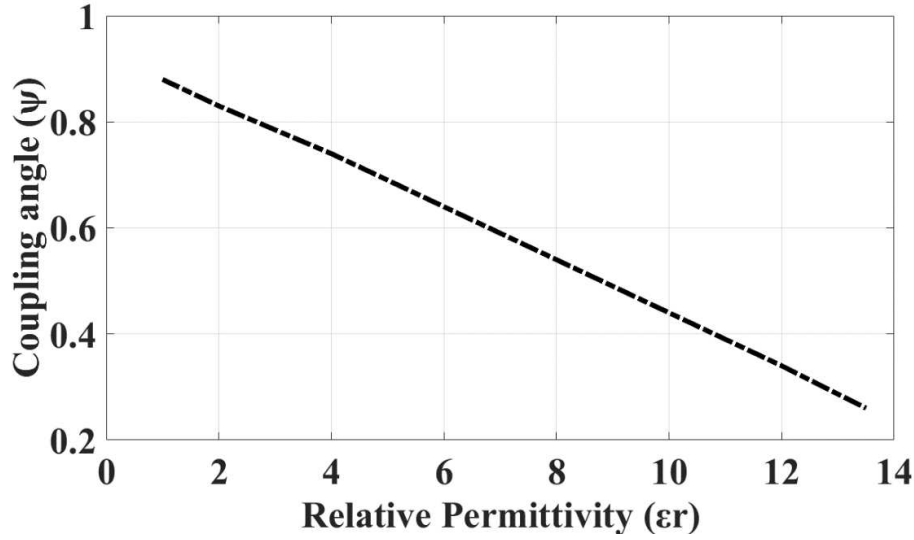


Fig. 4.4: Change in coupling angle due to change in permittivity.

where $\psi_{initial} = 0.53$ rad. is the initial coupling angle, ϵ_f is the ferrite dielectric constant, and ϵ_d is the permittivity of the surrounding material. The dielectric constant of the filling and the ferrite material is $\epsilon_d = 2$, and $\epsilon_f = 13.5$, respectively. So, from the above equation, the calculated coupling angle is 0.82 rad. This proposed equation gives an excellent starting point for understanding the possible coupling angle due to the change in the dielectric filling, as shown in Fig. 4.4. It is visible from the figure that when the permittivity of the medium is higher, it will require a less coupling angle to circulate. On the contrary, when the dielectric constant of the medium is lower, it will require a more coupling angle due to the more fringing fields. Based on this equation, the designers can greatly benefit from starting and optimizing the initial design process. For this work, the surrounding material's reflective permittivity is $\epsilon_d = 2$, which required a coupling angle of 0.82 rad. Fig. 4.5 illustrates the S-parameter response with the new coupling angle $\psi = 0.82$ rad.

Another critical parameter for the circulator design is the ferrite disk thickness h_f . In [31], the recommended value suggested for the disk height was $0.4a$, where "a" is the ferrite disk radius. For this design, the ferrite radius is considered 0.925 mm, so the thickness h_f will be 0.375 mm. However, the surrounding dielectric material Rogers 5880 LZ that is regarded to support the ferrite disk does not contain this size and is not a standard substrate. Therefore, the ferrite thickness h_f

has to be changed to standard substrate size with 0.254 mm thickness. In the case of [31], it was a metal ridge gap waveguide with the flexibility to go beyond the required standard substrate dimensions, which is not an option with the proposed work.

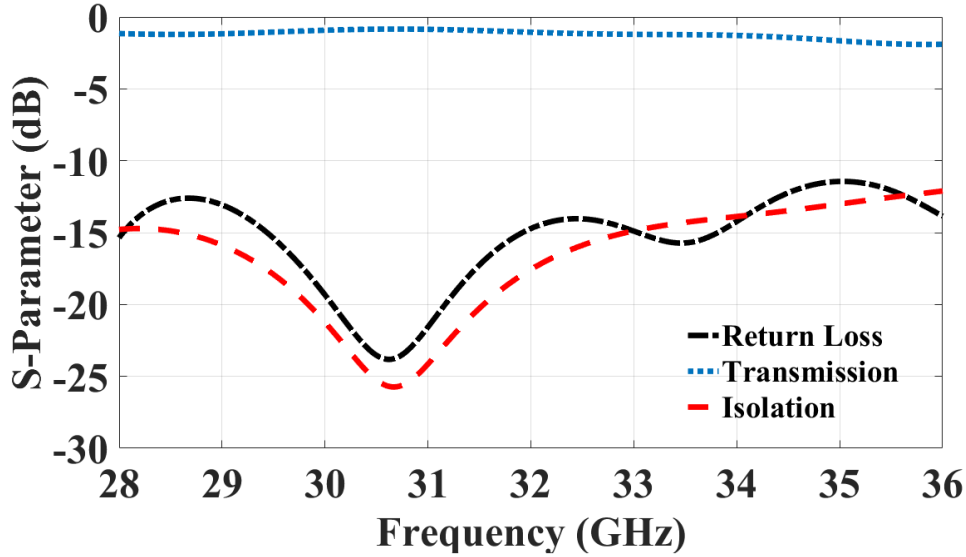


Fig. 4.5: Circulator design with calculated coupling angle $\psi = 0.82$ rad.

The design of the circulator based on this technology goes through some significant steps, including ferrite disk selection and matching line design. The ferrite disk design and the matching line design procedure are covered in Subsections 4.2.1 and 4.2.2, respectively.

4.2.1 Ferrite Disk Selection

This section discusses the ferrite disk calculation and a numerical example to explain the proposed design.

1. The first step of the ferrite disk design is to define the design frequency, f_d through the following Equation,

$$f_d = 1.05 * \left(\frac{f_{start} + f_{stop}}{2} \right) \quad (4.22)$$

where f_{start} and f_{stop} are the starting and end frequency of the circulator, respectively. For this work, the start and stop frequencies are 28 and 36 GHz, respectively, resulting in a design frequency, $f_d = 33.6$ GHz. The center frequency is increased by 5% to compensate for the fringing field effect outside the ferrite disk. The analysis is based on a virtual PMC boundary around the

ferrite disk as a valid approximation with a slight deviation.

2. The saturation magnetization, $4\pi M_s$ is related to the design frequency through the following expression:

$$4\pi M_s = \frac{g_k f_d}{2.8 \times 10^6} \quad (4.23)$$

Keeping the gyrotropy values between -0.2 to -0.8 to avoid resonance losses and below saturation losses [110]. For the proposed work, a -0.6 gyrotropy is assumed. From the above Equation, the value obtained for the $4\pi M_s = 7150$. However, the closest available material in the market is C-48, which has a dielectric constant of 13.5, with $4\pi M_s = 5300$ [109]. The magnetic biasing ratio, α is considered to be 0.15. The internal magnetic biasing field H_0 is considered to be 900 O_e for the illustrated example where $H_0(0_e) = 4\pi M_s(G) * \alpha$.

3. From the key circulator design Equations (4.9) and (4.10), the values of both x and ψ are calculated. Later, based on Fig. 4.4 curve fitting, the optimum coupling angle can be determined. Hence, the ferrite disk radius can be obtained using $x = k_{eff} a$, from which the dimension of the disk radius, a , is obtained.

4. Substituting the value of coupling angle ψ and disk radius a in Equation (4.3) provides the ridge width, W . The calculated ferrite radius and the width of the ridge are used as initial values for an optimization procedure to achieve a deep matching over the required bandwidth. The final disk radius and line widths are 0.925 mm and 1.5075 mm, respectively.

5. The height of the disk must be kept $h < a$, and for the proposed SIGW circulator, the disk height is considered to be $h_f = 0.25 a$. The height of the ferrite disk is kept similar to the dielectric-filled substrate, $h = 0.254 \text{ mm}$, which is a standard substrate from Rogers Corporation.

All the required design parameters calculated for the ferrite disk are summarized in Table 4.1.

Table 4.1: Design Parameters of the Ferrite Disk

Parameters	Value
Gyrotropy g_k	0.6
Magnetic Saturation $4\pi M_s$	5300 G
Magnetic biasing ratio α	0.15
Magnetic biasing field H_0	900 0_e
Coupling angle ψ	0.82 rad
Coupling junction radius b	1.1 mm
Disk radius a	0.925 mm
Coupling area width W	1.50 mm
Ferrite disk height h_f	0.254 mm

4.2.2 Matching Section Design

This section will discuss the matching line design, which will feed the ferrite disk junction. The input impedance real part of the ferrite disk can be calculated from the following Equation, which approximately equals 15.1Ω at the design frequency.

$$R_{in} = \text{Re} \left\{ \frac{Z_0}{\eta_0} \left(\eta_{11} - \frac{\eta_{12}^2}{\eta_{13}} \right) \right\} \quad (4.24)$$

Z_0 , and η_0 are the characteristic and intrinsic impedance, respectively. The selected dielectric constant deployed in the matching must be small compared to the dielectric constant of the ferrite disk, which is an essential condition to ensure the validity of the PMC boundary assumption. The impedance of the dielectric-filled ridge $Z_{dielectric}$, is calculated through the following Equation,

$$Z_{dielectric} = \frac{\eta_0}{4\sqrt{\epsilon_d}} \left[\frac{W}{2h} + 0.441 \right]^{-1} \quad (4.25)$$

The proposed maximum value of the dielectric constant is $0.15*\epsilon_f$, which is 2. This value results in a characteristic impedance of 18.7Ω , which is close enough to provide good matching to the ferrite disk with a disk resistance of 15.1Ω . To achieve the matching level, two-section Chebychev transformers are added with the feeding line, as indicated in Fig. 4.7, where this part

will be discussed in the following section.

4.3 SIGW Circulator Design

Substrate integrated gap waveguide uses periodic cells to control the structure's bandgap without signal dispersion. For a SIGW, the propagating gap is filled with dielectric and should always be less than a quarter wavelength. The surrounded medium has a significantly lower dielectric material compared to the ferrite material, so the PMC assumption remains valid around the ferrite disk where $H_{tan} = 0$ in between the ports [108]. The proposed cell configuration, and the dispersion diagram of one row of SIGW, are illustrated in Fig. 4.6.

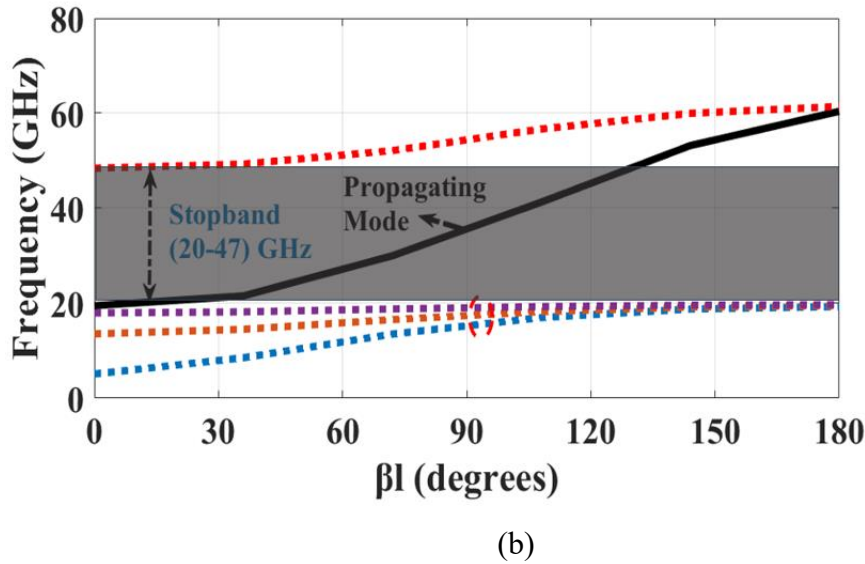
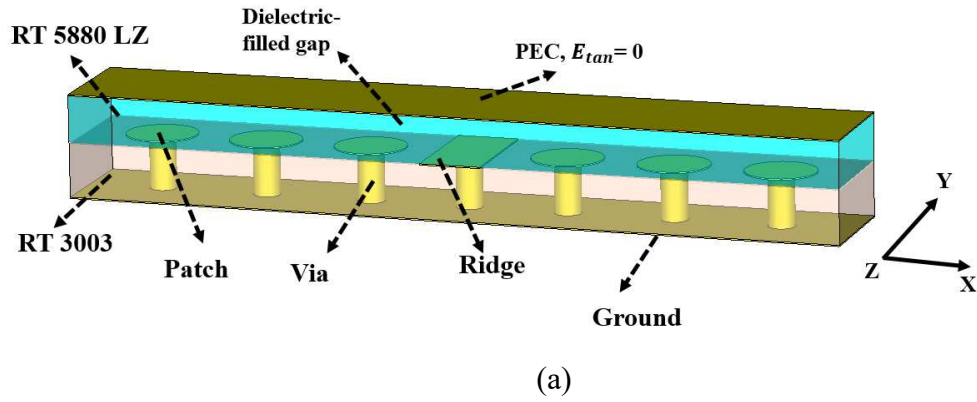


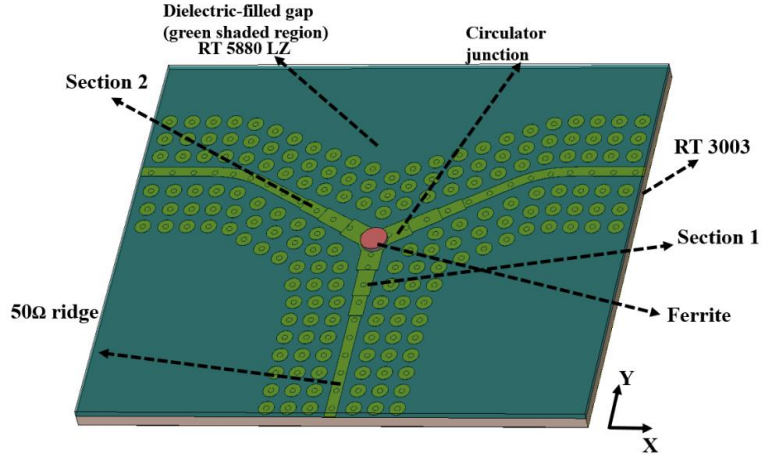
Fig. 4.6: Periodic bed of mushrooms (a) 3D view of one row of unit cells, (b) Dispersion diagram of a dielectric-filled ridge.

The dispersion diagram is extracted using Eigen Mode Solver (CST Microwave Studio); it can be observed from the dispersion diagram that the unit cell provides a realized bandgap from 20-47 GHz. The waves propagate along the ridge only, with a Q-TEM mode inside the dielectric-filled gap. Since SIGW supports Q-TEM mode, it is not subjected to signal dispersion, mitigating the signal distortion. The shaded region in Fig. 4.6(b) highlights the structure's bandgap. Table 4.2 lists the design parameters of the SIGW unit cell.

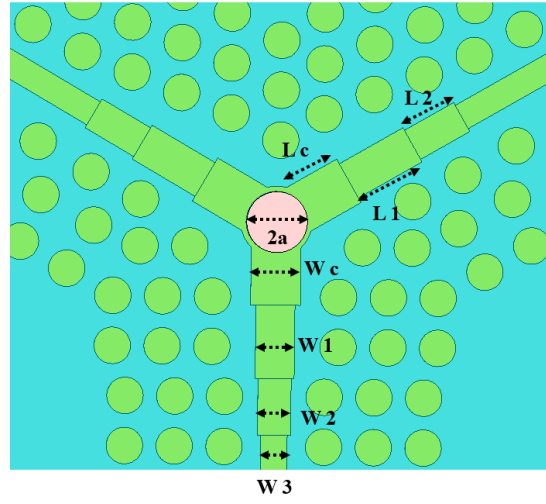
Table 4.2: Dimensions of SIGW unit cell row (in mm)

Parameters	Value
Ridge width, W_r	0.85
Dielectric-filled gap, h	0.254
Via height, d	0.75
Via radius, d_{rad}	0.1875
Cell radius, c_{rad}	0.5
Via to via distance, p	1.5

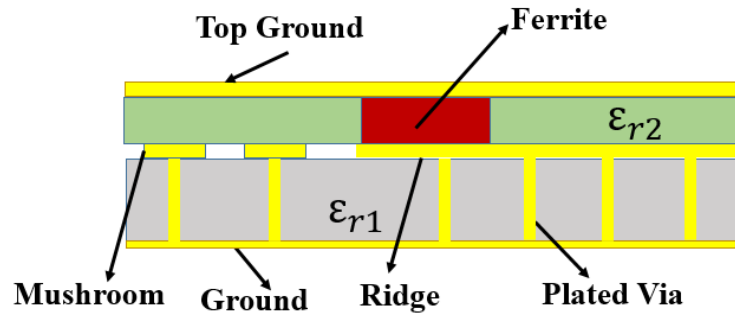
The substrate used for the dielectric filling is Rogers 5880 LZ with a relative permittivity, $\epsilon_d = 2$, where the ferrite disk dielectric constant is around 13.5. The proposed SIGW Y-junction circulator is illustrated in Fig. 4.7, where the upper ground is kept hidden for a clear illustration. Two multi-section transformers are added to the circulator feeding line to improve the bandwidth matching. Connecting the circulator junction directly with the ferrite disk will result in poor return loss and isolation, so multi-section transformers are added to match the circulator junction to a 50Ω line. Table 4.3 illustrates the dimensions of two-section transformers, including the circulator junctions.



(a)



(b)



(c)

Fig. 4.7: SIGW Y-junction circulator, (a) 3D view of the proposed design, (b) Schematic of feeding lines using two-section transformers, (c) side-view of SIGW circulator (cross-section).

Table 4.3: Dimensions of SIGW multi-section transformers (in mm)

Parameters	Values	Parameters	Values
Wc	1.5075	Lc	1.778
W1	1.157	L1	2.13
W2	1.025	L2	1.68
W3	0.85	L3	9

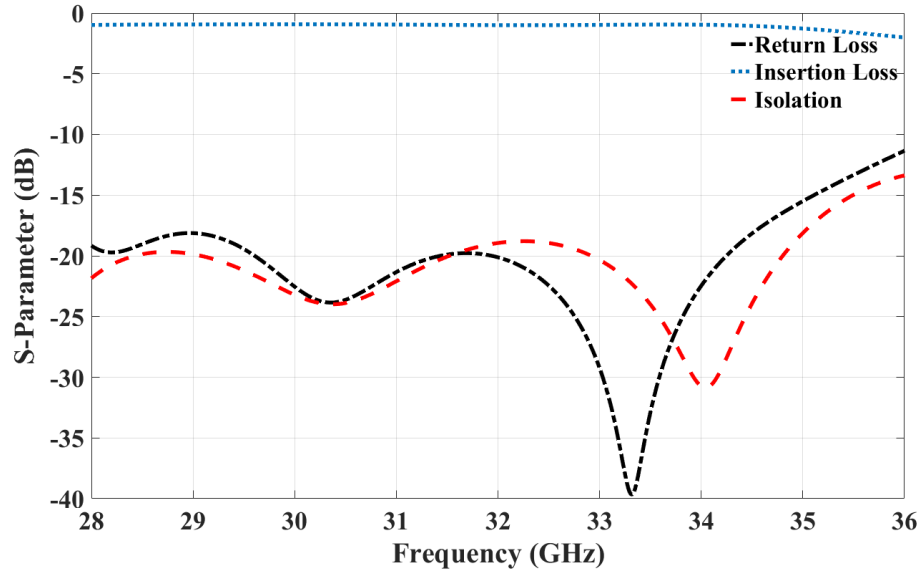


Fig. 4.8: SIGW Y-junction ferrite circulator's simulated S-parameter response.

The proposed circulator covers a wide bandwidth with an excellent matching bandwidth below -15 dB from 28-35 GHz. S_{31} represents the isolation of the circulator, S_{21} represents the power transfer from Port 1 to 2. All the power from Port 1 goes to Port 2, as illustrated in Fig. 4.8. The insertion loss is around -0.9 ± 0.2 dB, including material and radiation losses from 28-34 GHz. The Electric field distribution at 30 GHz is highlighted in Fig. 4.9, covering the periodic cells and ferrite disks. All the power from the input port has coupled into coupled port, while the third port remains isolated. The filling dielectric materials significantly contribute to the losses, but the mode has kept its quasi-TEM type, ensuring non-dispersive propagation.

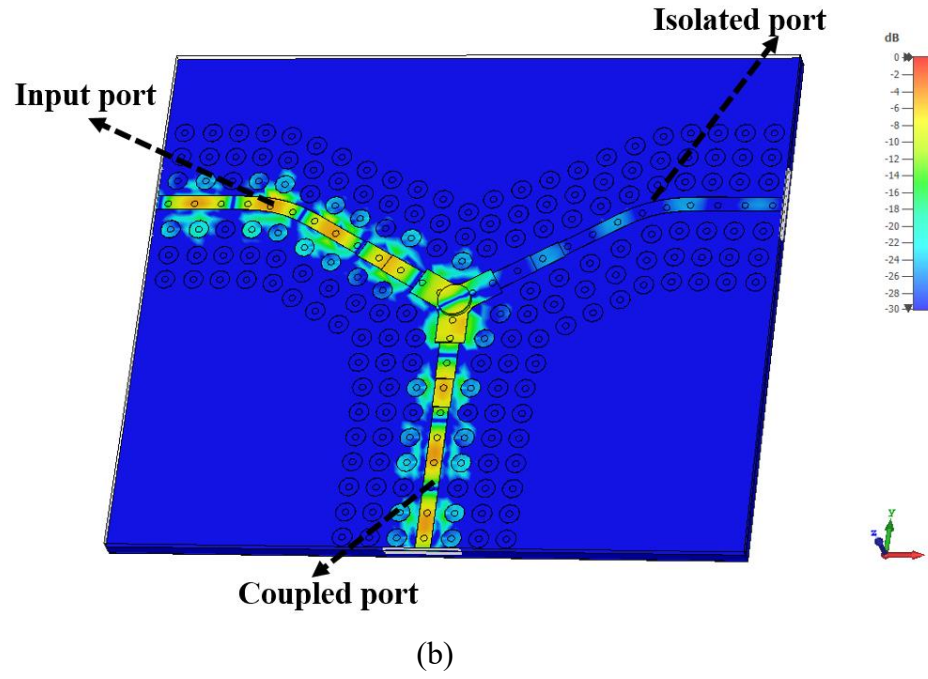
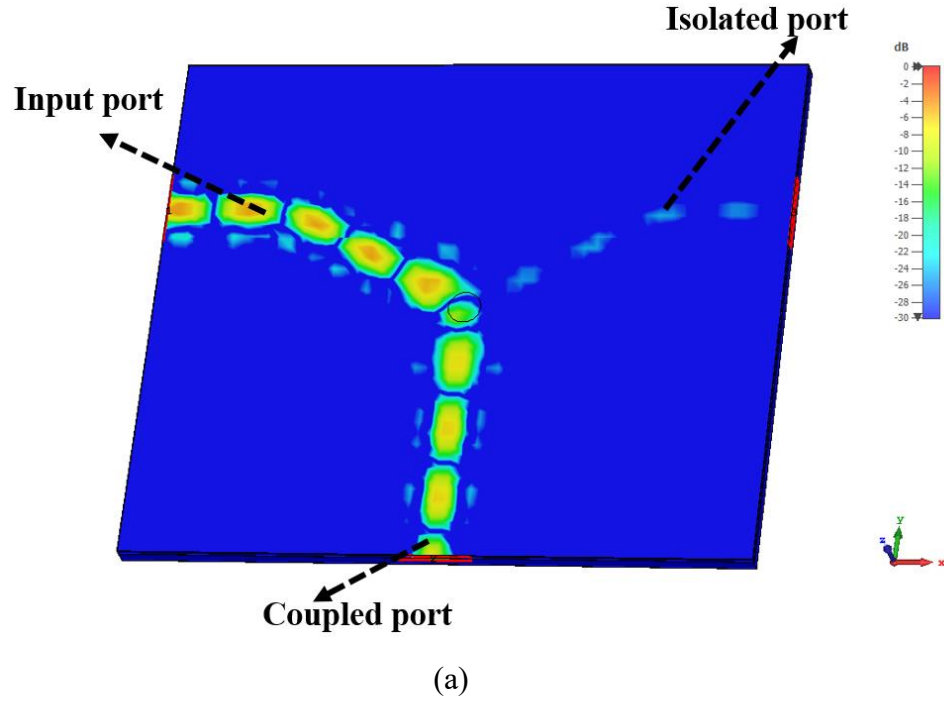


Fig. 4.9: Electric field distribution of the SIGW ferrite circulator, (a) inside the dielectric-filled gap, (b) inside the substrate.

4.3 Experimental Validation and Prototyping

The proposed SIGW circulator is fabricated to validate our work. The fabricated prototype has three major parts: periodic mushroom cells with ridge, the ferrite disk, and the metal housing required for the biasing of the circulator. The ferrite disk is C-48, with a dielectric constant of 13.5, with a $4\pi Ms$ of 5300 [109]. The ferrite disk is glued to the junction, and the top layer is fitted and pressed. The metal housing part was built using Aluminum material with low-cost CNC milling from Xeometry with a fabrication tolerance of 0.001" [111]. The simulated 3D model of the SIGW circulator is illustrated in Fig. 4.10. For a clear illustration, the top metal part is hidden. The fabricated printed circuit board (PCB) and CNC-milled metal housing prototypes are shown in Fig. 4.11. The measurement setup is illustrated in Fig. 4.12. It is worth mentioning that while performing the simulation, waveguide ports are considered, and the metal housing part is not considered. However, the lossy aluminum material will now be considered on the 3D full-wave simulator for a fair comparison with the measured results. This will add additional insertion losses due to the lossy material. The back-to-back transition of the line varies from 1.8-2.2 dB for a 2.92 K end-launch connector (f), SMA Connector [112].

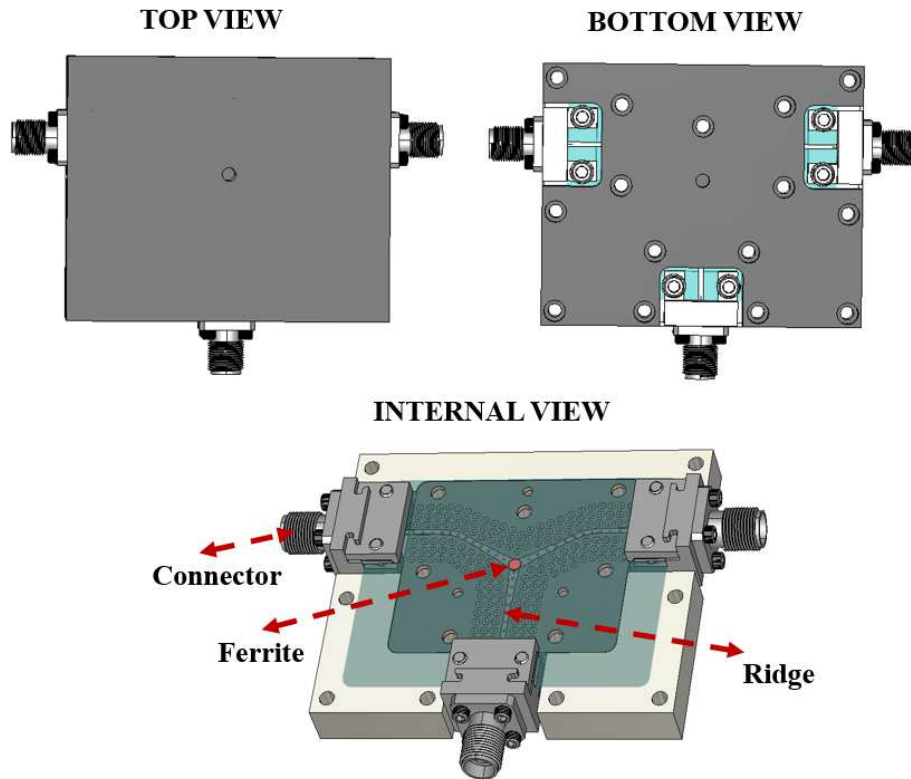
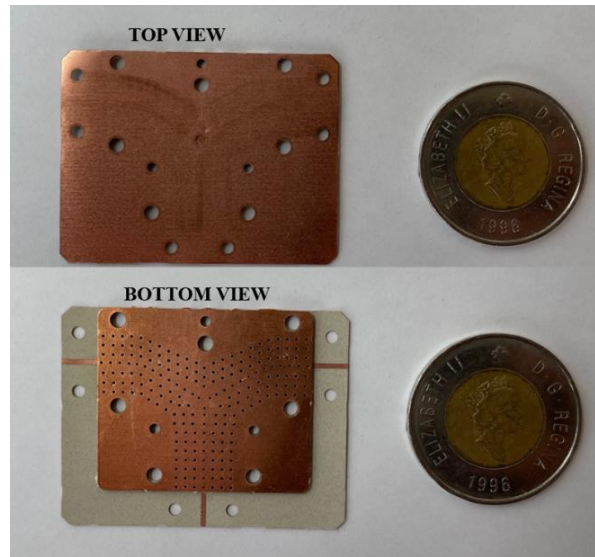
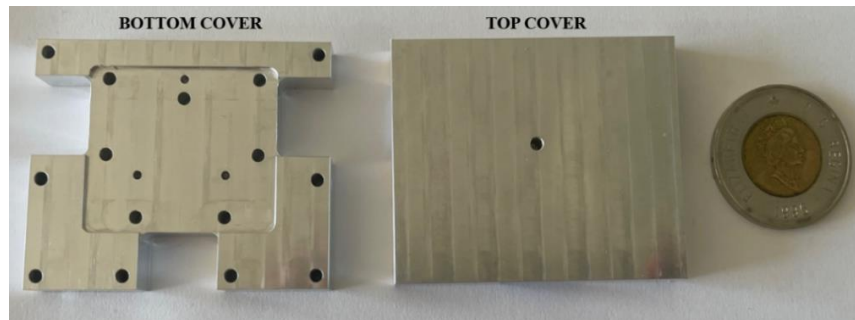


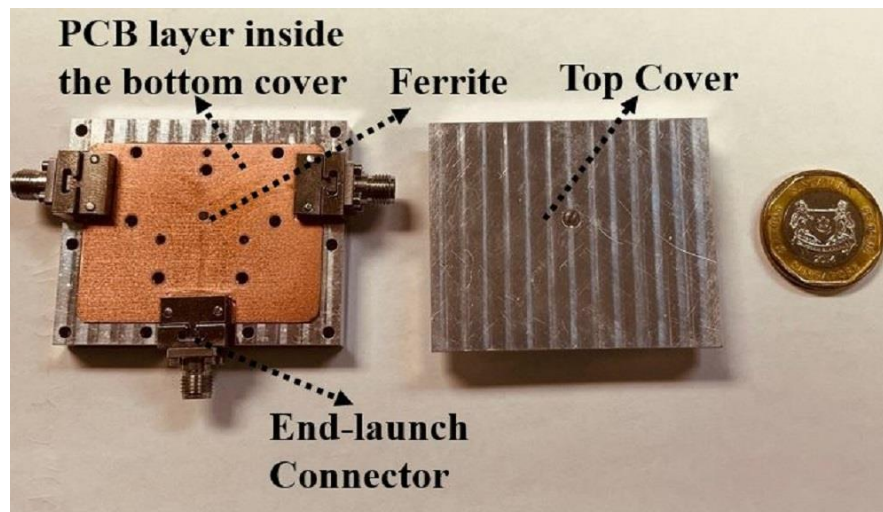
Fig. 4.10: 3D simulated model of the proposed SIGW circulator.



(a)



(b)



(c)

Fig. 4.11: Fabricated SIGW Circulator, (a) PCB fabrication part, (b) CNC-milled metal housing, (c) Internal configuration with ferrite.

For the measurement, a two-port coaxial calibration is performed, where the reference plane is assumed at the 2.92mm connector to include the transition in the measured response. The circulator is a three-port device, so a coaxial load is deployed to terminate the isolated port during the measurement using the Vector network analyzer (VNA). DC Magnets are placed on both sides of the metal housing part to have a proper magnetic biasing. In this case, the S_{21} will provide the transmission co-efficient of the circulator, and S_{12} will provide isolation. The PCB and the ferrite were placed inside the housing, tight with the screws to ensure appropriate contact. The connector loss was eliminated based on the data available for the back-to-back transition from the southwest connector [112]. For future work, the TRL calibration can be done to eliminate the effect of the connectors. The back-to-back transition of the line varies from 1.8-2.2 dB for a 2.92 K end-launch connector (f), SMA connector [112]. Fig. 4.13 illustrates the scattering parameter measurement response of the SIGW Circulator.

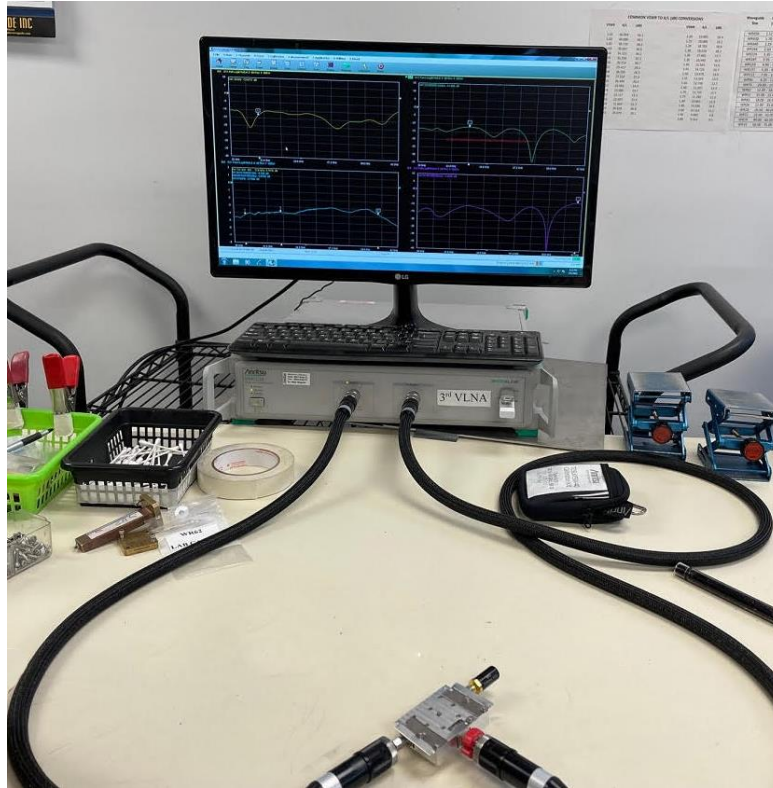


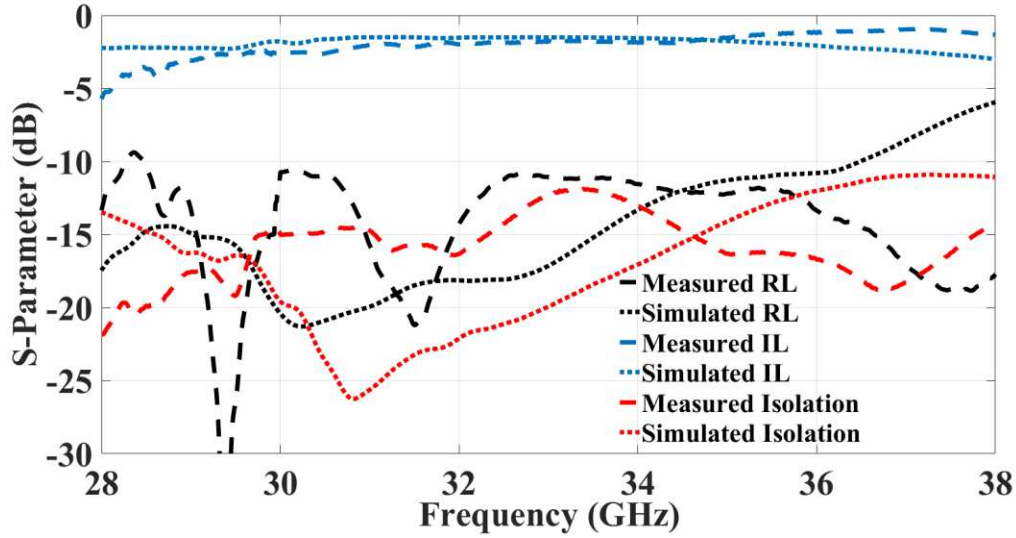
Fig. 4.12: Measurement setup of SIGW Ferrite Circulator.

It is observed from the S-parameter response that the circulator covers an extensive bandwidth throughout the operating frequency range. It is noticeable from Fig. 4.13(a) that the measured insertion loss is very high, around 28 GHz; also, there is some discrepancy between the simulated and measured responses. The ferrite disk is measured with the Vernier scale to verify the size to identify this deviation in the response. After the measurement, it was figured that the measured ferrite's diameter and thickness were significantly different from the one considered in the simulator. The optimum diameter and thickness of the ferrite we considered for this work are 1.85 mm and 0.254 mm, respectively. However, the measured diameter and the thickness were 1.74 mm and 0.22 mm, respectively, which is 7.5% more than our original dimension. In the mm-wave range, this could deviate the result tremendously. In addition, the ferrite diameter controls the resonant frequency for the ferrite circulator design. It is noticeable from the S-parameter response that the measured result shifted towards the higher frequency band due to the ferrite diameter.

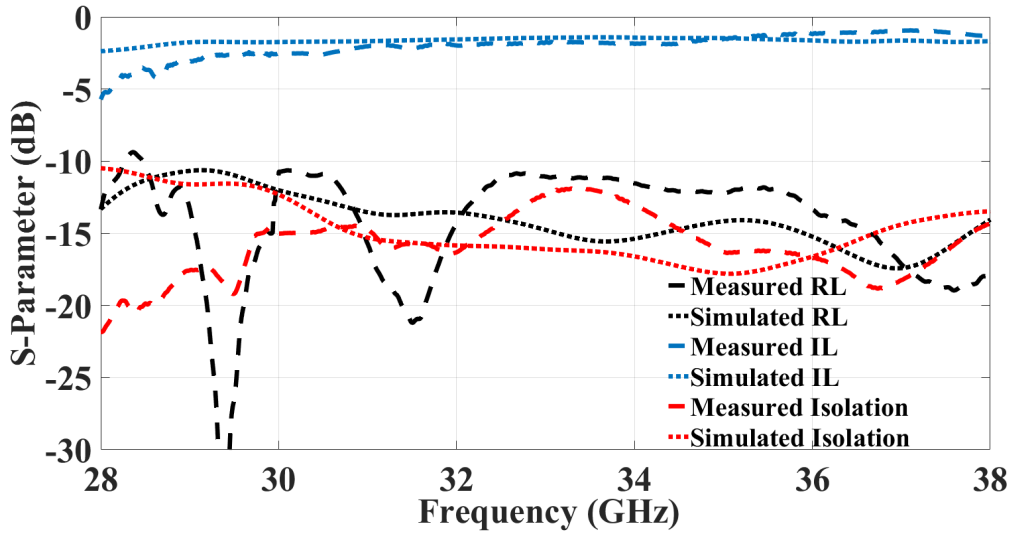
Moreover, the PCB material has some fabrication tolerance, which could change the result. The fabricated layers are assembled using high temperature and pressure, which uses adhesives at layer corners to provide good mechanical stability [102]. Epoxy glue is used between the PCB layers for the thermal pressing, with a dielectric constant of 3.5. Because of this adhesive, the effective dielectric of the material can be changed. Another simulation is performed to justify the change in results using the new ferrite diameter and thickness dimensions. Fig. 4.13(b) compares the measured and simulated results with the new ferrite dimensions.

It can be noticed that after changing the ferrite diameter and thickness, the result changed significantly, and the simulated and measured results are more comparable than previously. The insertion loss is around 1.7 ± 1.3 dB and is in agreement with the simulated results from 29-38 GHz. The isolation of the circulator is better than 12 dB throughout the whole operating bandwidth. Furthermore, the result can be enhanced based on optimization using the full-wave analysis. After knowing the exact ferrite size, the Y-junction section and the two-section transformers can be adjusted to improve the matching level. Based on the new dimensions, another fabrication of the PCB will be required. The insertion loss can be improved by using copper or silver-plated coating on the lossy aluminum body. Another low-cost solution can be to use 3D printing for the housing

and later use copper plating (stereolithography), which can significantly improve the performance because of the high-precision 3D printing facilities available. This can be an interesting extension for future research work on this topic. The proposed wideband circulator covers 28.5% impedance bandwidth, which can be used for Ka-band satellites and radar applications.



(a)



(b)

Fig. 4.13: Measured and simulated S-Parameter comparison of SIGW Circulator, (a) original disk size, (b) new disk size.

A ridge gap waveguide of ferrite circulator was proposed, covering a whole Ku-Band, with excellent return loss and isolation level [31]. However, using a metal ridge gap waveguide requires higher accuracy CNC milling, which will be expensive, and the structure is bulky, which will not be a suitable option in the mm-wave range. In addition, an X-band circulator and antenna as a single integrated system was proposed using microstrip technology that provided a return loss above 14 dB, insertion loss below 2.5 dB, and isolation beyond 25 dB over the band from 9-10 GHz [32]. A similar approach was made to integrate a circulator and antenna in a single layer at Ku-band, where the insertion loss is improved using an impedance equalizer to balance the circuit [33]. Table 4.4 compares the proposed and previously published work in the same area.

A self-biased Y-junction ferrite circulator operating at 13.65 GHz was proposed, where the insertion loss is around 1.52 dB and a 15 dB isolation bandwidth of 220 MHz [94]. In addition, a ferrite LTCC multifunctional circulator with integrated winding was designed at Ku-band, where both external magnets and external 200 mA current were applied to achieve 1.6 dB insertion loss and 23 dB isolation at 14.2 GHz [95]. Moreover, a Y-junction circulator based on ESICL has been designed, covering 33% impedance bandwidth with a measured insertion loss of 1 dB covering from 10-14 GHz [96]. An integrated microwave circulator and antenna assembly were proposed using a complex port impedance to have a maximum power transfer to cover 4 GHz bandwidth from 12-16 GHz [98]. A Substrate integrated waveguide-based ferrite circulator-based antenna module was designed at Ka-band that provided 5% bandwidth and a measured transmission coefficient of 4 dB, attributed to the dielectric loss and discontinuities between the circulator and the ferrite surface [99].

Moreover, a self-biased, wideband microstrip circulator for an integrated antenna system is proposed with an insertion loss of around 2.7 dB with 10.7 % impedance bandwidth (covering 32-35.6 GHz) for 15 dB return loss and isolation level [100]. In [116], a 35 GHz barium hexaferrite composite-based circulator suitable for mm-wave CMOS integration is deployed. However, high loss-tangent, large linewidth, and surface roughness affected the IL tremendously. Our proposed packaged SIGW circulator provides wideband and strong mechanical support compared to the other published designs. The proposed SIGW circulator covers the 28.5-38 GHz range, with

acceptable return loss and isolation level throughout the operating bandwidth. Most of the previously published circulators are designed with microstrip line technology, which will have a massive loss at the mm-wave range and encounter surface waves and leakage issues. The packaged SIGW circulator system will not encounter any leakages within a specified bandgap and will provide strong mechanical support compared to the other published designs.

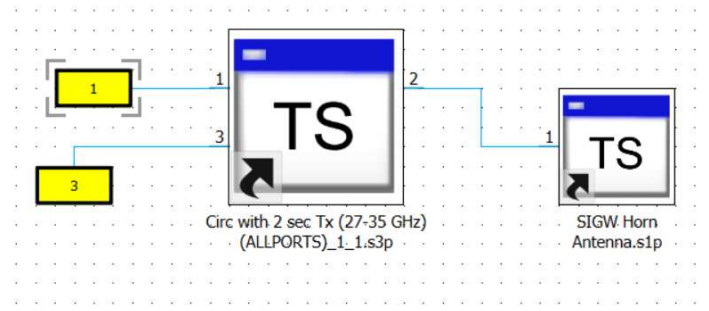
Table 4.4: Comparison of the proposed SIGW circulator with other works

Ref	Center Freq. (GHz)	Technology	BW (%)	IL (dB)	RL (dB)	ISO (dB)
This work	32	SIGW	28.5	1.8	15	15
[31]	15	Ridge gap waveguide	40	1.6	20	20
[32]	9.5	Microstrip Line	10.25	2.5	15	25
[33]	14.5	Microstrip Line	20.6	0.8	20	20
[94]	13.65	Rectangular waveguide	3	1.52	NA	15
[95]	14.2	Low-temperature Co-fired Ceramic (LTCC)	4.25	1.6	20	23
[96]	12	Empty Substrate Integrated Coaxial Line (ESICL)	33.3	1	10	10
[98]	14	Microstrip Line	28.4	1.5	18	17
[99]	38	SIW	5	4	28	18
[100]	34	Microstrip line	10.7 (Sim)	2.7	15	15
[116]	35.4	Microstrip line	3.5	7.8	13	5.7

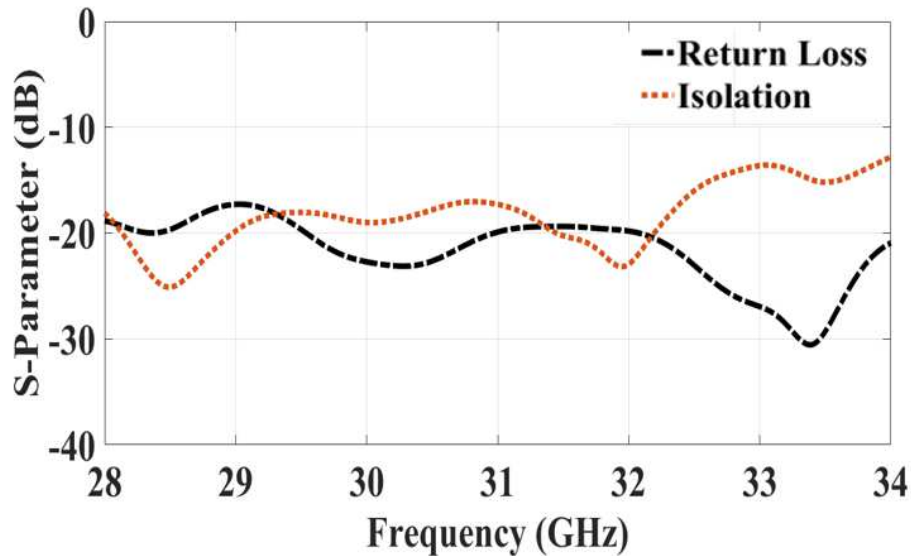
4.4 Circulator Integration with the antenna forming a Full-duplex System:

It is common for a typical communication system to break down into components designed separately with a specific interfacing specification. We followed the same approach by developing and analyzing the circulator with mathematical formulations and a full-wave EM solver. Before performing the full-wave simulation using the EM solver, a good practice is to separate the s-parameter matrix of the circulator and antenna separately and simulate using an Advanced design

system (ADS) or CST microwave studios schematic circuit design. This gives a good starting point for understanding the possible scattering parameter performance of the circulator antenna system integration. Not only the approximation leads to a good guess, but it also saves much computational time. The circulator is a three-port network where the coupled port will be connected directly to the antenna. After getting an acceptable performance, the final full-wave simulation can be performed. The circulator antenna integration block diagram is displayed in Fig. 4.14(a), where the isolation and return loss response are shown in Fig. 4.14(b). The antenna is incorporated on the same layer using the same thickness and dielectric constant of the surrounding material outside the ferrite disk to ensure deep matching. The SIGW circulator antenna system is shown in Fig. 4.15, where the upper circulator conductor is hidden for a clear illustration.

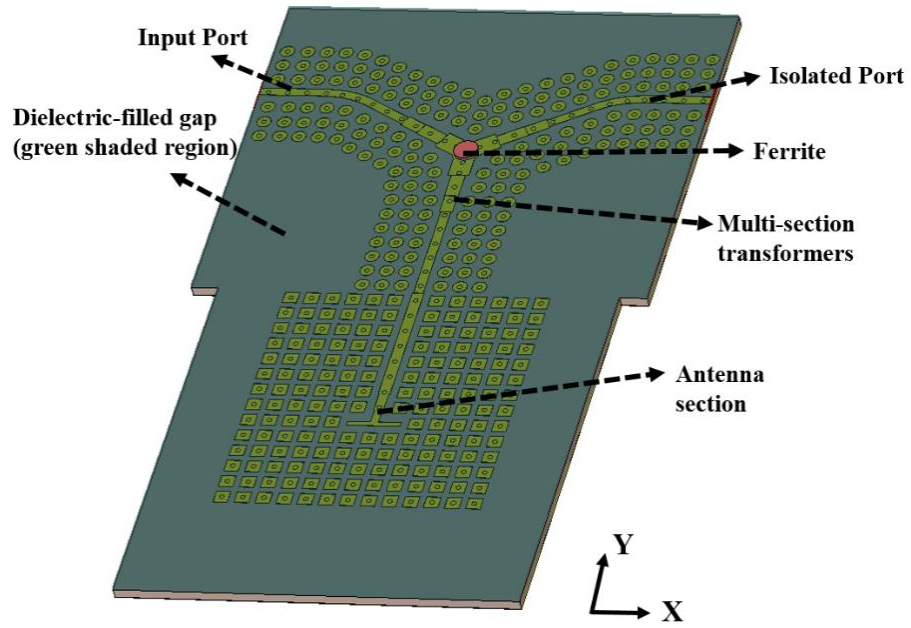


(a)

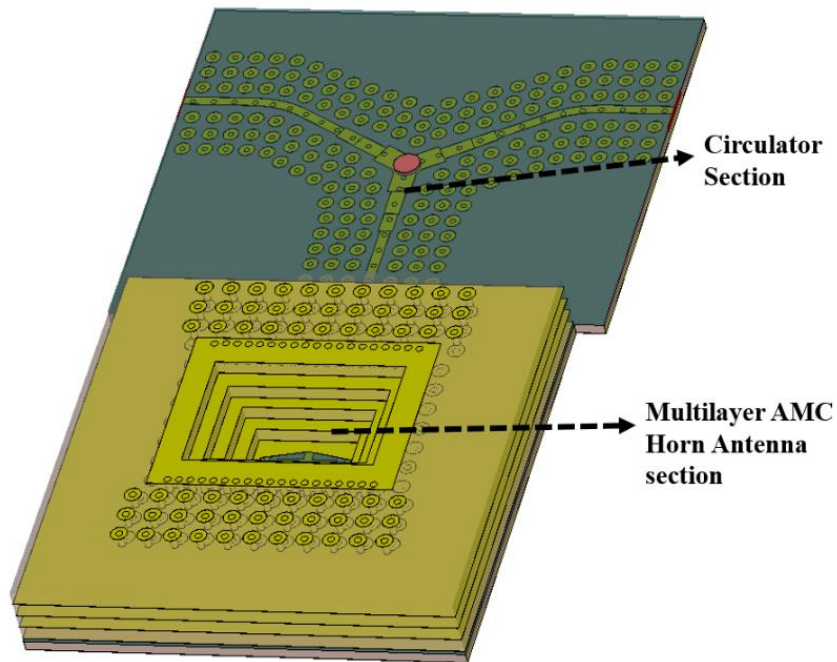


(b)

Fig. 4.14: Block diagram of the circulator antenna system, (a) block diagram, (b) Return loss & isolation.



(a)



(b)

Fig. 4.15: SIGW circulator antenna system (a) feeding layer, and (b) 3D view of the complete structure.

Integrating an antenna with a circulator will form a full-duplex system allowing transmission/reception. Building the complete circulator antenna system in one layer with the same guiding structure will facilitate the fabrication process providing a compact system. However, the antenna is directly connected to the circulator and must be internally matched. While designing an antenna for RF frontends, we consider -10 dB as a sufficient matching level. However, considering the integration between the antenna and the circulator, it is better to have an antenna with a deep matching characteristic. A wideband printed AMC multilayer horn antenna is considered to avoid leakage for circulator antenna integration [117].

The simulated isolation level is below -16.5 dB from 28.2 to 32.5 GHz, while the return loss is better than 18 dB, as shown in Fig. 4.16. The return loss shows an excellent matching bandwidth covering 28 to 34 GHz. Fig. 4.17 portrays the measured circulator antenna system response. While measuring the circulator antenna system, the circulator was connected with the previously measured horn antenna in chapter 3. The connection of the antenna and the circulator was made using a male-to-male 2.92 mm (k) adapter (bullet). While performing the measurements for both the circulator and the antenna female 2.92 mm (K) connector from Southwest Microwave was used.

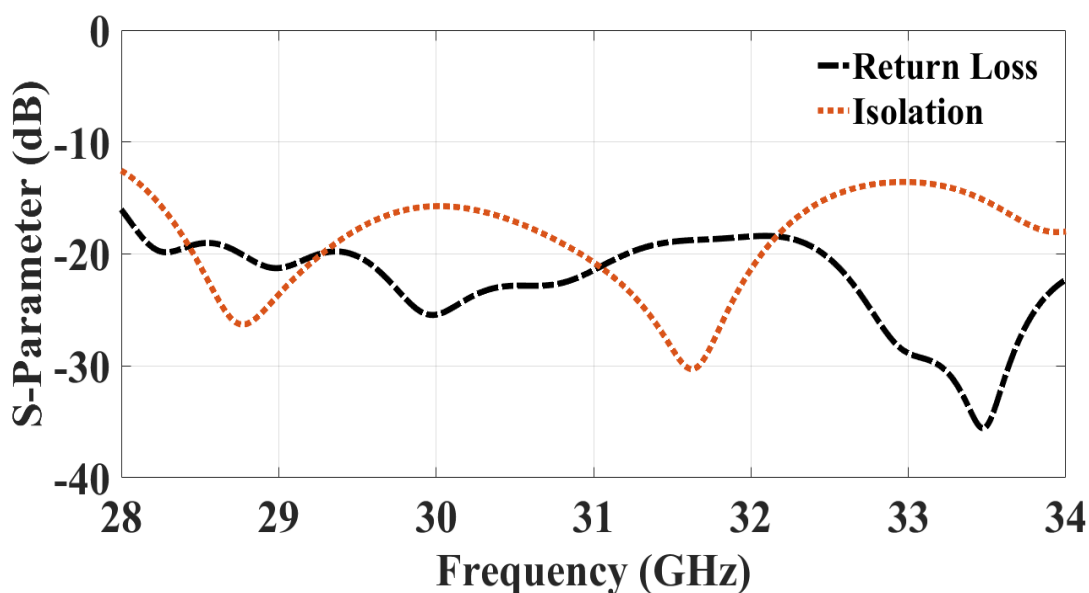


Fig. 4.16: SIGW Circulator Antenna Systems Simulated S-Parameter response.

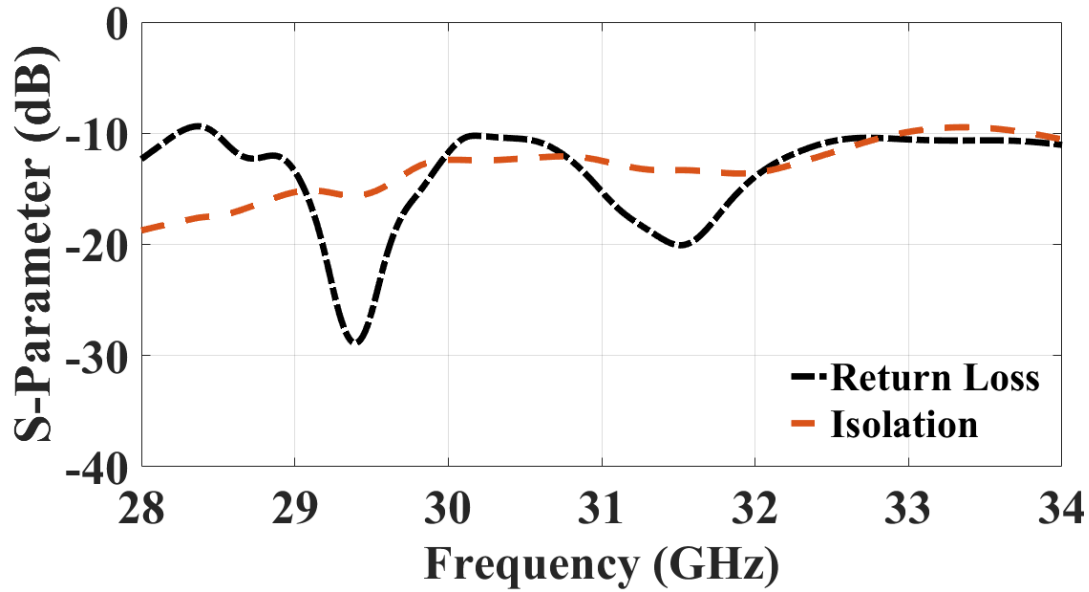


Fig. 4.17: SIGW Circulator Antenna Systems Measured S-Parameter response.

It is worth mentioning that the measured horn antenna operates from 27.2-34 GHz; therefore, it affected the isolation of the circulator antenna systems at the higher frequency range. The smaller ferrite size, compared to the original one, has affected the overall return loss of the circulator antenna system.

A single junction circulator will not be able to provide more than 15 dB isolation over the operating frequency range. However, it is possible to get a high-isolation by employing a dual or triple junction circulator in a cascading formation, which can increase the isolation level significantly exceeding 45 dB isolation. Usually, for satellite communication full-duplex system with high-isolation beyond 45 dB is preferable.

Chapter 5

Fabrication Technique of Millimeter-wave High-Magnetization Nickel-Zinc Ferrite Disk Using Chemical Co-Precipitation Method

5.1 Introduction

Nickel ferrites with spinel crystal structure have exhibited a superior development due to their electronic and magnetic properties that are essential for some applications [124], [125]. Ferrites are used in a lot of microwave and radio applications such as electromagnetic absorbers, circulators, phase shifters, switches, etc., [126]-[128]. Moreover, ferrite materials are beneficial for gas and ethanol sensor applications [129], [130]. For obtaining ferrite nanocrystalline powders, plenty of techniques have been utilized for the synthesis of ferrite powders, such as the hydrothermal method [131], [132], sol-gel [133], [134], and co-precipitation method [135], [136]. The chemical co-precipitation method is a low-cost technique supporting mass production, and it ensures the proper distribution of various metal ions resulting in smaller particle sizes compared to other procedures. Among ferrites, the Ni-Zn ferrite is of particular interest due to its high saturation magnetization [136]-[137]. Nickel-zinc ferrites also exhibit high magnetic permeability, high mechanical strength, good chemical stability, low coercivities, and low dielectric losses.

The ferrite powder fabrication process requires heat treatment to achieve a certain magnetization level. Different atmospheres such as oxygen, vacuum, and nitrogen were already implemented in the previously invented works [140]-[152]. However, the abovementioned works do not provide a high magnetization compared to the proposed novel technique of nickel-zinc ferrite powder presented in this chapter. Some of the previously registered patents have a significantly long process with multiple sintering processes, which will increase the manufacturing time, cost, and complexity [140], [142]. Some of the reported works used different chemical compositions, where the saturation magnetization was low compared to our novel fabricated ferrite powder, and it is not suitable for millimeter-wave RF components [141], [149]-[151], [153]. Schoch, Jr. *et al.* proposed a fabrication process using magnesium oxide, manganese oxide, and ferric oxide composition that provided a saturation magnetization of 2150 (G), which cannot be used for high-frequency applications beyond the X band [145]. A previously registered patent demonstrated the

ferrite disk fabrication from the powders reaching a magnetization saturation of $4\pi M_S$ ranging from 5250 (G) [144], which is close to the magnetization available in the commercial market [109]. In [148], a ferrite disk was fabricated and deployed with a circulator design operating from 1.785-1.9 GHz. The magnetization achieved in [148] is significantly lower compared to our proposed work. In [152], the maximum saturation magnetization of 92.9 emu/g was achieved by heating at 650° C for 4 hours in the ambient air and later heated at 1250° C for 4 hours in an atmosphere having 0% by the volume of oxygen. In [154], Kaneko *et al.* invented ferrite particles capable of exhibiting high magnetization above 100 emu/g. In [156], a ferrite powder having a core-shell structure provided a saturation magnetization of 200 emu/g; however, the ferrite core cannot be used above the MHz range due to high eddy current loss. In [155], a soft magnetic material using cobalt manganese ferrite composition was used to provide a magnetization beyond 200 emu/g, however; at high frequencies, metallic soft magnetic materials cannot be used due to high eddy current losses, and the cobalt composition will affect the insertion loss of the microwave isolators or circulators. Therefore, soft ferrites become more desirable, ferromagnetic with crystal structures with nickel, zinc, or manganese compositions.

This chapter highlights a complete material production and characterization procedure for Ni-Zn ferrite powder, starting with the chemical co-precipitation method to form ferrite powder, which was later heated in the oven and pressed with a hydraulic pressed machine to form a circular-shaped disk. The circular ferrite disk can be incorporated with a non-reciprocal microwave circulator to form a full-duplex system. At first, nickel-zinc ferrite, $Ni_{0.5}Zn_{0.5}Fe_2O_4$ the powder was prepared using the chemical co-precipitation method. The structural and magnetic properties were verified using X-ray diffraction (XRD) and vibration sample magnetometer (VSM). The phase of the ferrite powder was confirmed with an X-ray diffractometer, which uses $CuK\alpha$ radiation. The magnetization saturation was investigated using VSM with a measured $M_s = 48$ emu/g at 550°C. Later, the magnetization saturation was investigated again at 1100°C in the Nitrogen medium enhanced the M_s significantly from 48 emu/g to 78.5 emu/g. In order to verify the increase in saturation magnetization, the $Ni_{0.5}Zn_{0.5}Fe_2O_4$ powder was heated in two other different atmospheres Nitrogen + 3% Hydrogen, and Argon + 3% Hydrogen at 1100°C. The magnetization jumped from 77 emu/g to 147 emu/g, which is highly magnetic. The scanning electron microscopy (SEM) images show the surface morphology details and particle size.

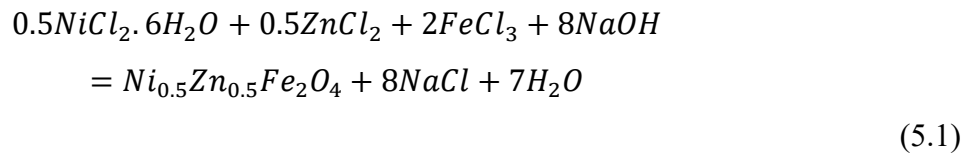
Appendix B highlights the standard operating procedure (SOP) of the Nickel Zinc Ferrite (NZF) powder experiment.

5.2 Sample Preparation and Measurement

This section is organized as follows. Section 5.2.1 illustrates the experimental procedure of the ferrite powder using the co-precipitation method. This is followed by the experimental results of the x-ray diffraction (XRD), scanning electron microscopy (SEM), and saturation magnetization results using the vibration sample magnetometer (VSM) of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder in Sub-sections 5.2.2, 5.2.3 and 5.2.4 respectively.

5.2.1 Experimental Procedure

Fig. 5.1 shows the experimental procedure with all the steps indicated. At first, all the chlorides were weighed separately, put in a separate beaker, and added with de-ionized water. The chlorides used for this experiment were Nickel chloride ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$), Zinc chloride (ZnCl_2), and Ferric chloride (FeCl_3). Similarly, the sodium hydroxide (NaOH) was taken in a separate beaker after weighing and dissolved with de-ionized water using a magnetic stirrer. NaOH was used as a precipitating agent and added with chlorides while continuously stirring the beaker. The solution was continuously stirred for one hour until the formation of a brown precipitate. Each chemical's weight was calculated from the balanced equation, as shown in Table 5.1.



The brown ferrite residue is washed with de-ionized water for seven consecutive days to remove possible chlorides. After that, the filtration is done using a vacuum filtration with a Buchner funnel, as shown in Fig. 5.2. The extracted ferrite paste is then heated in an oven at 550°C for 4h. After getting the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder, the magnetic and structural properties of the ferrite need to be verified using x-ray diffraction (XRD) and vibration sample magnetometer (VSM) to check the emu/g of the powder. The size and morphology of the nanoparticles were characterized using scanning electron microscopy (SEM).

Table 5.1: The Chemical Composition of Nickel Zinc Ferrite Powder

Chemicals	Molecular weight (g/mol)	Weight (g)
$0.5\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$	237.69	2.86
0.5ZnCl_2	136.30	1.64
2FeCl_3	162.20	7.8
8NaOH	39.99	7.7

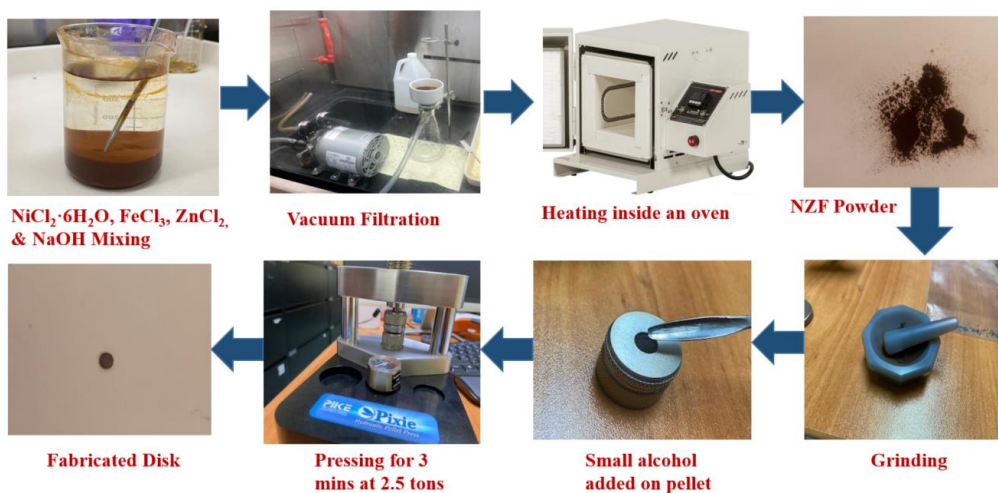


Fig. 5.1: Proposed experimental steps of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder to disk fabrication.



Fig. 5.2: Vacuum filtration using Buchner Funnel inside the fume hood.

5.2.2 Phase Identification Using X-Ray Diffraction

The phase of particle structure was characterized by X-ray diffraction (XRD) analysis which was performed using a Bruker D8 Advance Diffractometer with $\text{CuK}\alpha$ radiation. The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders were scanned over the range from 20° to 90° with a step size of 0.02° with a fixed integration time of 0.5 s. Fig. 5.3 shows the x-ray diffraction patterns for the ferrite $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders annealed at 550°C .

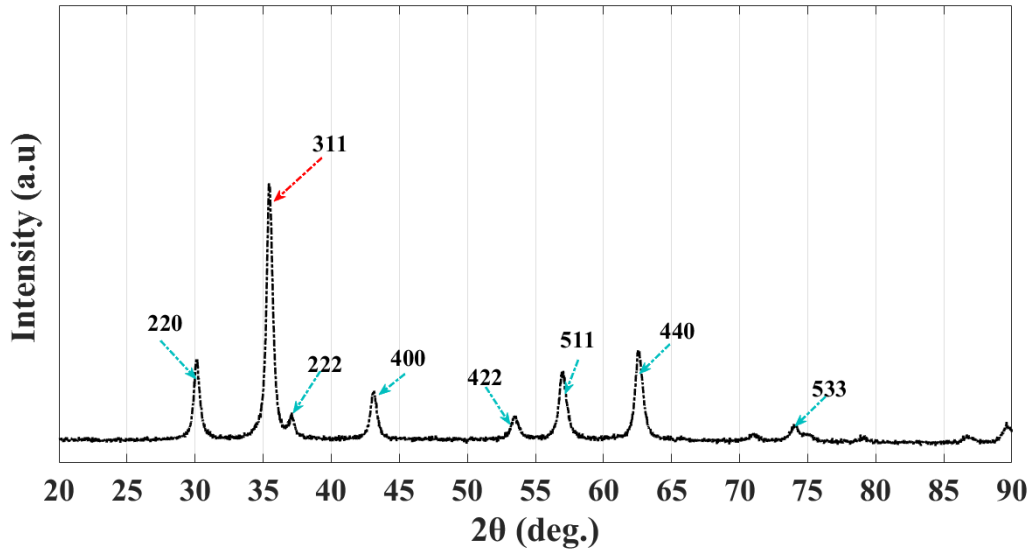


Fig. 5.3: XRD patterns of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders using NaOH annealed at 550°C for 4h. (This measurement was conducted by Dr. Ettiene from Polytechnic Montreal).

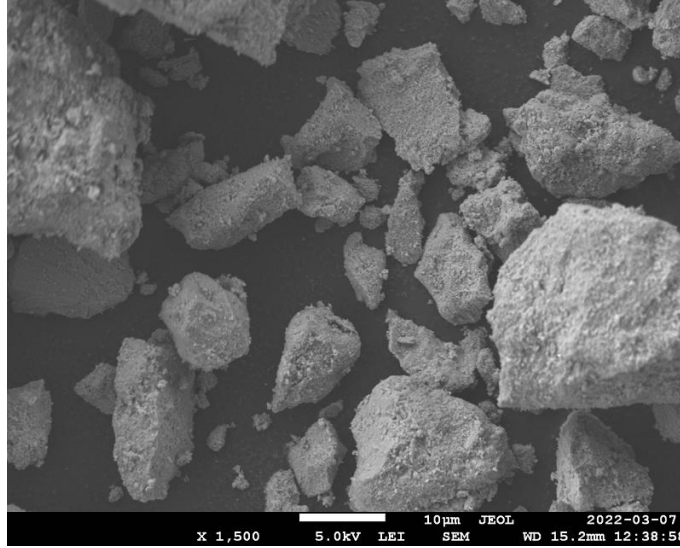
$\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders annealed at 550°C indicated a single-phase spinel structure, implying the temperature was sufficient for the reaction to form desired spinel ferrites with well-oriented textures. From the phase versus the intensity diagram, it is visible that the highest peak, 35.42° , corresponds to the (311) plane. It is worth to the point that the crystallite size of the samples was calculated according to the (311) peak in the XRD patterns using Debye-Scherrer's Equation:

$$D = k\lambda/\beta\cos\theta \quad (5.2)$$

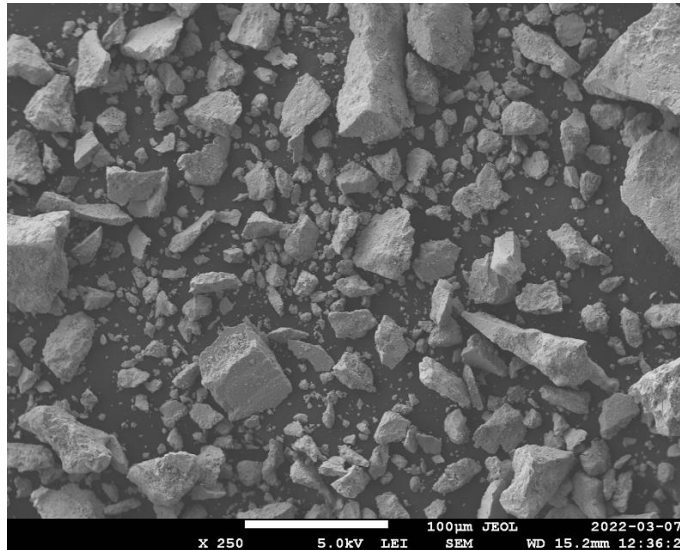
Where λ is the X-ray wavelength, θ is the Bragg's angle, β is the full width at half the maxima (FWHM), D is the average crystallite size (nm), and k is the Scherrer constant. Since the diffractometer used for this work provides $\text{CuK}\alpha$ radiation, where $\lambda=1.54060$ Armstrong or 0.154060 nm.

5.2.3 Scanning Electron Microscopy (SEM) Element Composition Analysis

The Scanning electron microscope (SEM) of the nickel-zinc ferrite powder shows that most particles are of good crystalline nature and have a fine particle size, as illustrated in Fig. 5.4. It is worth pointing out that the ferrite powder was grinded with mortar and pestle as a cost-effective solution, so the grinding is not as perfect as the ultra-fine powder grinding machine.

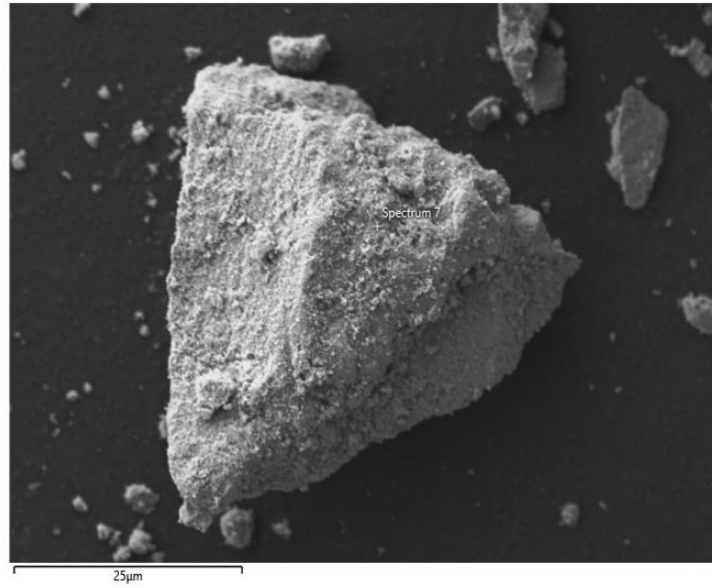


(a)

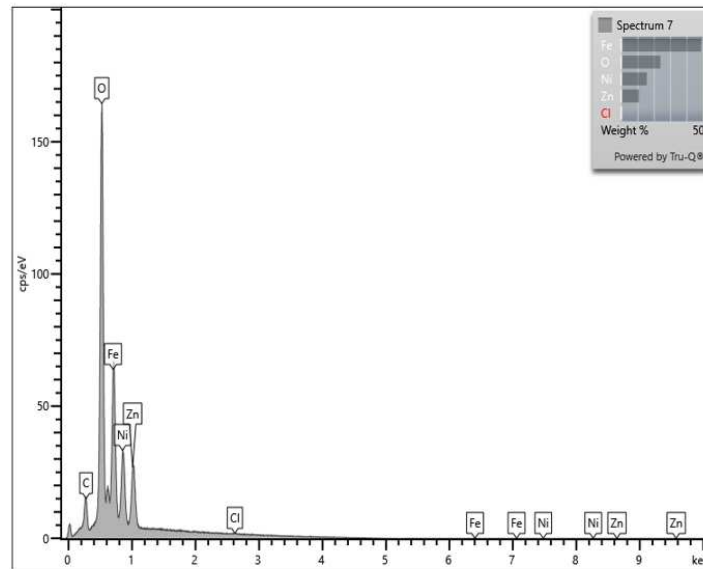


(b)

Fig. 5.4: SEM Images of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders using NaOH annealed at 550°C for 4h.
(This measurement was conducted by Dr. Ettiene from Polytechnic Montreal).



(a)



(b)

Fig. 5.5: EDAX profile of pure $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ compositions, (a) SEM of a particle, (b) EDX spectra (This measurement was conducted by Dr. Ettiene from Polytechnic Montreal).

The SEM was sensitive to ferrite powders, so carbon tape was used where the ferrite powder was placed. From the energy-dispersive X-ray spectra (EDAX), some small amount of carbon is present with the other compositions. The EDAX confirms that the synthesized ferrite particles'

elemental composition mainly contains Ni, Zn, Fe, and O elements with no other impure elements, as illustrated in Fig. 5.5. A negligible amount of chloride Cl is present from the co-precipitation process, where the chlorides was mixed with NaOH.

5.2.4 Verification of Magnetic Properties in Different Atmospheres

The magnetic properties of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder are verified using the vibration sample magnetometer (VSM) at room temperature. The VSM technique evaluates the magnetic properties of synthesized particles at ambient conditions, and the observed hysteresis loops are presented in Fig. 5.6.

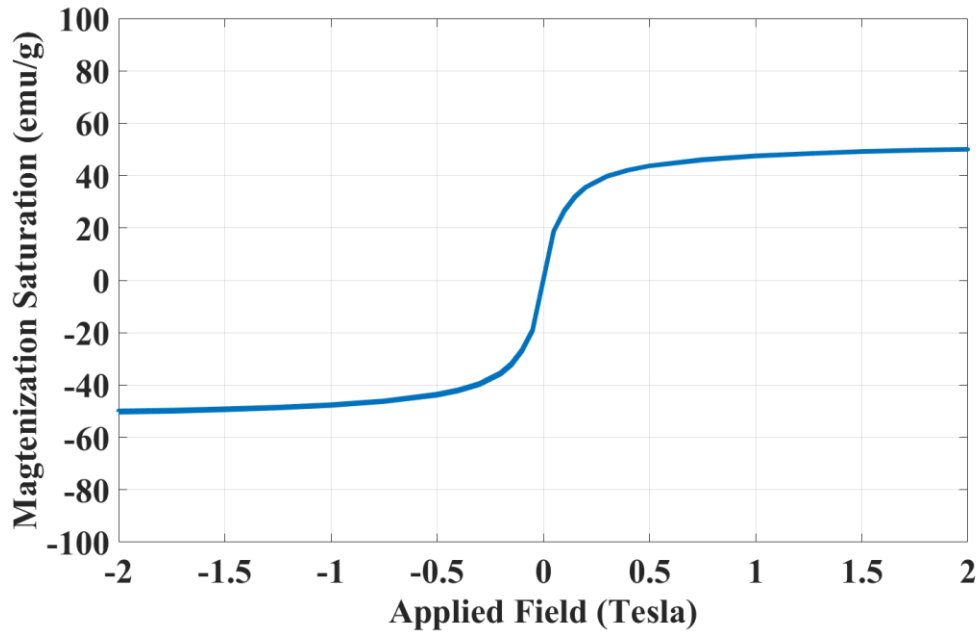


Fig. 5.6: Saturation magnetization of NZF powders using NaOH annealed at 550°C for 4h (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

The M-H hysteresis loops clearly show the ferromagnetic nature of the samples. The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder was measured at room temperature with an applied field of ± 2 Tesla or 20000 (Oe). It is evident from the curve that the saturation magnetization obtained from the VSM is around 48.5 emu/g. The powder goes to almost saturation level at a 1.5 T applied field, and a very smooth M-H loop can be observed.

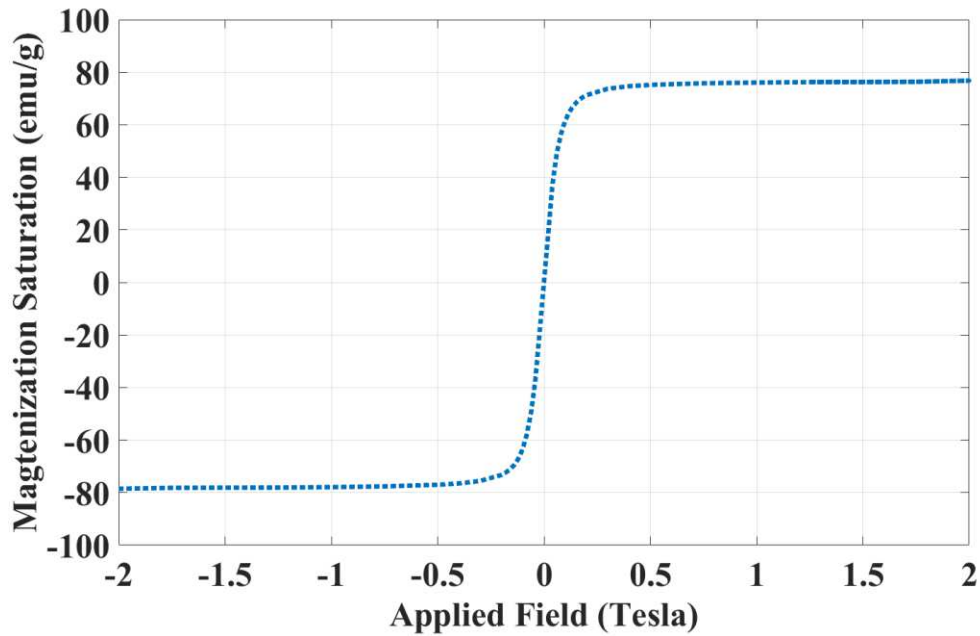


Fig. 5.7: Saturation magnetization of NZF powders using NaOH annealed at 550°C for 4h in a vacuum, and 1100°C for 4h in the nitrogen environment (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

Later, the same powder is heated again at 1100°C for 4 hours in the nitrogen environment to see a possible change in the saturation magnetization. To conduct this experiment, we followed two different approaches. The first nickel zinc ferrite powder sample, which was previously heated at 550°C, in the vacuum environment, was heated again at 1100°C in the nitrogen environment. The second sample was heated directly at 1100°C in the nitrogen environment. Fig. 5.7 highlights the M-H hysteresis loop curve at 1100°C in the nitrogen environment that was heated previously.

A significant increase in the emu/g is observed after heating the powder at 1100°C in the nitrogen environment. The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder was measured at room temperature with an applied field of ± 2 Tesla or 20000 (Oe). It is evident from the curve that the saturation magnetization obtained from the VSM is around 79 emu/g. The powder reaches almost saturation level at a 1 T applied field, and a very smooth M-H loop can be observed. Fig. 5.8 shows the M-H hysteresis loop of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder measured directly at 1100°C for 4h in the nitrogen environment.

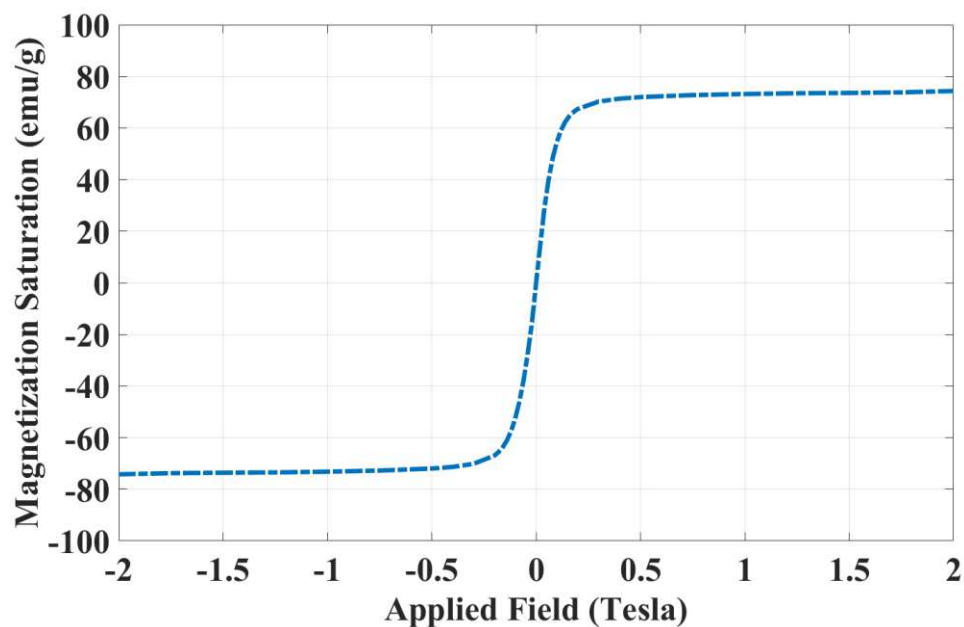


Fig. 5.8: Saturation magnetization of NZF powders annealed directly at 1100°C for 4h in the nitrogen environment (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

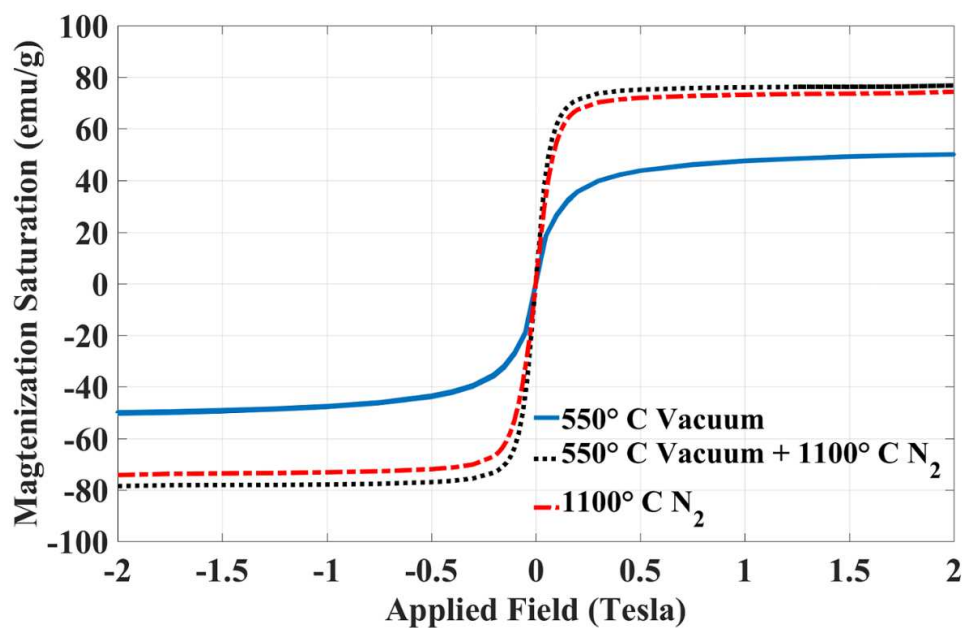


Fig. 5.9: Saturation magnetization comparison of NZF powders in different environments and temperatures (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

It is observed from the Magnetization saturation Versus Applied field diagram that the ferrite powder shows 77 emu/g at 1100°C. The powder almost goes to the saturation level at 1 T (tesla) applied field. A comparison between the emu/g in different temperatures is demonstrated in Fig. 5.9. The difference between heating the powder directly at 1100°C in the nitrogen environment and heating the powder in the vacuum environment at 550°C and later at 1100°C in the nitrogen is negligible. Heating the powder initially at 550°C in the vacuum atmosphere will make it dry. Fig. 5.10 shows the x-ray diffraction (XRD) pattern in the nitrogen and vacuum environment. It can be noticed that the nickel-zinc ferrite powder (NZF) in the nitrogen environment also shows a single spinel phase behaviour, and the peaks of powder are obtained at the same phase as the vacuum. The EDAX confirms that the synthesized ferrite particles elemental composition mainly contains Ni, Zn, Fe, and O elements with no other impure elements, as illustrated in Fig. 5.11.

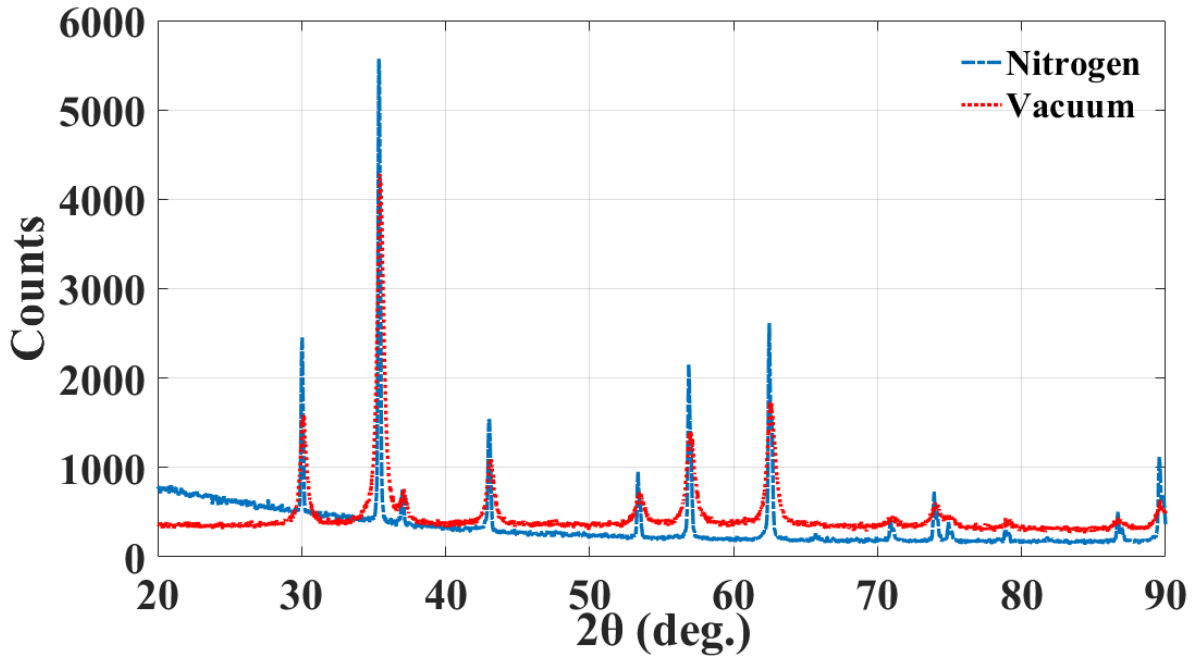


Fig. 5.10: XRD patterns of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders annealed in a vacuum and nitrogen environment (This measurement was conducted by Dr. Ettiene from Polytechnic Montreal).

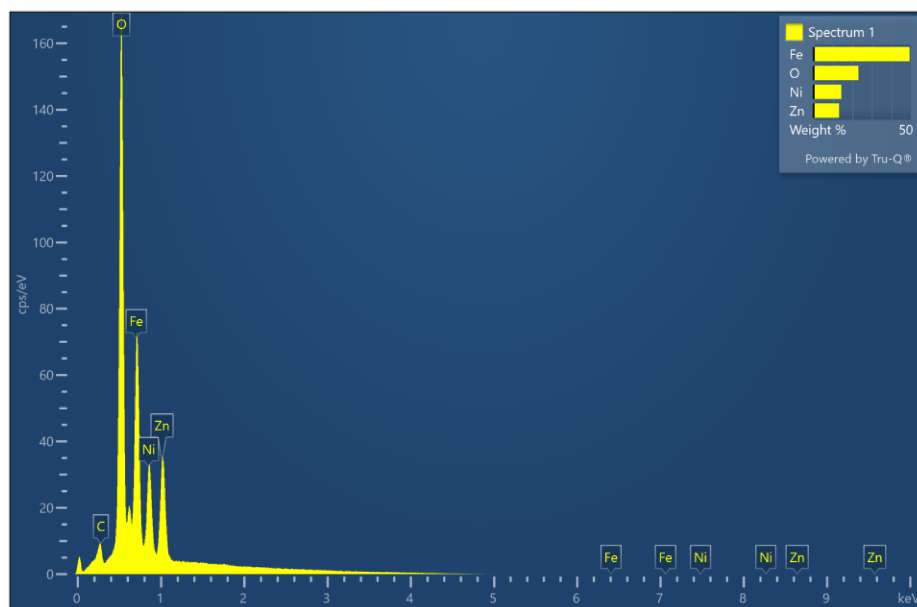


Fig. 5.11: EDAX profile of pure $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ compositions annealed in a Nitrogen atmosphere (This measurement was conducted by Dr. Etienne from Polytechnic Montreal).

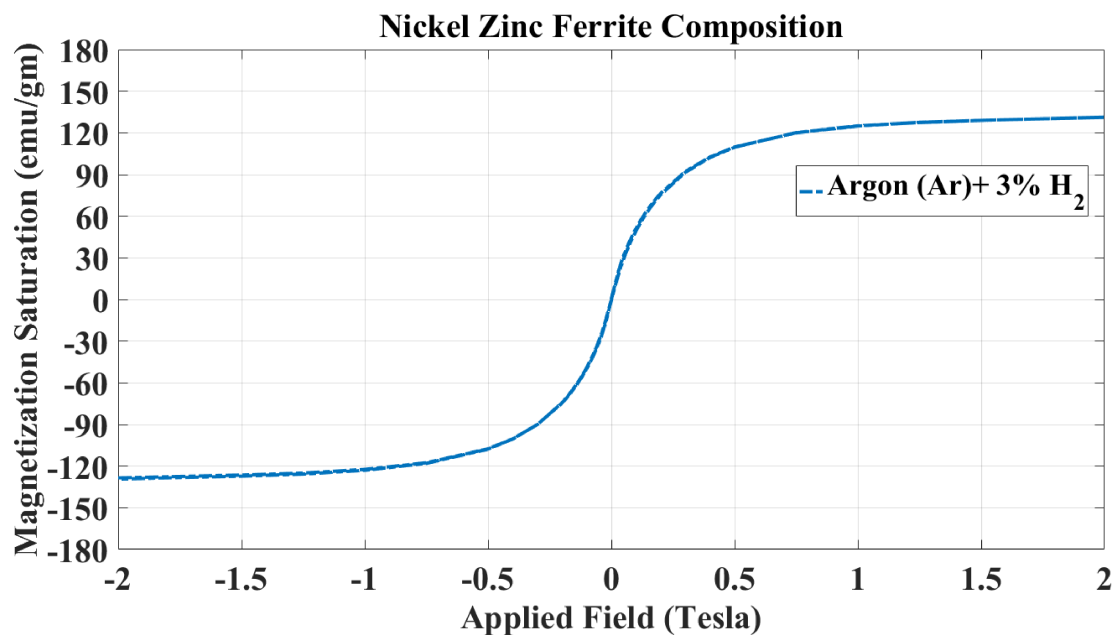


Fig. 5.12: Magnetic hysteresis loop (M-H) of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders annealed at 1100°C in Argon + 3% Hydrogen atmospheres (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

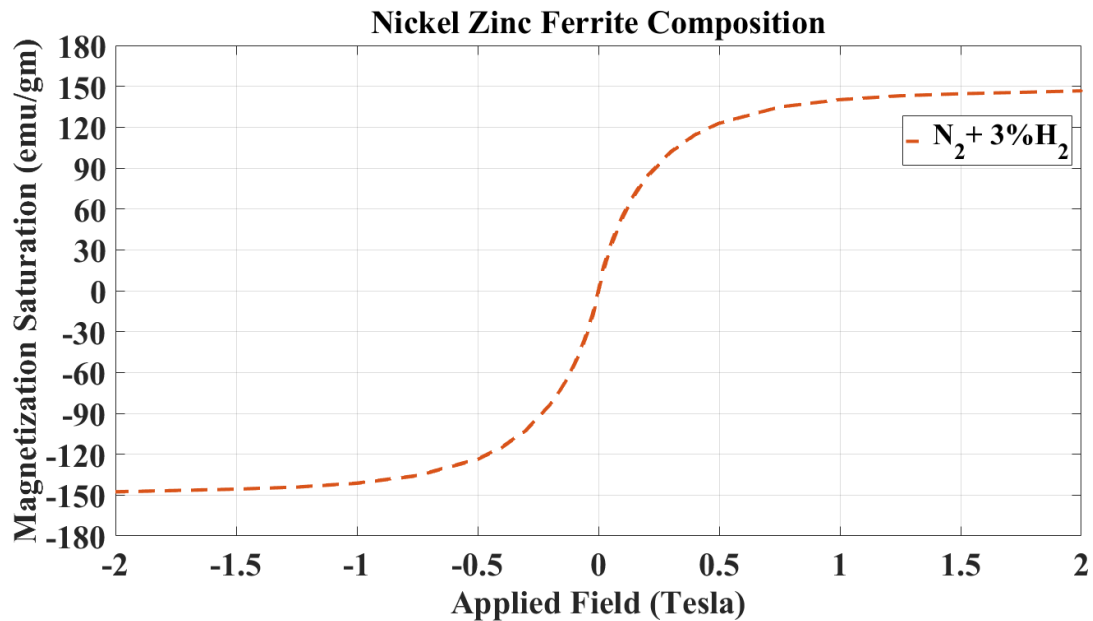


Fig. 5.13: Magnetic hysteresis loop (M-H) of the $Ni_{0.5}Zn_{0.5}Fe_2O_4$ powders annealed at $1100^\circ C$ in Nitrogen + 3% Hydrogen atmospheres (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

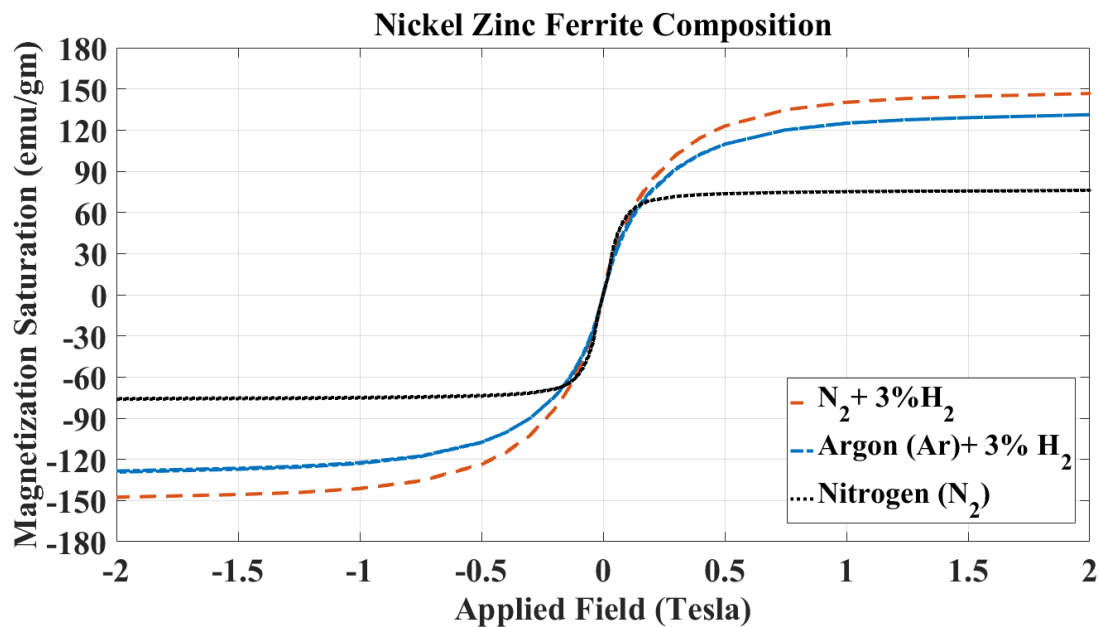


Fig. 5.14: Magnetic hysteresis loop (M-H) comparison of the $Ni_{0.5}Zn_{0.5}Fe_2O_4$ powders annealed at $1100^\circ C$ in different atmospheres (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

To verify the magnetization of the powder, two other experiments were conducted while doing the heat treatment at Argon + 3% Hydrogen atmosphere and Nitrogen + 3% Hydrogen atmosphere. The M-H loop of the two heat treatments Argon + 3% Hydrogen atmosphere and Nitrogen + 3% Hydrogen atmosphere are demonstrated in Fig. 5.12 and Fig. 5.13, respectively. It is worth pointing out that the maximum temperature the oven can handle is 1150° C, so we experimented with 50° C, less than the maximum temperature. The samples calcined in Argon + 3% Hydrogen and Nitrogen + 3% Hydrogen show excellent stability with hysteresis loop exceeding 127 emu/g and 147 emu/g, respectively. The powder reaches almost saturation level at a 1.5 T applied field, and a very smooth M-H loop can be observed. Fig. 5.14 compares the magnetization saturation of the ferrite powder in the Argon + 3% Hydrogen atmosphere and Nitrogen + 3% Hydrogen atmosphere, respectively, using VSM. It is possible to control the magnetization by reducing the temperature or even by employing different heat treatment methods. Besides, there was a restriction with the heating in the oven which supported up to 1100°C temperature. There is a possibility that the magnetization can be increased further by going to higher temperatures. The proposed experiment is repeatable and stable as some of the experiments were carried out during the harsh winter in Canada when the temperature goes below -25°C. The fabricated powder is highly magnetic and can be incorporated with microwave nonreciprocal components in the mm-wave spectrum, such as circulators, isolators, ferrite-based differential phase-shifters, etc. After baking the powder, the next step will be to put it in a circular-shaped pellet and press it with a hydraulic press machine.

5.3 Ferrite Disk Fabrication Using Hydraulic Press:

This section will cover the ferrite disk fabrication using the hydraulic press machine. The hydraulic press machine used for this work was purchased from Pike Technologies. The two critical factors for forming the disks are the applied force (F) and the surface area (A). For a larger disk, the surface area will be more extensive; thus, it will require more force to form the disk. For this work, a 3 mm pellet is used to fabricate the disk. Therefore, a 1.5-ton force is sufficient for developing the disk. Before deciding to go with a 1.5-ton force, 2-ton pressure was applied to pressurize the disk. Due to heavy pressure, some parts of the pellet's back plate broke; after that, the force is reduced to 1.5 tons. In addition, 7 mm disks were also fabricated using this technique, where the maximum force of 2.5 tons is applied to form the ferrite disk. It is worth pointing out that the disk

is considered 3 mm and 7 mm due to the available pellet size in the market. Making a custom-made pellet will be more expensive. The fabricated powder was grinded with Mortar and pestle. This method is handy for grinding powders. An excellent fine powder is obtained after grinding it for 5 minutes, as shown in Fig. 5.15. Later, the powder was put inside the 7 mm die, and a similar experiment was done with a 3 mm die. It is worth mentioning to have solid back support; a bottom plate is also used. A small drop of isopropyl alcohol is poured on the powder with a spatula, as illustrated in Fig. 5.16.



Fig. 5.15: Fabricated ferrite powder after grinding with mortar & pestle.



Fig. 5.16: Fabricated ferrite powder inside die-set with isopropyl alcohol.

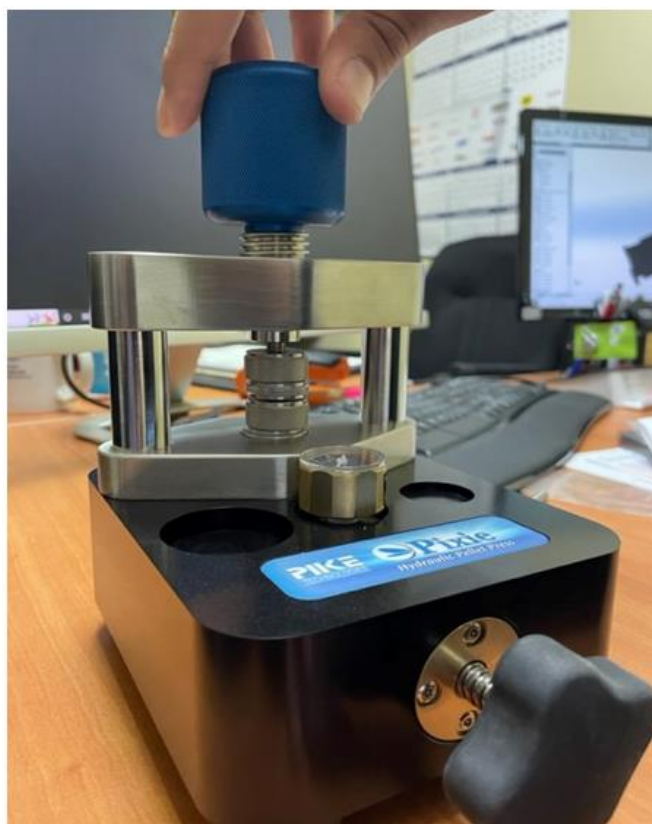


Fig. 5.17: 2.5-ton hydraulic press machine from Pike technologies.

The hydraulic press that was used for this work is from Pike Technologies. The maximum pressure that it can handle is 2.5 tons. The 7 mm die set is capable of handling this pressure. The higher the surface area, the higher the force required to form the disk. Fig. 5.17 shows the 2.5-ton hydraulic press machine. The black knob is rotated to increase the applied force. Full pressure was applied for 3 minutes; the top cover was removed and flipped to remove the disk. The final disks are shown in Fig. 5.18. Both the fabricated disks are in good shape; however, before incorporating the ferrite disk with a circulator, it needs to be baked at 100-200 °C for 1-2 h before the measurement, which will make the ferrite disk strong.



Fig. 5.18: Fabricated disk after pressing with a 2.5-ton hydraulic press machine.

5.4 Calculation of $4\pi M_s$ from the ferrite powder's emu/g:

After fabricating the disk from the ferrite powder, the weight of the disk was calculated using the weighing scale. In addition, with the vernier scale, the diameter, and the height, were calculated. From the diameter and height, the volume of the disk can be calculated using the cylindrical equation of the volume. The density of the ferrite disk can be known easily from the weight and volume of the disk. Table 5.2 shows the measured values of the fabricated disk, including the weight, volume, density, emu/g, and $4\pi M_s$. The conversion from emu/g in A/m to Gauss can be calculated from the equation below,

$$\text{Emu/g (Ms)} \times \text{density (g/cm}^3) \times 1000 \times \frac{4\pi}{1000} = 4\pi M_s \text{ (G)} \quad (5.3)$$

The above calculations show that the fabricated disk has a high magnetization, which is significantly higher than the available ferrites in the market [109]. From the proposed technique, a magnetization $4\pi M_s$ of 9500 (G) is obtained, which is 1.8 times more than the magnetization commercially available in the microwave and space industry. This will open a new doorway for the microwave and space industry supporting various future applications in the mm-wave

spectrum. In the next section, the application & integration of the ferrite disk in three different mm-wave frequency bands for a wideband circulator design will be discussed.

Table 5.2: Fabricated ferrite disk's measured dimensions

Parameters	Sample 1 Argon + 3% H2 Environment	Sample 2 N2 + 3% H2 Environment
Weight	0.023 g	0.019 g
Diameter	0.335 cm	0.325 cm
Height	0.0508 cm	0.0445 cm
Volume, $V = \frac{\pi d^2 h}{4}$	0.004485 cm^3	0.003690 cm^3
Density, $d = \frac{W}{V}$	5.35 g/cm^3	5.15 g/cm^3
Emu/g (Ms)	127	147
$4\pi\text{Ms}$ (G)	8540 G	9513 G

5.5 Experimental Validation of the ferrite disk with a Ka-band Circulator:

5.5.1 Electrical Characterization of Ferrite Material:

The fabricated ferrite disks will now be incorporated with a Ka-band circulator. Fig. 5.19 shows the measurement setup for the electrical characterization of the fabricated ferrite disk with WR 28 waveguide setup. From Equation 5.3, the ferrite magnetization in Gauss was calculated. The ferrite material's permittivity is an essential parameter for the circulator design. Till now, only the magnetic properties of the ferrites were measured. Now the electrical characterization of the ferrite material will be discussed using the material perturbation method to calculate the permittivity of the ferrite disk. A ferrite disk with 8500 (G) is inserted inside the WR28 waveguide, where a Coaxial probe is used to excite the ferrite while terminating the open-ended waveguide with a short circuit to perform this measurement. The location of the ferrite is moved to observe any possible resonance. After moving the ferrite by 20.3 mm from the shorted plate side at 33 GHz, a resonance is observed.

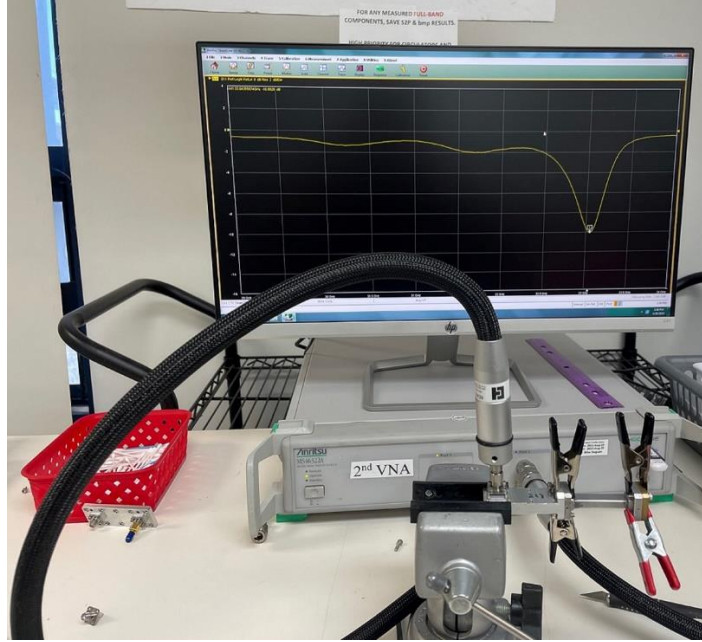


Fig. 5.19: Electrical characterization of ferrite using WR28 Waveguide.

Later, to verify the measurement results, the exact adapter dimensions and the location of the ferrite are used to perform a simulation. At the simulation's starting point, initial ferrite permittivity of 10 was considered. Later some parametric studies were performed using CST Microwave Studio to predict the permittivity of the ferrite. Fig. 5.20 shows the simulated electrical characterization setup, and the simulated and measurement results comparison is demonstrated in Fig. 5.21.

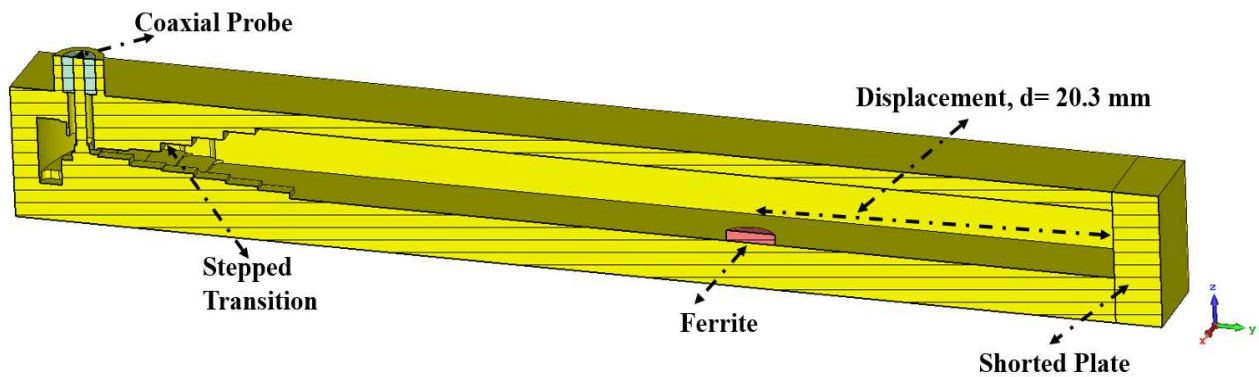


Fig. 5.20: Electrical characterization of the fabricated ferrite using WR28 Waveguide and Coaxial Probe.

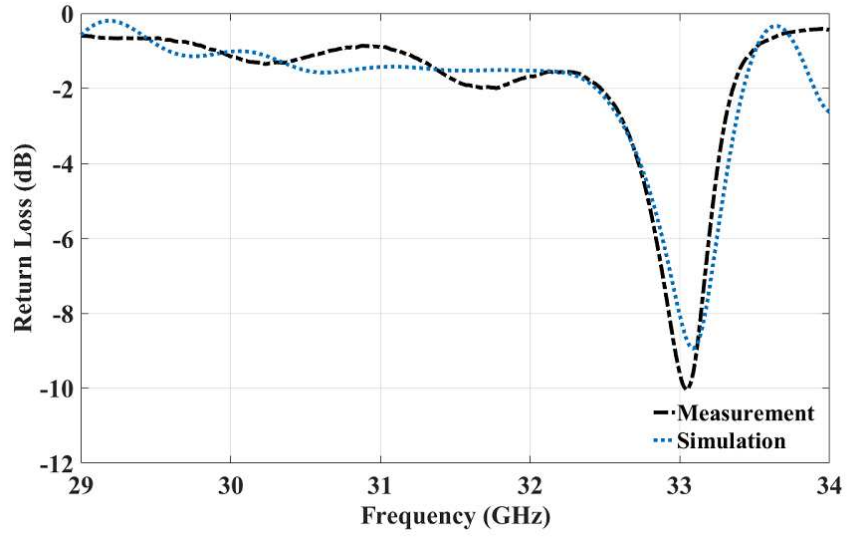


Fig. 5.21: Simulation and measurement result comparison of ferrite material to predict the permittivity using WR28 waveguide and coaxial probe.

The simulation and measurement comparison in Fig. 5.21 showed excellent agreement when the ferrites permittivity was considered as 14.5 with a loss tangent, $\tan(\delta) = 0.0075$. In addition, the permeability was varied in the EM solver, and the best agreement was observed when it was $0.83 \mu_0$. This technique can provide a perfect starting point to guess the initial parameters before designing the circulator.

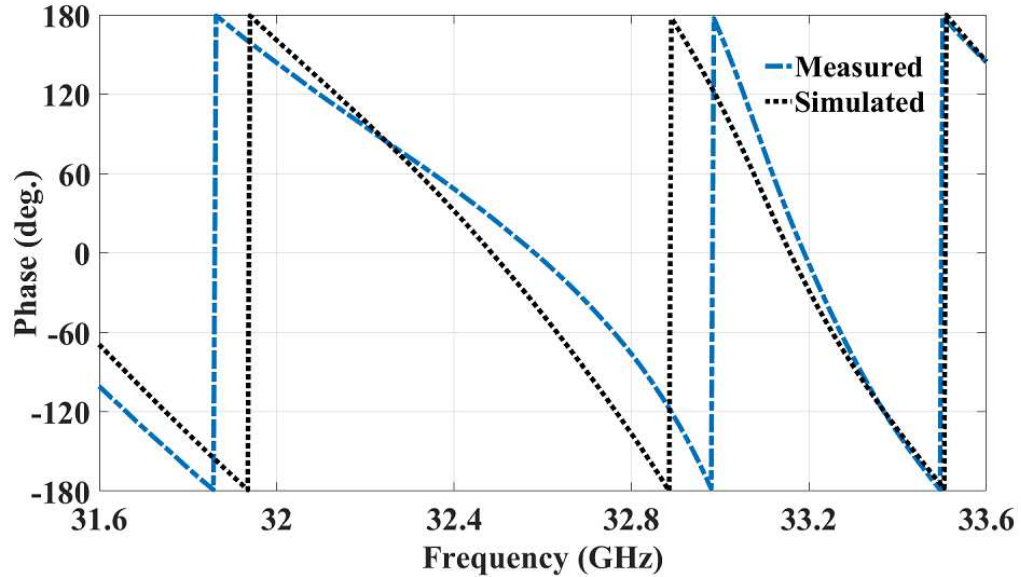


Fig. 5.22: Simulated and measured phase of the ferrite material to predict the permittivity.

Fig. 5.22 shows the comparison of the measured and simulated phase differences. It is noticed that there is a phase difference between the simulated and measured results, which could be from the cable used to perform the measurement using the vector network analyzer (VNA) and also the connector. In the simulator, only the coaxial probe was considered; however, there was a coaxial connector in the measurement setup. The coaxial connector has a certain length which can change the phase as this length is not known to us. Fig. 5.23 & 5.24 shows the real and Imaginary parts of the permittivity.

The prediction error of the proposed technique can be estimated from the following equation:

$$\text{Error (\%)} = |S_{11,\text{measured}} - S_{11,\text{simulated}}|^2 \quad (5.4)$$

The error percentage is highlighted in Fig. 5.25 to predict the estimated error between the measured and simulated response.

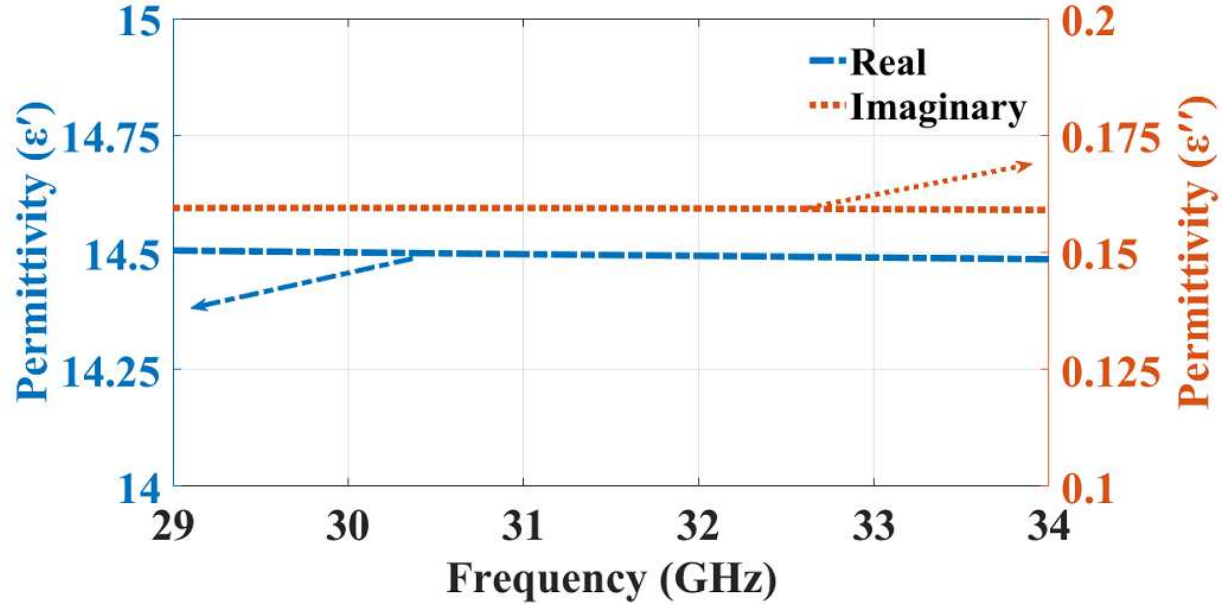


Fig. 5.23: Permittivity (Real & Imaginary) of the fabricated ferrite material.

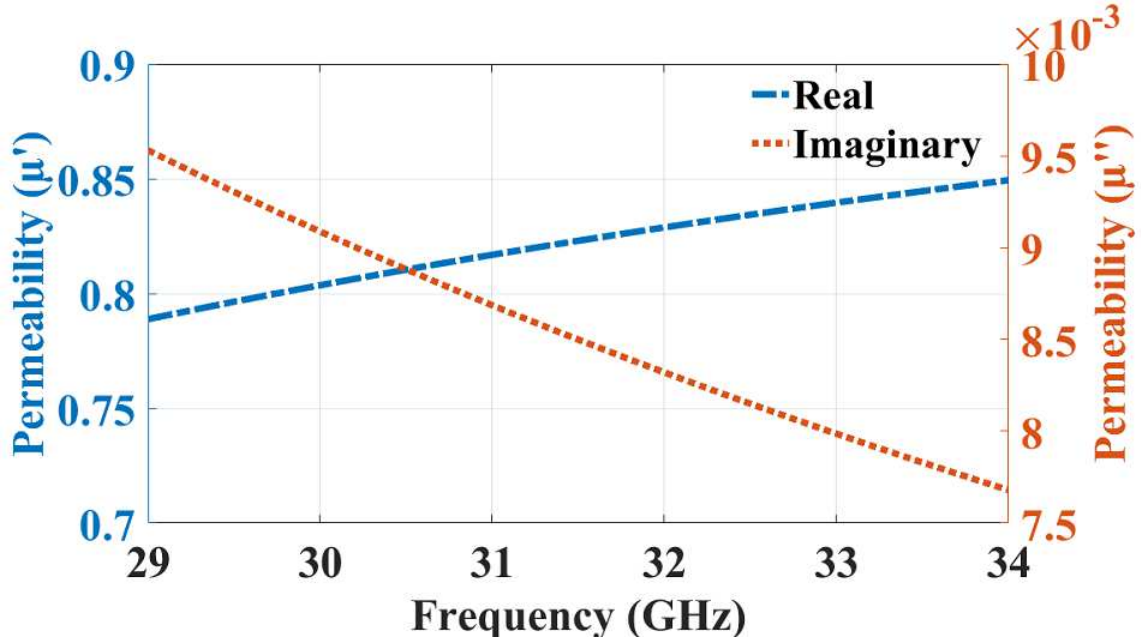


Fig. 5.24: Permeability (Real & Imaginary) of the fabricated ferrite material.

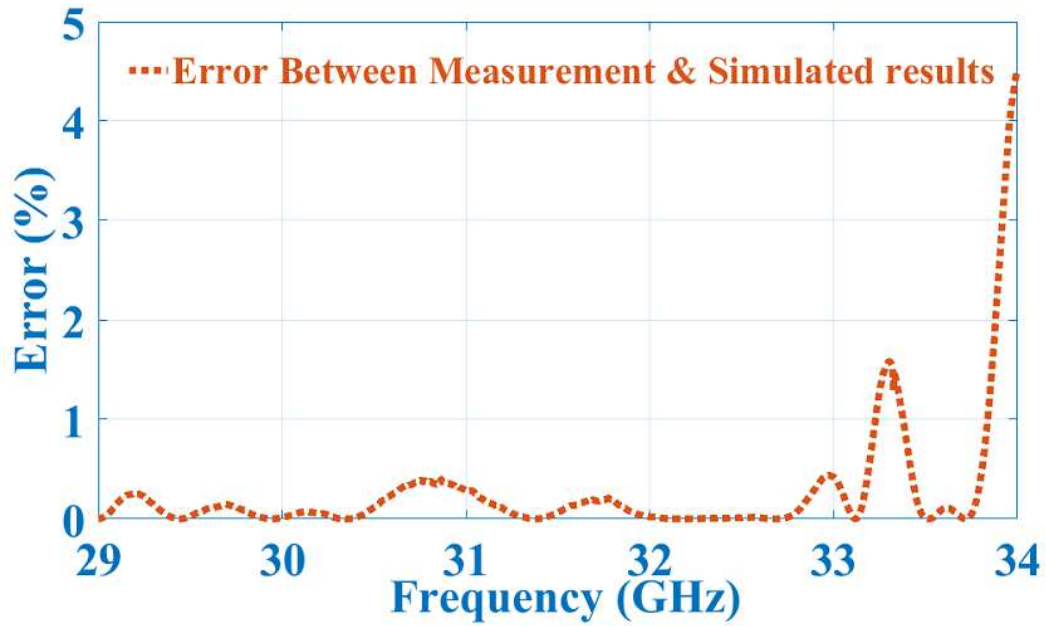


Fig. 5.25: Error percentage between the measured and simulated response.

It is evident from Fig. 5.25 that the proposed technique provides an excellent prediction between the simulated and measurement response. From 29-33.2 GHz, the error percentage is less than 1%, which is perfect for predicting the initial parameters of the ferrite material.

5.5.2 Ka-band Circulator with Fabricated Ferrite with WR28 Waveguide:

WR 28 standard waveguide dimensions are used to design the Ka-band circulator. Connecting the circulator directly with the rectangular waveguide will lead to a poor matching level since the rectangular waveguide impedance is significantly higher than the ferrite disk impedance. Therefore, three-section Chebychev transformers are added to match the impedance with the ferrite disk section. Here, the detailed discussion of the design procedure will not be covered since it is extensively discussed in the literature [110], [158], [159]. Fig. 5.26 shows the Ka-band rectangular waveguide junction circulator, where the upper part is kept hidden for a clear illustration.

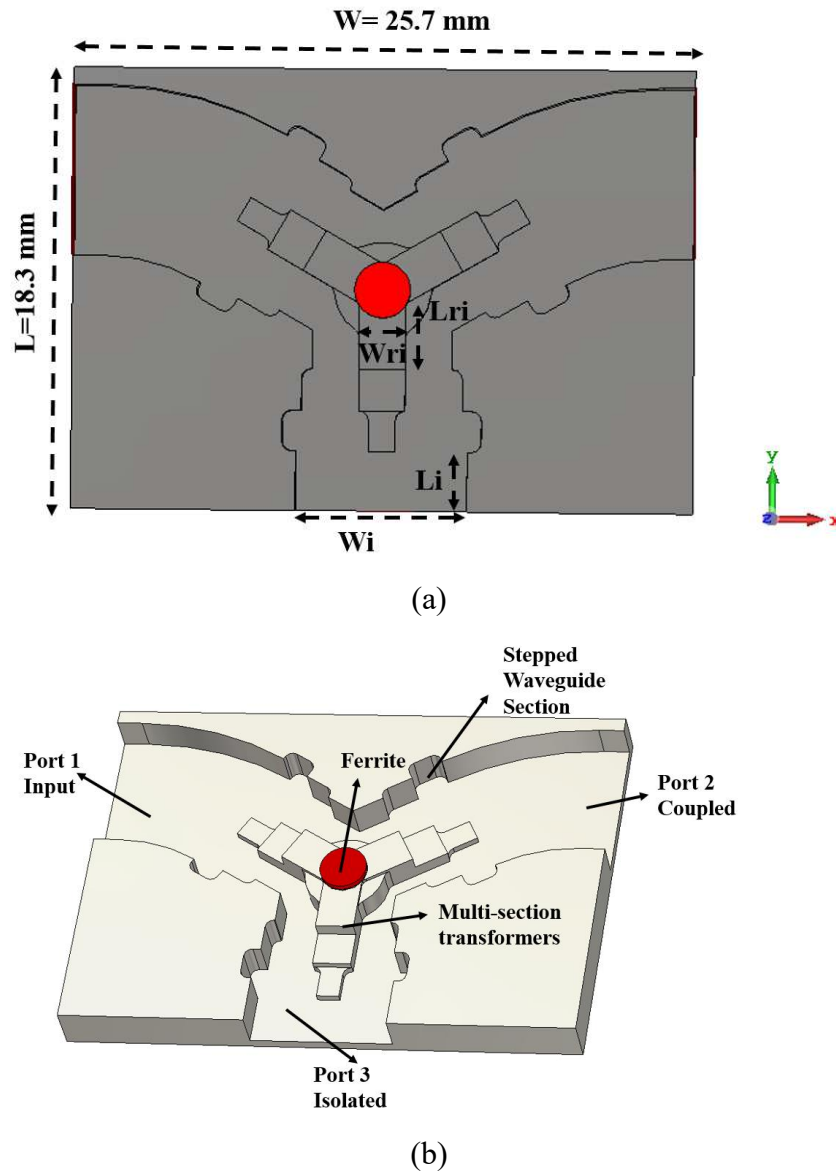


Fig. 5.26: WR 28 Ka-Band Rectangular Waveguide Circulator, (a) 2D View, (b) 3D View.

Table 5.3 shows the ferrite disk design parameters and the biasing and material properties. The design parameters of the Ka-band circulator's design, including the matching transformers, are highlighted in Table 5.4.

Table 5.3: Design Parameters of the Ka-Band Circulator Ferrite Disk

Parameters	Value
Magnetic Saturation $4\pi M_s$	8500 G
Magnetic biasing ratio α	0.06
Magnetic biasing field H_0	510 O_e
Disk radius a	1.5 mm
Ferrite disk height h_f	0.4 mm
Effective gyromagnetic ratio, g	2.0
Ferrite permittivity	14.5

Table 5.4: Dimensions of Ka-band circulator design (in mm)

Parameters	Values	Parameters	Values
W1	7.11	L1	2.47
W2	8.26	L2	1.71
W3	6.67	L3	1.42
W4	5.8	L4	1.6
Wr1	1.9	Lr1	2.51
Wr2	1.88	Lr2	1.72
Wr3	1.12	Lr3	1.4
Hr1	1.36	Hr2	0.68
Hr3	0.35		

The simulated S-parameter response is highlighted in Fig. 5.27 with excellent return loss and isolation below -20 dB from 28.5-40 GHz. The circulator provides an impedance bandwidth of 40.6% with an insertion loss of around -0.2 ± 0.3 dB, covering the whole frequency band from 26.5-40 GHz.

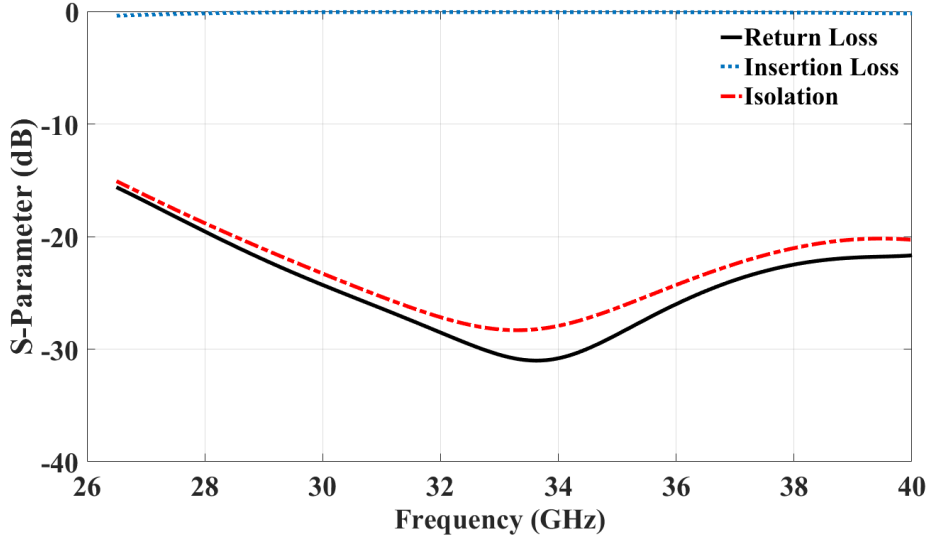
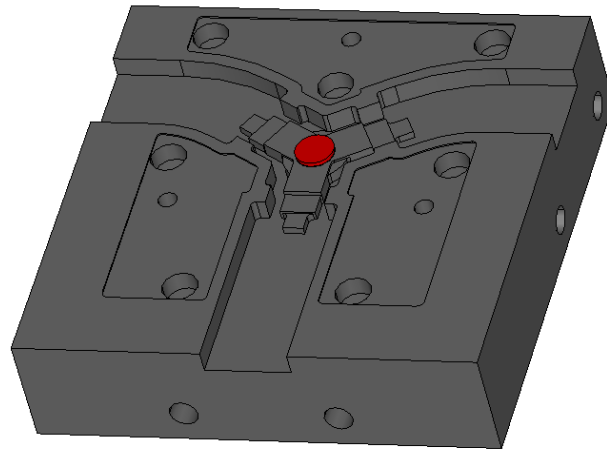


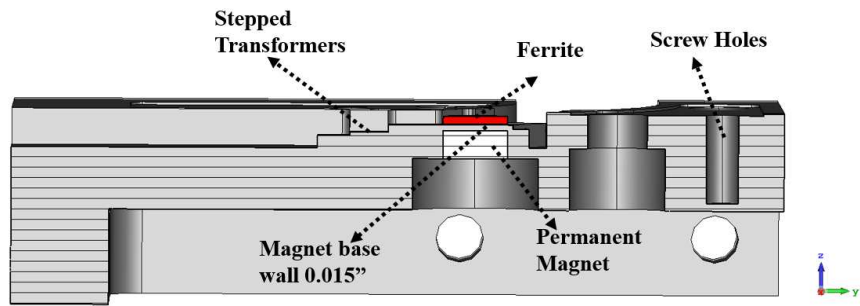
Fig. 5.27: Simulated S-parameter response of Ka-band Rectangular Waveguide Circulator with fabricated ferrite disk with magnetization 8500 (G).

To validate the work, the proposed work was fabricated using CNC milling with a 0.0025” tolerance from Xeometry [111]. The simulated cross-sectional and 3D view of the circulator is highlighted in Fig. 5.28. DC Magnets are placed on both sides of the circulator for proper magnetic biasing. The magnet wall thickness is kept at 0.015” for the fabricated prototype. Reducing the wall thickness can increase the fields between the two ferrites.

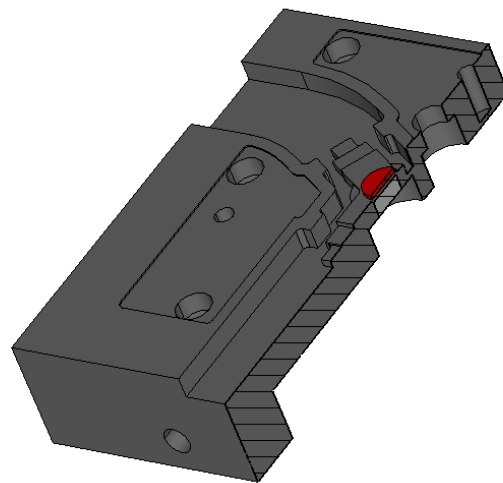
The circulator was biased using Neodymium N 52 magnet with a magnetization of 1.48 Tesla or 14800 G. The measured circulator shows no circulation with the fabricated high-magnetization ferrite disk, as shown in Fig. 5.29. Even after applying more magnets from both the top and bottom sides, there is no sign of possible circulation. To verify this, two possible steps were considered. The first step was to ensure whether the magnetization was still the same. Previously the magnetization of the NZF powder was calculated only using VSM measurement. However, it was not measured after compressing the disk from the powder. Fig. 5.30 shows the saturation magnetization of the NZF disk, which was heated at Argon + 3% hydrogen atmosphere. It is observed that the emu/g increased by 20-25% from the previous measurement from 127 emu/g to 160 emu/g. The rise in emu/g indicates that the ferrite disk has very high magnetization, and the newly calculated disk magnetization is 10700 (G) instead to 8500 (G). In other words, the proposed disk magnetization is more than double the magnetization of the available ferrite disk in the market.



(a)



(b)



(c)

Fig. 5.28: Simulated Final model (a) 3D view of the bottom layer of the circulator, (b) Bottom layer cross-section, and (c) cut-view of the circulator design.

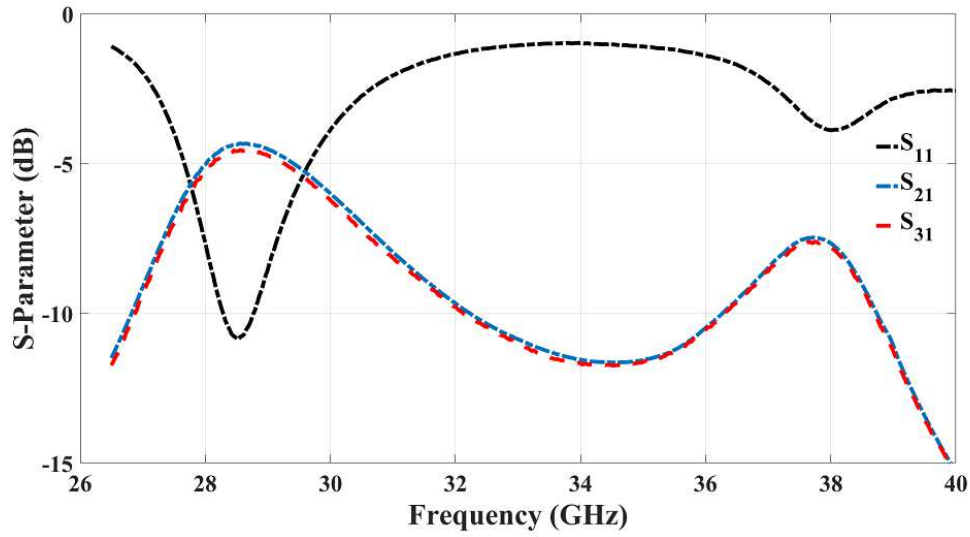


Fig. 5.29: Measurement of Ka-Band Circulator with a Ferrite Magnetization of 10700 (G).

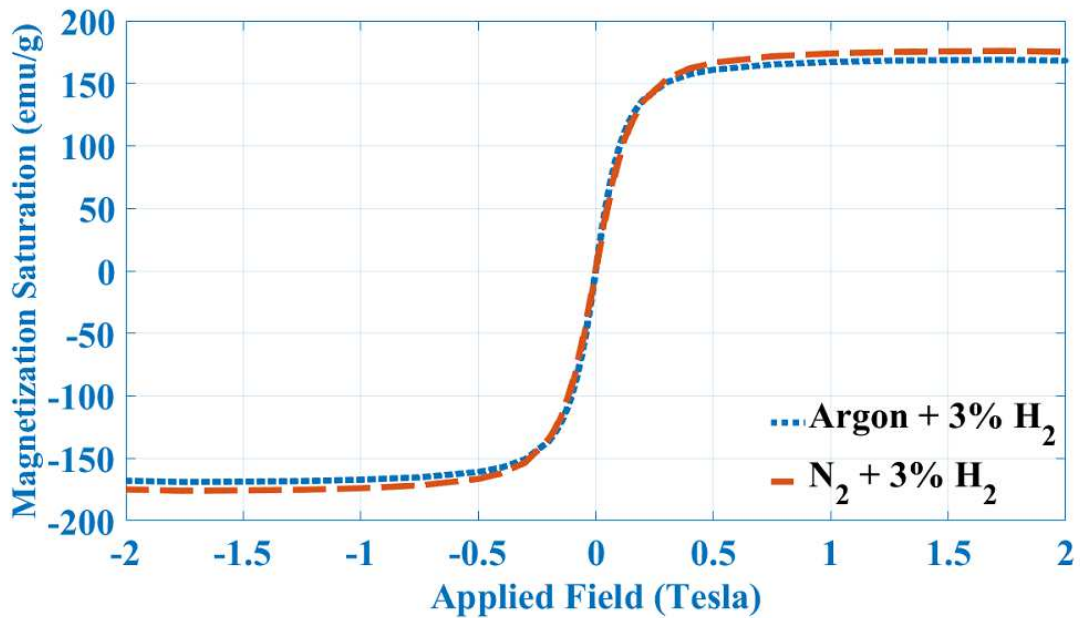


Fig. 5.30: (M-H) loop of the NZF disk previously annealed at Argon + 3% Hydrogen and Nitrogen + 3% Hydrogen atmospheres (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

5.5.3 M-Static Solver to Verify Magnetization Between Two Ferrites:

In the second step, an attempt to incorporate the permanent magnet's magnetization value using the M-static solver to evaluate the possible magnetic field at the center of the two-ferrite disks was

considered. This will indicate how much magnetic field is required to bias a circulator with the available permanent magnet. For this step, an available ferrite disk with 5300 (G) magnetization with similar ferrite dimensions to the proposed disk was considered. The circulator is simulated and measured with the new 5300 (G) commercially available disk, which shows a good agreement, as illustrated in Fig. 5.31. The applied external magnetic field for the measurement is 14800 (G) from the permanent magnet.

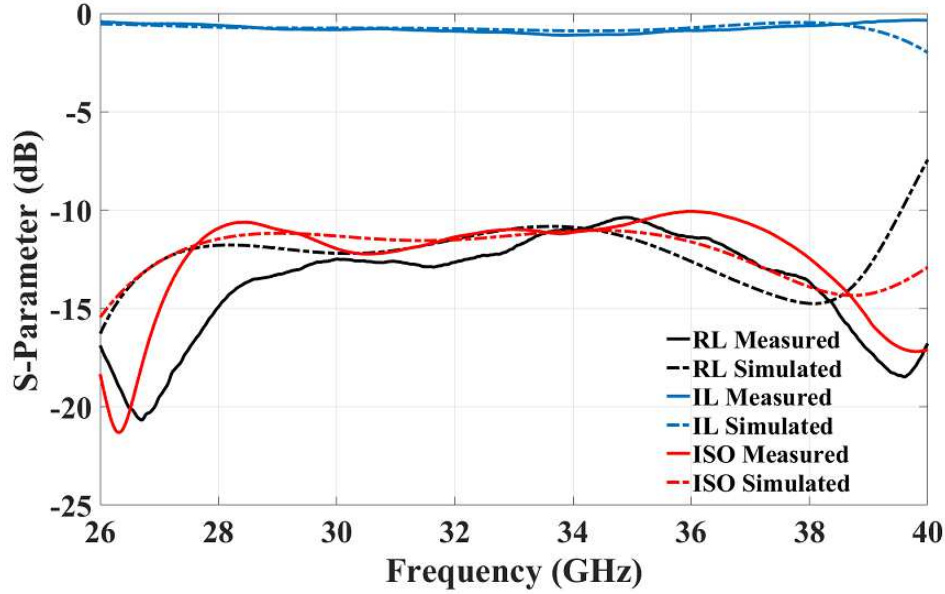


Fig. 5.31: Simulated and Measurement result comparison of Ka-Band circulator (Commercially available ferrite disk with a magnetization of 5300 (G)).

Using a permanent magnet with 14800 (G), a maximum field of around 4550 (Oe) can be obtained between the two ferrites based on the M-static solver [119]. In other words, the 4550 (Oe) field is capable of biasing a ferrite with 5300 (G) magnetization. However, in our case, the magnetization is doubled, 10700 (G) instead of 5300 (G). The field between the two ferrites 4550 (Oe) is not sufficient to bias the circulator with a ferrite magnetization of 10700 (G). The field can be enhanced in two ways, by reducing the magnet wall thickness and by using a permanent magnet, which provides double the magnetization of the current N52 Neodymium magnet. In the commercial industry, the highest magnetization for the permanent disk magnet is 14800 (G), which is already used in the proposed work. Therefore, it is not possible to bias such a high-magnetization ferrite disk with the current permanent disk magnet. To explain this point, simulations were

performed using the M-static solver by doubling & tripling the magnetization [119]. It is evident from Fig. 5.32 that increasing the permanent magnet's magnetization increases the fields (Oe) between the ferrites, which can bias the circulator with the fabricated ferrite disk. Fig. 5.33 shows the magnetic field distribution at the center of the junction with an external field of 2.96 T or 29600 (G).

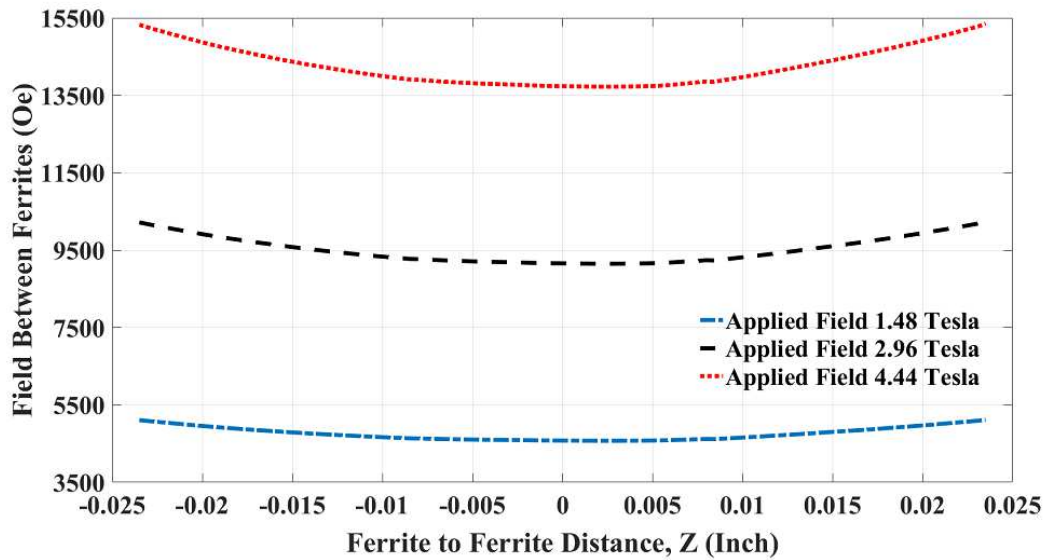


Fig. 5.32: Change in fields between ferrites by changing the magnetization of permanent magnets.

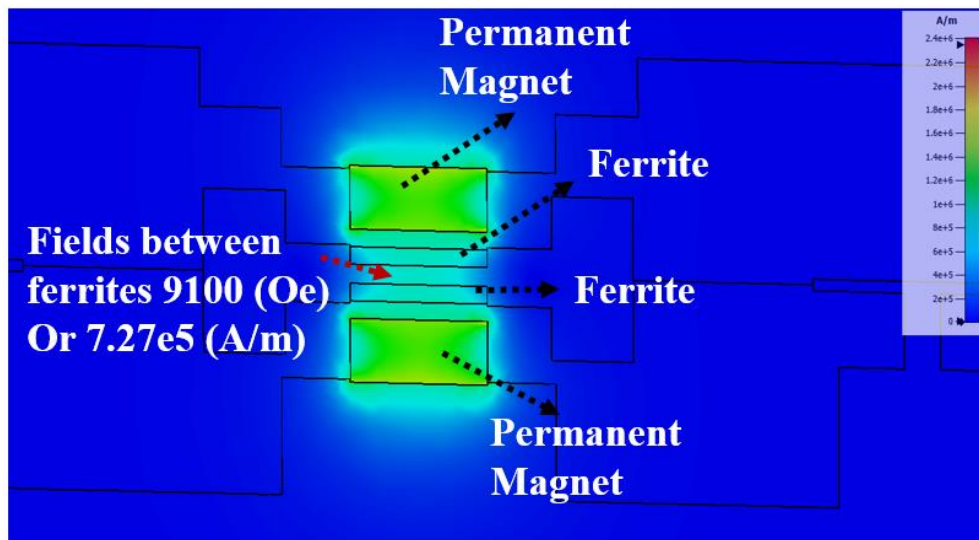


Fig. 5.33: Magnetic field distribution at the center of the junction with an applied field of 2.96 T.

It is noticed that at the center of both the ferrites, the magnetic field is 7.27×10^5 A/m or 9100 (Oe). This is the minimum field amount required to bias the circulator with 10700 (G) ferrite. Providing this extreme field amount at the center of the junction is only possible with a permanent magnet with a strong magnetization of 2.96 T.

It is worth mentioning that the proposed circulator design has considered a ferrite magnetization of 8700 (G), so the matching level of the circulator, return loss, and isolation levels will not be good with a low magnetization ferrite disk. Because while performing the full-wave simulation & optimization, an 8700 (G) magnetization is considered. To make a circulator work with a low-magnetization ferrite disk, the whole circulator design needs another optimization based on the new ferrite disk's magnetic properties and a new fabrication for the circulator design. To validate the proposed NZF ferrite disk fabrication process, a lower magnetization powder is processed and compressed to form ferrite disks. Afterward, the lower magnetization disks are used to design another Ka-band circulator.

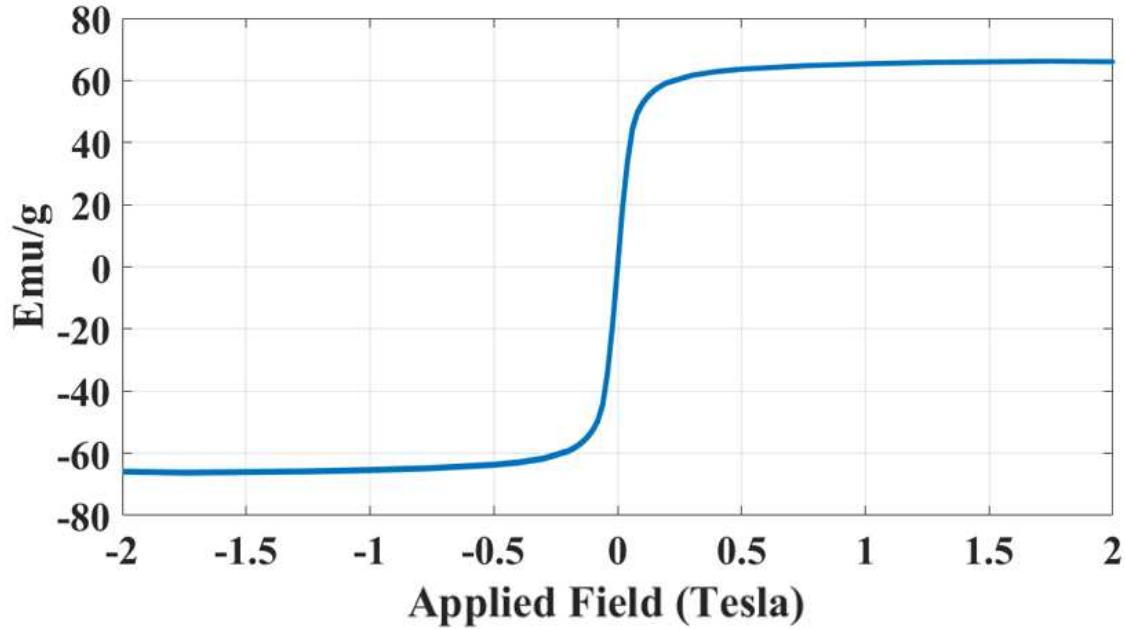


Fig. 5.34: Saturation magnetization of $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powders annealed directly at 700°C for 2h in the nitrogen environment (This measurement was conducted by Mr. Jael from Polytechnic Montreal).

In order to lower the magnetization of the ferrite powder, the NZF powder is heated in a nitrogen atmosphere with 700°C, which provided an emu/g of 66. Fig. 5.34 highlights the M-H hysteresis loop curve at 700°C in the nitrogen environment. The $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ powder is measured at room temperature with an applied field of ± 2 Tesla or 20000 (Oe). Later, the powder is compressed with the hydraulic press device to form the disk. The disk was weighed and measured to calculate the volume and density. The ferrites magnetization is 4200 (G), which is calculated using Equation 5.3.

5.5.4 Ka-band Circulator with Fabricated Ferrite with WR34 Waveguide:

The proposed work was fabricated for experimental validation using CNC milling with a 0.0005” tolerance from Scientific Microwave Corporation, Montreal. The simulated model of the WR34 circulator design is shown in Fig. 5.35.

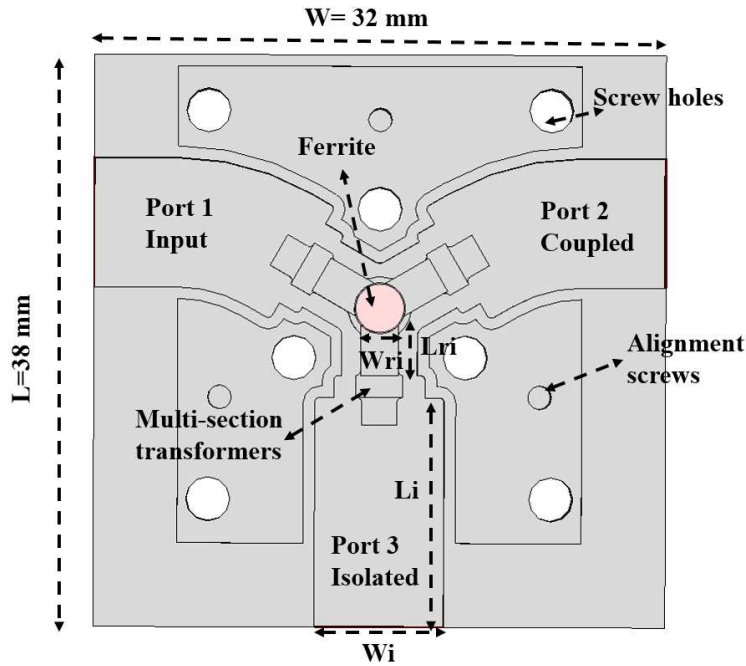
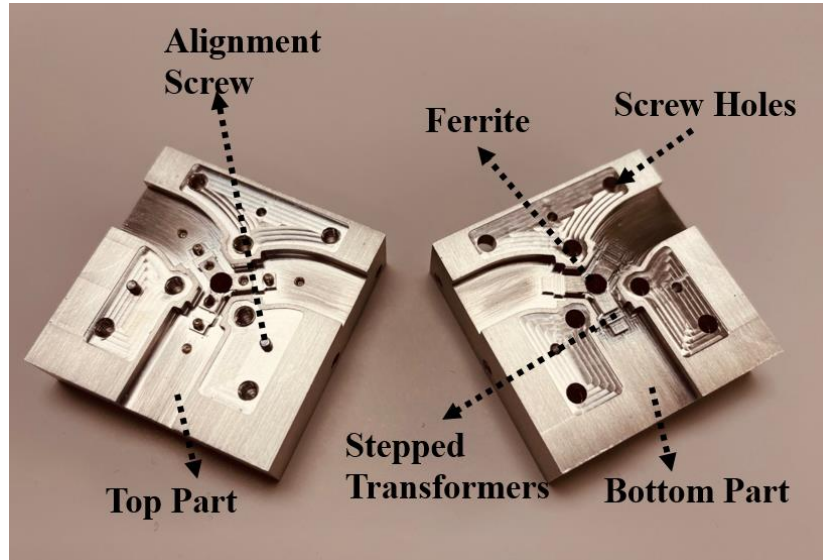


Fig. 5.35: Simulated Model of the WR34 Rectangular Waveguide Circulator.

The Ka-band rectangular waveguide circulator prototype with 4200 (G) ferrite is shown in Fig. 5.36, where the fabricated ferrite is placed at the center junction. A small amount of silicon is used at the center of the circulator's ferrite junction to hold the ferrite disk. DC Magnets are placed on both sides of the circulator for proper magnetic biasing. The measurement setup for the

manufactured circulator prototype is shown in Fig. 5.37. Since the magnetization of the ferrite considered here is much lower than the previous ferrite, it is more reasonable to incorporate it for a lower frequency band circulator using WR 34 rectangular waveguide. Table 5.5 shows the ferrite disk design parameters, biasing, and material properties. The design parameters of the WR34 Ka-band circulator, including the matching transformers, are shown in Table 5.6.



(a)



(b)

Fig. 5.36: Ka-Band Rectangular Waveguide Circulator Prototype, (a) Internal configuration with ferrite at the center, (b) Complete assembly.

Table 5.5: Design Parameters of the WR 34 Circulator Ferrite Disk

Parameters	Value
Magnetic Saturation $4\pi M_s$	4200 G
Magnetic biasing ratio α	0.06
Magnetic biasing field H_0	2500 0_e
Disk radius a	1.5 mm
Ferrite disk height h_f	0.5 mm
Effective gyromagnetic ratio, g	2.0
Ferrite permittivity	14.5

Table 5.6: Dimensions of WR34 Circulator Design (in mm)

Parameters	Values	Parameters	Values
W1	8.64	L1	14.1
W2	6.09	L2	1.37
W3	5.05	L3	2.65
Wr1	2.48	Lr1	2.31
Wr2	3.12	Lr2	1.45
Wr3	2.32	Lr3	1.52
Hr1	1.62	Hr2	0.94
Hr3	0.75	T1	0.55
T2	0.59	T2	0.62

Before the measurement of the circulator, a waveguide calibration is done. The fabricated circulator is measured using the Anritsu Vector Network Analyzer (VNA). Since the VNA just had two ports, the third port of the circulator is terminated by a matched load. So, S_{21} is the insertion loss, and S_{12} is the circulator isolation. The return losses of the circulator for Ports 1 and 2 are denoted with S_{11} and S_{22} , respectively. The simulated and measurement response comparison is demonstrated in Fig. 5.38. It is evident from the simulation and measurement response that there

is an excellent agreement between them where the circulator provides 7% bandwidth. The measured isolation and return loss is below -20 dB at the center frequency of 28 GHz. The insertion loss varies from 0.8 ± 0.6 dB over the operating range of the circulator. It is worth mentioning that while doing the measurement and tuning screws are used only on the second transformers of all three ports. The first transformer tuning screw had almost no effect on the matching level. The height of the tuning screws from the second transformers for the input, coupled, and isolated ports are $T1 = 0.55$ mm, $T2 = 0.59$ mm, and $T3 = 0.62$ mm. The dimensions of the height of the tuning screws are verified using the Dynamic Gage meter, and it is employed in the simulator to verify the results with the measurement response.

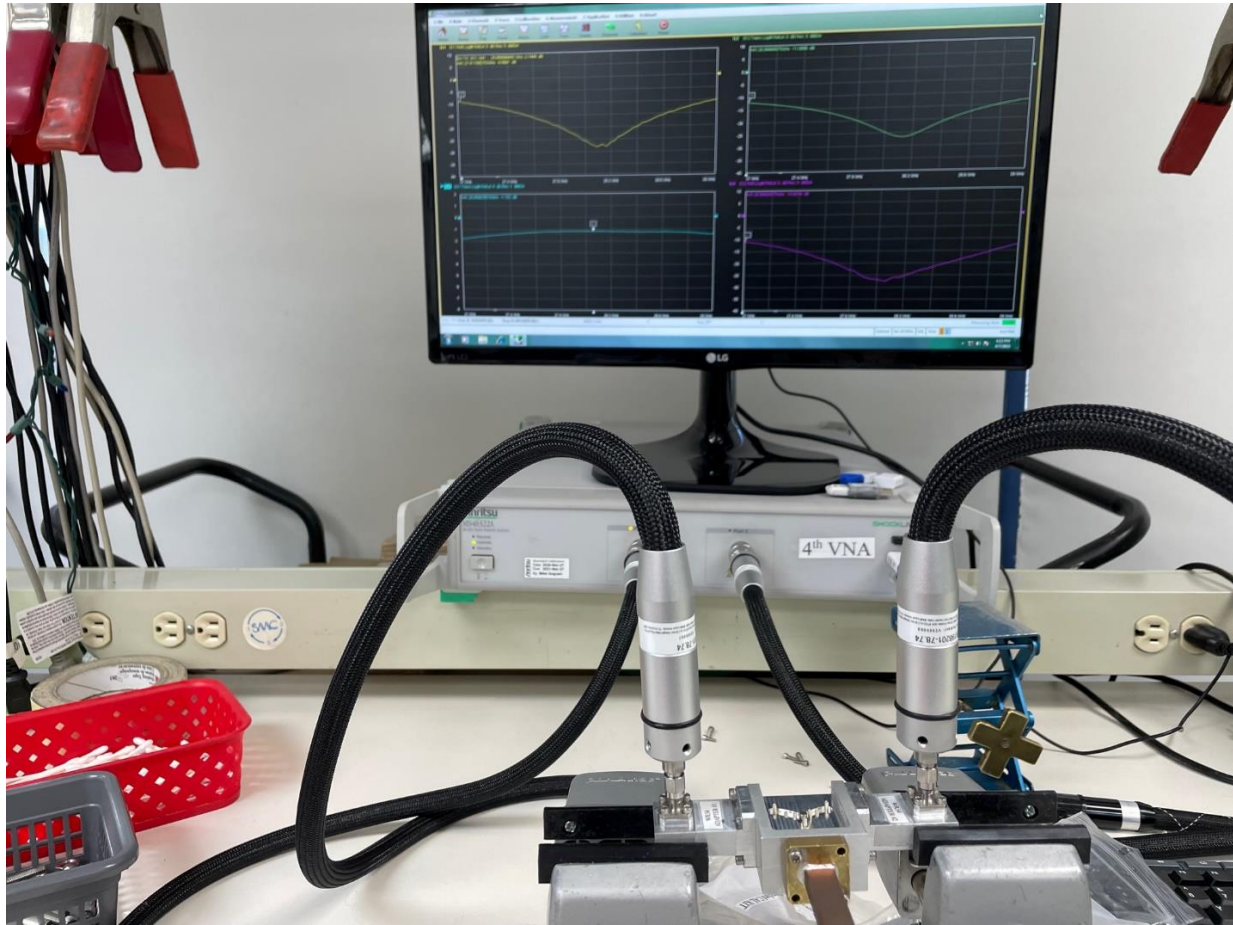


Fig. 5.37: Measurement setup of the fabricated Ka-band circulator design with a ferrite magnetization of 4200 (G).

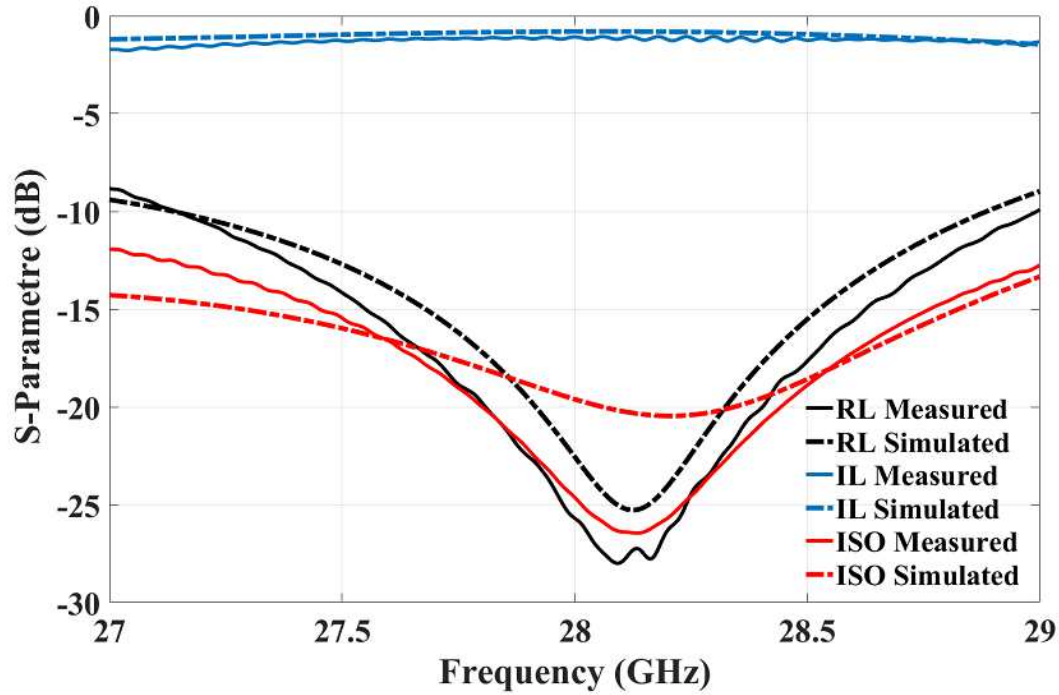


Fig. 5.38: Simulated and measured comparison of the Ka-band circulator with the fabricated ferrite disk with a magnetization $4\pi M_s$ of 4200 (G).

The proposed technique for fabricating the ferrite materials using a 2.5-ton hydraulic press provides a low-cost and simple solution. However, the manufacturing process had some limitations, especially in ensuring the exact ferrite height and the flatness on the surface or surface roughness. Although the proposed technique can be helpful, it can deteriorate the circulator performance in the mm-wave spectrum due to surface roughness. The ferrite has to sit correctly on the circulator junction for an excellent performance. If the surface is not flat, it will create more air gaps. Due to an asymmetric surface, the magnetization applied from the permanent magnet cannot be uniformly distributed over the ferrite surface, tremendously affecting the performance. As an extension and for further future work, more effective production can be employed to control the ferrite surface roughness and height. This will ensure a flat ferrite surface which can significantly enhance the circulator operating bandwidth. Fig. 5.39 shows a fabricated ferrite disk, where it can be seen that some small parts broke after manufacturing the disk. Although the commercially available disks can cover more extensive bands, our fabricated circulator with similar magnetization did not provide a wideband performance due to ferrite surface roughness. In

the industry, more complicated and expensive fabrication techniques are used for ferrite production. Here, we intended to use a simple approach to do the validation steps.

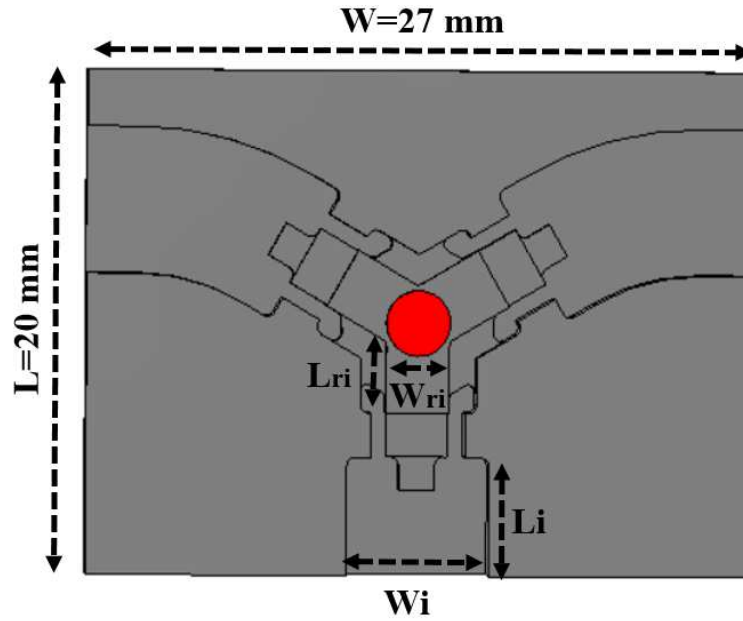


Fig. 5.39: Fabricated non-flat ferrite disk.

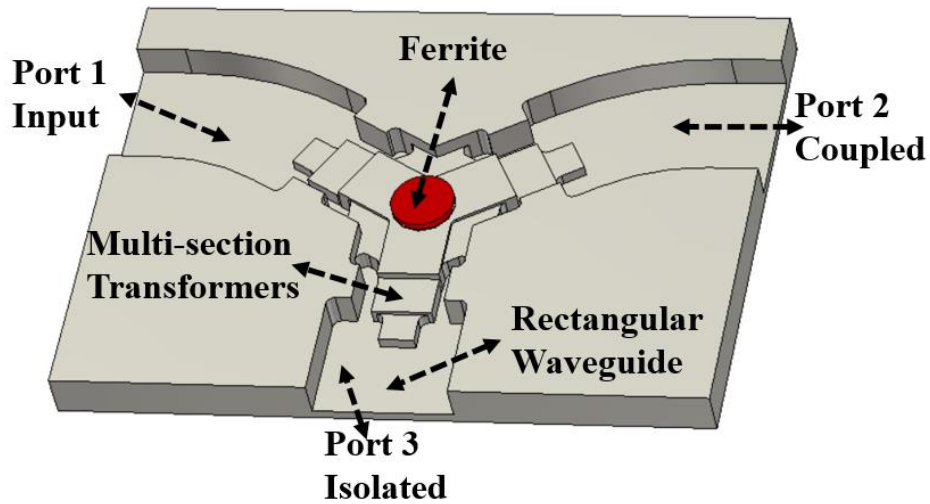
5.6 Q-Band Circulator Design with the Fabricated Ferrite Disk 8500 (G):

The fabricated high-magnetization ferrite disks are incorporated with a full Q-band rectangular waveguide circulator. We used the CST Microwave Studios Nelder-Mead Simplex Algorithm based on Finite Element Method (FEM) solver for the full-wave simulation optimization process. For the waveguide design part, WR 22 standard waveguide dimensions are used to design the Q-band circulator operating from 34-48 GHz. The cutoff frequency of the dominant mode of the WR 22 circulator is 26.3 GHz, and the higher-order mode starts from 52.7 GHz. Three-section Chebyshev transformers are added to match the impedance with the ferrite disk section. Connecting the circulator directly with the rectangular waveguide will lead to a poor matching level since the rectangular waveguide impedance is significantly higher than the ferrite disk impedance. In addition, at each port, three successive stepped waveguide sections are utilized to increase the matching level. The final design dimensions of the Q-band circulator are optimized through the optimization process using full-wave analysis, where the return loss, isolation, and insertion loss are taken as a multigoal function. Fig. 5.40 shows the Q-band rectangular waveguide

junction circulator, where the upper part is kept hidden for a clear illustration. Table 5.7 shows the ferrite disk design parameters, the biasing, and material properties. The Q-band circulator's design parameters, including the matching transformers, are highlighted in Table 5.8.



(a)



(b)

Fig. 5.40: WR 22 Q-Band Rectangular Waveguide Circulator, (a) 2D View, (b) 3D View.

Table 5.7: Design Parameters of the Q-Band Circulator Ferrite Disk

Parameters	Value
Gyrotropy g_k	0.6
Magnetic Saturation $4\pi M_s$	8500 G
Magnetic biasing ratio α	0.12
Magnetic biasing field H_0	900 O_e
Disk radius a	1.27 mm
Ferrite disk height h_f	0.3048 mm
Effective gyromagnetic ratio, g	2.0

The simulated S-parameter response is highlighted in Fig. 5.41 with excellent return loss and isolation below -20 dB from 35.4-46.2 GHz. The circulator provides an impedance bandwidth of 34.15% with an insertion loss of around -0.2 ± 0.3 dB, covering the whole frequency band from 34-48 GHz. The electric field distribution at 40 GHz is illustrated in Fig. 5.42. It is evident from the figure that almost all the power from the input port has coupled into coupled port, while the third port remained isolated.

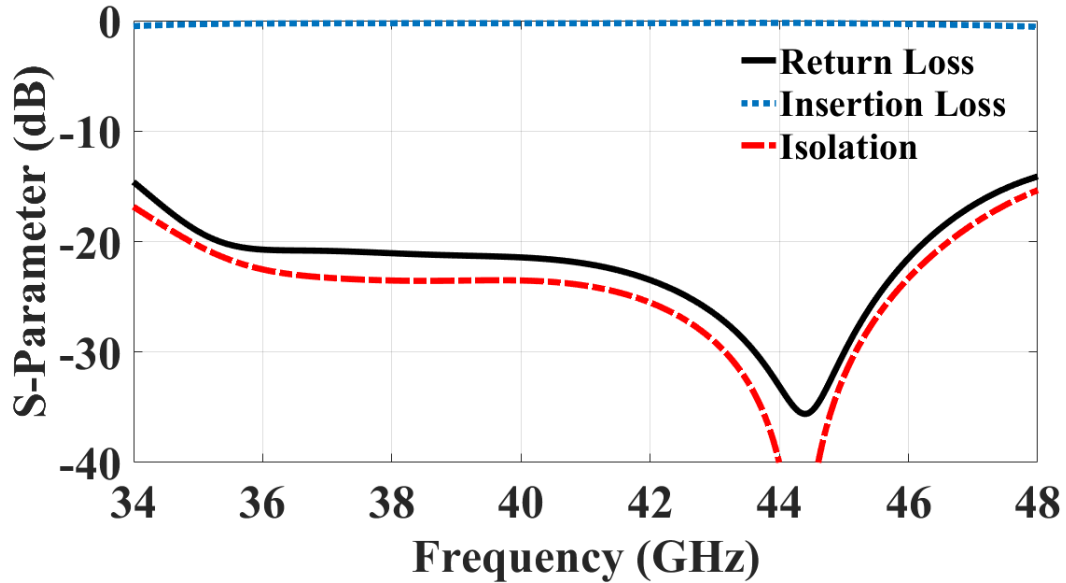
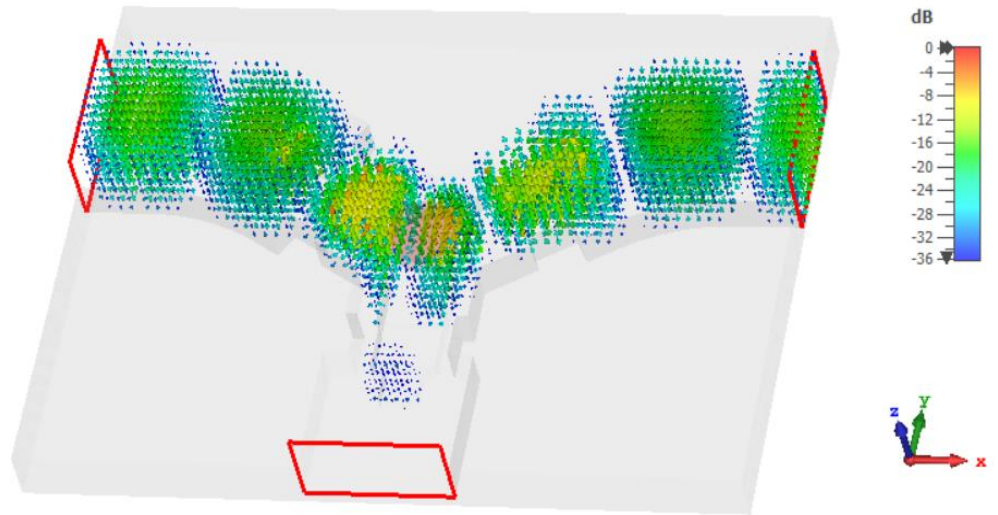
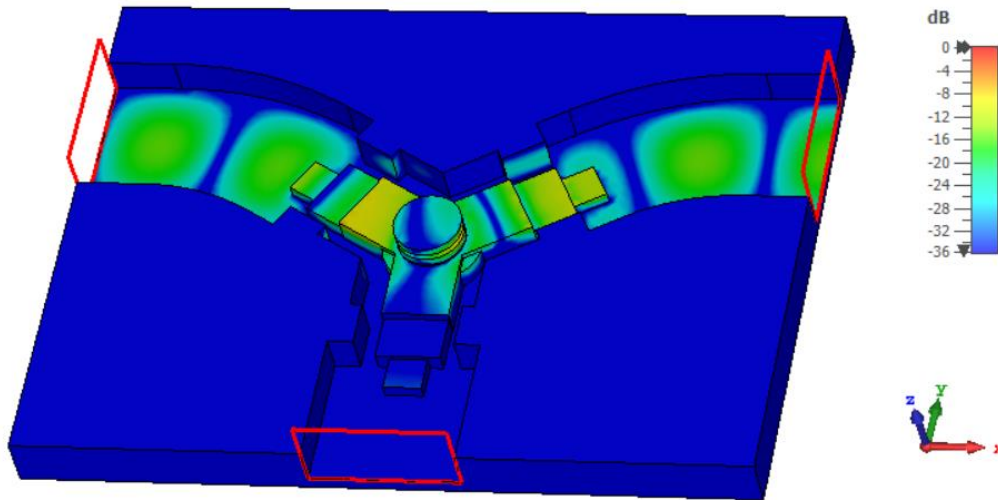


Fig. 5.41: Simulated S-parameter response of Q-band Rectangular Waveguide Circulator with fabricated ferrite disk with magnetization 8500 (G).

The power flow figure is highlighted in Fig. 5.43 at 40 GHz, where the injected power is 1.25 kW, and the E -field strength is 2.13 MV/m, below the breakdown voltage of 3 MV/m. This maximum field exists at the center ferrite, with a gap of 0.24 mm.



(a)



(b)

Fig. 5.42: Electric field distribution of a Q-band Rectangular Waveguide Circulator at 40 GHz, (a) E-field Vector, (b) E-field Absolute value.

Table 5.8: Dimensions of Q-band circulator design (in mm)

Parameters	Values	Parameters	Values
W1	5.68	L1	5.08
W2	3.73	L2	1.7
W3	4.62	L3	2.13
Wr1	2.48	Lr1	2.04
Wr2	2.43	Lr2	1.69
Wr3	1.43	Lr3	1.28
Hr1	0.93	Hr2	0.63
Hr3	0.47		

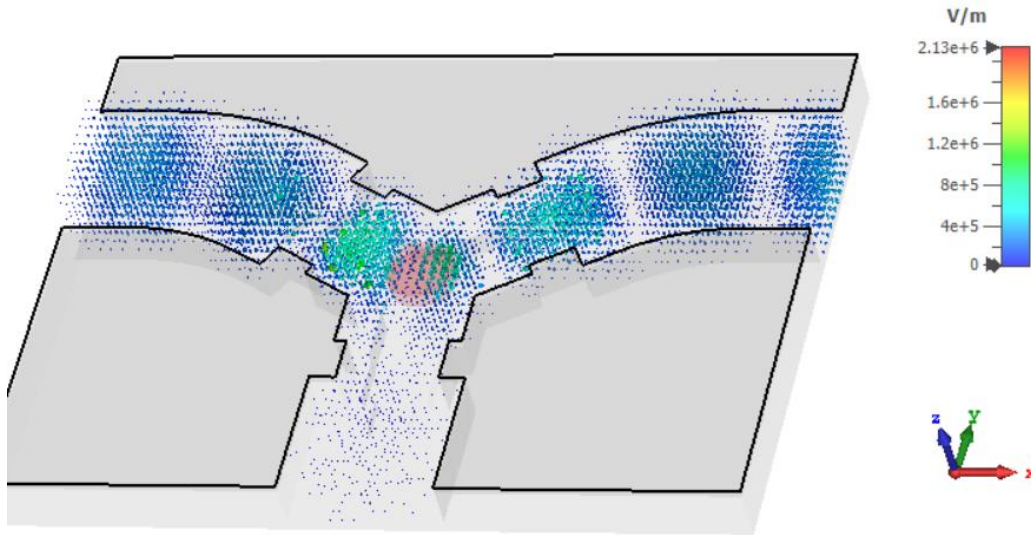


Fig. 5.43: Simulated Electric field of Q-band Circulator at 40 GHz for an input power of 1.25 KW (Peak).

5.7 V-Band Circulator Design with the Fabricated Ferrite Disk 9500 (G):

It is well-known that having a higher magnetization will allow microwave devices to operate at a higher frequency. Operating at low frequency will require materials with low saturation magnetization $4\pi M_s$. Thus, in the current invention work, our focus was to deploy multiple ferrite disks with very high magnetization beyond the available ferrite disks on the market with different

Table 5.9: Design Parameters of the V-Band Circulator Ferrite Disk

Parameters	Value
Gyrotropy g_k	0.6
Magnetic Saturation $4\pi M_s$	9500 G
Magnetic biasing ratio α	0.12
Magnetic biasing field H_0	1000 O_e
Disk radius a	0.84 mm
Ferrite disk height h_f	0.202 mm
Effective gyromagnetic ratio, g	2.0
Ferrite permittivity	14.5

The power flow figure is highlighted in Fig. 5.45 at 60 GHz, where the injected power is 0.615 kW, and the E -field strength is 2.44 MV/m, below the breakdown voltage of 3 MV/m. This maximum field exists at the center ferrite, with a gap of 0.15 mm. The high-power capacity of the Y-junction circulator is assessed through simulations only.

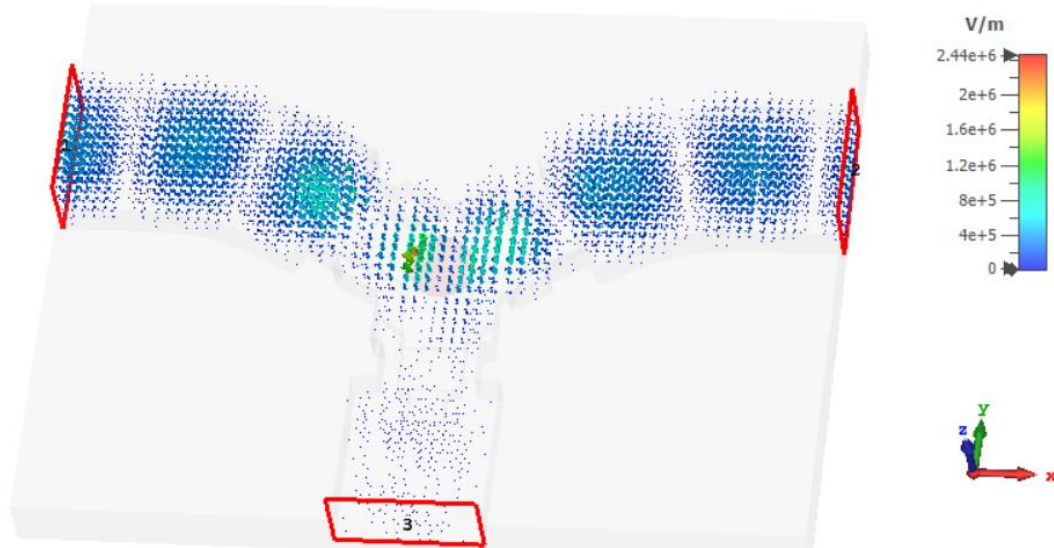


Fig. 5.45: Simulated Electric field of V-band Circulator at 60 GHz for an input power of 0.615 KW (Peak).

The simulated S-parameter response is highlighted in Fig. 5.46 with excellent return loss and isolation below -20 dB from 52-72 GHz. The circulator provides an impedance bandwidth of 40% with an insertion loss of around -0.2 ± 0.5 dB, covering the whole V-band from 50-75 GHz. It is evident from the s-parameter response that almost all the power from the input port has coupled into coupled port, while the third port remained isolated.

Table 5.10: Dimensions of V-band circulator design (in mm)

Parameters	Values	Parameters	Values
W1	3.75	L1	4.23
W2	2.47	L2	1.13
W3	3.06	L3	1.41
Wr1	1.65	Lr1	1.82
Wr2	1.6	Lr2	1.13
Wr3	0.95	Lr3	0.85
Hr1	0.62	Hr2	0.42
Hr3	0.31		

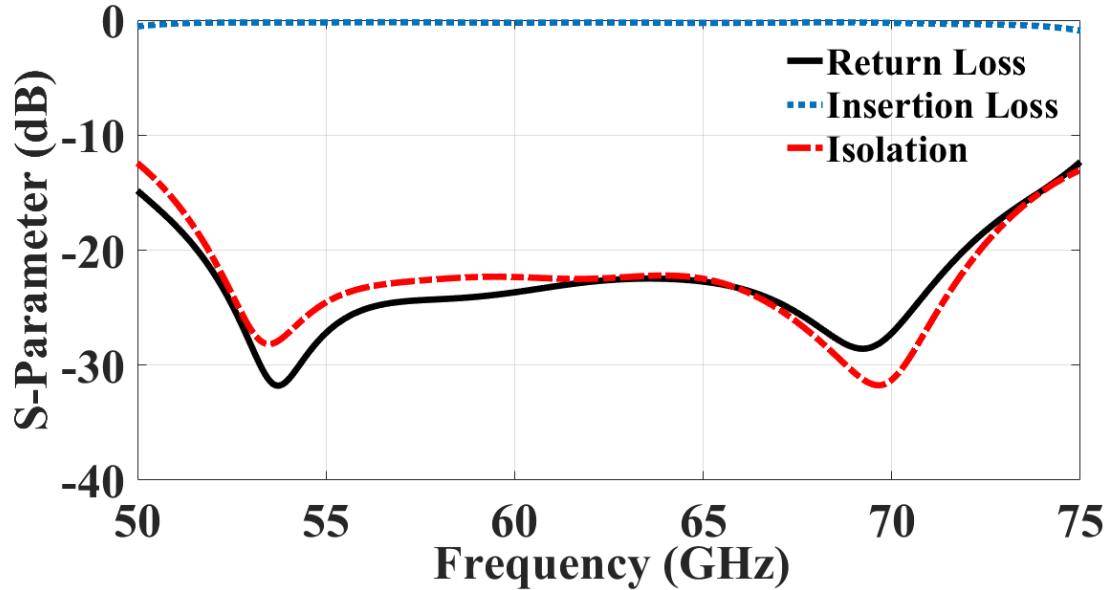


Fig. 5.46: Simulated S-parameter response of V-band Rectangular Waveguide Circulator with fabricated ferrite disk with magnetization 9500 (G).

5.8 Key Benefits of the Fabricated Ferrite Disk Fabrication

The present invention covers a fabrication technique of high-magnetization nickel-zinc ferrite (NZF) powder using co-precipitation measurement. Obtaining a higher magnetization is critical and requires different compositions, sintering processes, and heat treatments. A higher magnetization will allow microwave devices to operate at higher frequency bands. The invented ferrite has a significantly higher magnetization than the available ferrite disks in the market. The proposed ferrite disks magnetization exceeds 10700 (G), which is more than double the magnetization commercially available in the microwave and space industry. This will open a new doorway for the microwave and space industry supporting various future applications in the mm-wave spectrum. In the mm-wave range, the invented ferrite disk can be used with plenty of microwave devices, such as circulators, duplexers, isolators, differential phase shifters, etc. As a proof of concept, three different circulators were simulated with the proposed fabricated high-magnetization ferrite disk. In the microwave industries, such a wideband circulator cannot be achieved without high magnetization above Ka-band. For instance, in [160], the V-band circulators cannot achieve such a huge band. Thus, it was divided into three sub-bands operating from 58-64 GHz, 65-71 GHz, and 71-76 GHz. However, the proposed circulator can cover from 52-72 GHz, with a 20-dB matching bandwidth, with low insertion loss. With the proposed fabricated technique, it is even possible to have multi-ring ferrites, to be more precise, it is possible to employ multiple ferrite disks with different diameters having different magnetization $4\pi M_s$. This could help significantly to achieve a wideband performance. We can control the magnetization by reducing the temperature or even by employing different heat treatment methods. For instance, it is possible to design two ferrite disks with diameters X_1 and X_2 and place them in a single junction which can have a magnetization $4\pi M_s(X_1)$ of 4300 (G) and $4\pi M_s(X_2)$ of 8700 (G). This can be an interesting research topic for future work. Besides, there was a restriction with the heating in the oven which supported up to 1100°C temperature. There is a possibility that the magnetization can be increased further by going to higher temperatures.

Conclusion and Future Works

6.1 Conclusion

The thesis has presented several innovative approaches and techniques to investigate different PCB-based RF components in the Millimeter-wave spectrum. Based on the substrate-integrated gap waveguide (SIGW) technology, circulators, and multilayer horn antennas have been designed, which play an integral part in full-duplex communication. The first work has provided a solution with multilayer stacked dielectric substrates with the conducting cladding, aiming for electrical contact between them [perfect electric conductor (PEC)–PEC]. At mm-wave frequencies, surface roughness or imperfect flat surfaces present possible gaps that cause severe unexpected leakage. Many engineers overlooked this problem. To prevent this leakage, one of the PEC–PEC surfaces was transformed into artificial magnetic conductors (AMCs), creating a PEC–AMC layer that suppresses any leakage even with no contact between the surfaces with a gap less than a quarter wavelength. A wideband multilayer pyramidal horn antenna using substrate-integrated gap waveguide (SIGW) technology has been proposed as an example that highlights the proposed solution. In each layer of the horn, the opening has been surrounded by periodic cells to suppress leakage and spurious radiation. In addition, the upper surface surrounding the horn's opening has been surrounded by EBG mushroom cells to act as a soft surface that suppresses the surface waves, reducing edge diffraction and, in turn, improving the radiation characteristics of the horn antenna. The horn antenna has achieved a gain of 11.5 dBi, and 20.5% bandwidth (28.5–35 GHz) with an excellent front-to-back ratio (FBR). The simulated and measured results have shown excellent agreement.

In chapter 4, a simplified analysis has been implemented for a low dielectric-filled Ka-band Y-junction circulator, which led to the design and fabrication of such a circulator for the first time based on Substrate Integrated Gap Waveguide (SIGW) technology. A new design equation has been tailored based on a low dielectric filling considering the effect of fringing fields around the ferrite disk. Most PCB-based circulators have massive dielectric losses at the mm-wave range, leading to spurious radiation, leakages, and surface waves, degrading the overall system

performance. To improve the matching level, a two-section Chebyshev transformer has been added to the ridge. A low-dielectric filling has been considered to provide mechanical support to the ferrite disk, and the reflection between the feeding lines and the center ferrite disks has been reduced. The filling dielectric materials have added insertion loss, but the mode has kept its Quasi-TEM type, resulting in a non-dispersive operation. The proposed circulator has covered a wide frequency range with an acceptable return loss and isolation at the center frequency. Later, the circulator was connected to the horn antenna to form a full-duplex communication, which can be incorporated with Ka-band satellites and radars in the mm-wave range.

It is well-known that higher magnetization allows microwave devices to operate at a higher frequency, and operating at a low frequency will require materials with low saturation magnetization $4\pi M_s$. Thus, Chapter 5 has focused on deploying multiple ferrite disks with very high magnetization beyond the available ferrite disks on the market. Nickel-zinc ferrite (NZF) compositions have been annealed at different atmospheres, such as Vacuum, Nitrogen, Nitrogen + 3% Hydrogen, and Argon + 3% Hydrogen. This led to, in-house, achieving a saturation magnetization of $4\pi M_s$ beyond 9500 (G), which is almost 1.8 times higher than the magnetization available in the microwave and space industry. The microwave industry's highest available saturation magnetization is around 5300 (G). From the industrial point of view, only the standard ferrite diameter and thicknesses are available in the market. A custom-made disk requires much time and is expensive. A simple technique has been described to fabricate the ferrite disk using the chemical co-precipitation method to provide an easy solution. The highly magnetic disk can be used in the mm-wave band by incorporating it with an isolator and circulator to support various radars and satellite communications applications. Three examples have been highlighted using three different frequency bands to design wideband circulators using the proposed ferrite materials. In addition, for validation purposes, a circulator was measured with isolation and return loss better than 20 dB at the center frequency of 28 GHz.

6.2 Future Works

Among the most promising wireless communication systems is satellite communications, which has grasped more attention recently to establish satellite Internet networks. This network is expected to form a new backbone around the globe with complete coverage at a reasonable cost.

However, many technical challenges are associated with these emerging RF devices limiting their proper deployment. One major limitation is the absence of non-orthogonal full-duplex Multiple Input Multiple Output (MIMO) system operations in satellite and space communications. Traditional satellite communication systems are structured to work in a virtual-duplex mode, where both transmitter (TX) and receiver (RX) bands are separated with a guard band.

The full-duplex system can provide several advantages, such as better spectral efficiency, doubling data throughput, and reducing signal delays. In addition, TX power handling remains a challenging problem, especially for a full-duplex system that integrates a shared antenna interface. The next generation of wireless networks can significantly improve performance by combining the full-duplex and MIMO system. MIMO technology provides a solution to improve system performance in coverage, capacity, and user data rate through diversity gain [162]. The data rate can be doubled by implementing the full-duplex system. The full-duplex system can be realized by adding a circulator and an antenna in the same feeding layer to transmit and receive signals simultaneously. Obtaining high-efficiency printed mm-wave isolators is challenging due to various limitations, such as high dielectric losses, leakages, and surface waves. In addition, to get high isolation, dual or triple junctions are used. In printed technologies, two-dimensional degrees of freedom exist, while the dielectric substrate thickness has discrete values limiting the design parameters. A compact printed multilayer circulator hosted by a low-loss guiding structure can resolve this problem by enabling the power transfer from one layer to another in a specific direction. This will ensure high isolation, while the size will be significantly compact compared to dual or triple cascaded junctions. The Substrate integrated gap waveguide (SIGW) technology can be a convenient option as a host guiding structure for full-duplex systems.

Many possible solutions can be incorporated with SIGW technology in the future. It is possible to incorporate this technology with a dual-polarization antenna array configuration with low isolation supporting the mm-wave spectrum [138]. Dual-polarization antennas have a significant influence on satellite communications. Using the SIGW excitation will reduce the back radiation, as there would be no direct back radiation from the slots.

Appendix A

Electric Field Distribution of Cylindrical Ferrite Disk

We start solving Maxwell equations for a source-free medium,

$$\nabla \times \bar{E} = -j\omega[\mu]\bar{H} \quad (\text{A.1})$$

$$\nabla \times \bar{H} = j\omega\epsilon\bar{E} \quad (\text{A.2})$$

where the magnetic flux density is $\bar{B}=[\mu]\bar{H}$ and the electric flux density is $\bar{D}=\epsilon\bar{E}$. The permeability tensor for a ferrite material is biased in the z-direction of the cylindrical coordinates [161]. Table A summarizes the expressions for the permeability tensor,

$$[\mu] = \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix} \quad (\text{A.3})$$

Based on the assumption of no axial variation, the solution of Maxwell equations in the cylindrical coordinates, taking into consideration this permeability tensor, is listed below,

$$\frac{1}{\rho} \frac{\partial E_z}{\partial \phi} = -j\omega(\mu H_\rho + j\kappa H_\phi) \quad (\text{A.4})$$

$$-\frac{\partial E_z}{\partial \rho} = -j\omega(-j\kappa H_\rho + \mu H_\phi) \quad (\text{A.5})$$

Solving these two equations gives the magnetic field components H_ρ and H_ϕ

$$H_\rho = \frac{jY_{0eff}}{k_{eff}\mu} \left(j\kappa \frac{\partial E_z}{\partial \rho} + \mu \frac{\partial E_z}{\partial \phi} \right) \quad (\text{A.6})$$

$$H_\phi = -\frac{jY_{0eff}}{k_{eff}\mu} \left(\frac{-j\kappa}{\rho} \frac{\partial E_z}{\partial \phi} + \mu \frac{\partial E_z}{\partial \rho} \right) \quad (\text{A.7})$$

where the effective permeability, effective wavenumber, and effective intrinsic admittance are denoted as μ_{eff} , k_{eff} and Y_{0eff} , respectively.

$$\mu_{eff} = \frac{\mu^2 - \kappa^2}{\mu} \quad (\text{A.8})$$

$$k_{eff} = \omega \sqrt{\epsilon \mu_{eff}} \quad (\text{A.9})$$

$$Y_{0eff} = \sqrt{\frac{\epsilon}{\mu_{eff}}} \quad (\text{A.10})$$

Substituting in (A.2), the axial electric field E_z can be expressed in terms of the transverse magnetic field components H_ρ and H_ϕ as,

$$\frac{1}{\rho} \left[\frac{\partial(pH_\phi)}{\partial \rho} - \frac{\partial H_\rho}{\partial \phi} \right] = j\omega\epsilon E_z \quad (\text{A.11})$$

Substituting by (A.6) and (A.7) in (A.11), a second-order differential equation for the axial electric field E_z can be expressed as

$$\rho^2 \frac{\partial^2 E_z}{\partial \rho^2} + \rho \frac{\partial E_z}{\partial \rho} + \rho^2 k_{eff}^2 E_z + \frac{\partial^2 E_z}{\partial z^2} = 0 \quad (\text{A.12})$$

The solution of the previous Equation is commonly addressed in cylindrical waveguide problems, and it takes the form of:

$$E_{zn} = \sum_{n=-\infty}^{\infty} A_n J_n(k_{eff}\rho) e^{jn\phi} + C_n N_n(k_{eff}\rho) e^{jn\phi} \quad (\text{A.13})$$

where $J_n(k_{eff}\rho)$ and $N_n(k_{eff}\rho)$ are the Bessel and Neumann functions of order n , respectively. The electric field amplitude is represented by A_n . As $N_n(k_{eff}\rho)$ is infinite at the axis of the cylinder, the coefficient C_n must vanish ($C_n = 0$). Then the electric field expression becomes

$$E_{zn} = \sum_{n=-\infty}^{\infty} A_n J_n(k_{eff}\rho) e^{jn\phi} \quad (\text{A.14})$$

Substituting (A.14) in Equation (A.7), the magnetic field, H_ϕ takes the following form shown in (A.15):

$$H_{\phi n} = -jY_{o\text{eff}} \sum_{n=-\infty}^{\infty} A_n \left[J'_n(k_{\text{eff}}\rho) + \frac{ng_k}{k_{\text{eff}}\rho} J_n(k_{\text{eff}}\rho) \right] \quad (\text{A.15})$$

The permittivity of the ferrite material ϵ_r is nominally higher than the surrounding medium. This leads to assuming PMC condition around the ferrite disk where $H_{\text{tan}} = 0$ in between the ports. Since the input power at Port 1 is equal to the output power at Port 2, this leads to having an $E_{z1} = -E_{z2}$ and $H_{\phi1} = H_{\phi2}$ as discussed previously in Section II. These two expressions ensure that the power densities at both ports are identical in magnitude and opposite in direction. To apply the circulator boundary condition of the magnetic field can be expressed in the Fourier series form as,

$$H_{\phi, \text{required}}(a, \phi) = \frac{\psi}{\pi} \cdot \frac{\sin(n\psi)}{n\psi} \sum_n (1 + e^{-\frac{j2\pi n}{3}}) e^{jn\phi} \quad (\text{A.16})$$

This ideal field boundary condition can be satisfied by equating the magnetic field inside the ferrite disk with the required tangential magnetic field outside. This amplitude A_n is expressed in Equation (A.17).

$$A_n = j \frac{1}{Y_{o\text{eff}}} \frac{\sin(n\psi)}{n\pi} \left[\frac{(1 + e^{-\frac{j2\pi n}{3}})}{J'_n(x) + \frac{ng_k}{x} J_n(x)} \right] \quad (\text{A.17})$$

where, $x = k_{\text{eff}}\rho$ is considered to simplify the equations. The effective characteristic admittance can be written as,

$$\frac{1}{Y_{o\text{eff}}} = \sqrt{\frac{\mu_{\text{eff}}}{\epsilon}} = n_{\text{eff}r} \cdot \eta_0 \quad (\text{A.18})$$

η_0 is the free space intrinsic impedance. Substituting Equation (A.17) into Equation (A.14) gives the required average electric field distribution,

$$E_z = \sum_{n=-\infty}^{\infty} j n_{\text{eff}r} \cdot \eta_0 \frac{\sin(n\psi)}{n\pi} \left[\frac{(1 + e^{-\frac{j2\pi n}{3}}) J_n(x)}{J'_n(x) + \frac{ng_k}{x} J_n(x)} \right] e^{jn\phi} \quad (\text{A.19})$$

Table A.1: Permeability Tensor Expressions

Physical Quantity	Symbol	Expression
Gyrotropy, g_{κ}	κ/μ	$\frac{\omega\omega_m}{\omega_0^2 - \omega^2 + \omega_0\omega_m}$
Larmor angular freq.	ω_0	$\mu_0\gamma "H_0"$
Magnetic freq.	ω_m	$\mu_0\gamma "M_s"$
Diagonal elements	μ	$\mu_0(1 + \frac{f_0 f_m}{f_0^2 - f^2})$
Off Diag. elements	κ	$\mu_0(\frac{f f_m}{f_0^2 - f^2})$

Synthesis of Nickel-Zinc Ferrite (NZF) Nanoparticles

1) Introduction/Context

Magnetic nanoparticles, including nanostructured spinel ferrite materials, are of interest in developing electromagnetic devices. More specifically, Nickel-doped ZnFe_2O_4 nanostructures (also called Ni-Zn ferrite or NZF) exhibit promising properties that potentially could be exploited in different applications in supercapacitors, MRI, microelectronics, magneto-optics, catalysts, or absorbents due to their soft magnetic properties. Many methods have been utilized to synthesize ferrite nanoparticles, which size and shape are generally controlled by the synthetic method. Various techniques have been reported to synthesize Ni-Zn ferrite nanoparticles, including chemical co-precipitation, thermal decomposition, and sol-gel process [131]-[137]. The co-precipitation methodology will be the object of this SOP.

2) Purpose

This SOP has been elaborated to provide a detailed set of written instructions that will document and support a repetitive research activity involving the use of corrosive chemicals in the synthesis of NZF nanoparticles. **This procedure is intended to provide the user(s) with the needed information to perform the task safely and adequately, facilitating consistency in the quality and integrity of the process and results.**

3) Scope

This SOP only applies to the research activity aiming to synthesize NZF nanoparticles performed in the H-007 laboratory on the SGW campus.

4) Reference documents

- Nickel(II) chloride hexahydrate – [SDS](#) [163]
- Zinc chloride – [SDS](#) [164]
- Iron(III) chloride – [SDS](#) [165]
- Sodium hydroxide (pellets – [SDS](#) and 2M solution in water – [SDS](#)) [166]
- Concordia University [Laboratory Safety Manual](#) [167]

- Concordia University [Nanomaterials Safety Guidelines](#) [168]
- Concordia University [Chemical Waste Disposal Procedures](#) [169]
- VPS-40 [Environmental Health and Safety Policy](#) [170]
- VPS-41 [Policy on Personal Protective Equipment](#) (PPE) [171]
- VPS-47 [Policy for the Management of Hazardous Materials](#) [172]
- VPS-48 [Hazardous Materials Spill Response Policy](#) [173]

5) Roles and Responsibilities

Before conducting any work with corrosive substances and nanomaterials, the designated laboratory personnel (users) must have successfully completed EHS-provided safety training in direct relation to the hazards involved in working with these substances and understand the work area decontamination and emergency procedures. The list of mandatory pieces of training shall include the following:

- ✓ *WHMIS for Laboratory Personnel,*
- ✓ *Corrosive Substances,*
- ✓ *Hazardous Waste Disposal for Laboratory Personnel,*
- ✓ *Safe Handling of Nanomaterials, and*
- ✓ *Hazardous Material Minor Spill Response.*

6) Description of the chemicals and associated hazards – Safe handling

6.1 Description of the chemicals and related hazards:

▪ **Nickel(II) chloride hexahydrate**

CAS number: 7791-21-0

Form (physical state): Solid

Color: Green



WHMIS: *Acute toxicity – Oral and Inhalation (Cat.3); Skin irritation (Cat.2); Respiratory sensitization (Cat.1); Skin sensitization (Cat.1); Germ cell mutagenicity (Cat.2); Carcinogenicity – Inhalation (Cat.1B); Reproductive toxicity (Cat.1B); STOT – repeated exposure by inhalation (Lungs-Cat. 1).*

Very toxic to aquatic life.

Avoid generation, inhalation of dust, and substance contact in all circumstances. Keep away from alkali metals.

▪ **Zinc chloride**

CAS number: 7646-85-7

Form (physical state): Powder

Color: White

WHMIS: *Acute toxicity – Oral* (Cat.4); *Skin irritation* (Cat.1B); *Serious eye damage* (Cat.1).

Very toxic to aquatic life.

Avoid inhalation of dust and substance contact in all circumstances. Keep away from sodium and strong oxidizing agents.



▪ **Iron(III) chloride**

CAS number: 7705-08-0

Form (physical state): Solid, with a pungent odor when wet

Color: Dark green to purple red

WHMIS: *Corrosive to metals* (Cat.1); *Acute toxicity – Oral* (Cat.4); *Skin irritation* (Cat.2); *Serious eye damage* (Cat.1).



Avoid inhalation of dust and substance contact in all circumstances. Keep away from alkali metals and ethylene oxide, as an explosion could occur.

Iron (III) chloride is also known as ferric chloride. Depending on the viewing angle, it can appear as a dark green or purple-red solid in its solid form and odorless. When Iron (III) chloride is wet, it can be very corrosive to different types of Metal, including Aluminium, and has the potential to release flammable Hydrogen (H₂) gas. Additionally, the solid form is a powerful dehydrating agent.

When mixing Ferric Chloride in water, typically at concentrations around 40%, a strongly acidic

reddish-brown solution with a pH below one will be produced. This is due to the generation of a large quantity of Hydrochloric acid. Iron (III) species also have relatively strong oxidizing properties. **Most of the chlorinated salts, including Zinc (II), Ni (II), Copper (II), Gold (III), Aluminium (III), and Manganese (II) Chloride, may generate hydrochloric acid in the presence of water, and they possess similar corrosive hazards when dissolved in water.**

In addition to their corrosive properties, health hazards, including acute and chronic toxicities through repeated exposures, are also described for those chemicals.

▪ **Sodium hydroxide (solid and liquid form)**

CAS number: 1310-73-2

Form (physical state): Solid (Pellets)

Color: White

WHMIS: *Corrosive to metals* (Cat.1); *Skin corrosion* (Cat.1A); *Serious eye damage* (Cat.1).



CAS number: 1310-73-2

Form (physical state): Liquid (2M solution¹)

Color: Colorless

WHMIS: *Skin corrosion* (Cat.1B); *Serious eye damage* (Cat.1).



Sodium Hydroxide is a strongly basic ionic salt that ionizes completely when dissolved in water. It is one of the strongest alkalis and is a highly reactive substance. It is very hygroscopic (*i.e.*, absorbs water from the air) and will also absorb carbon dioxide from the air. As such, it is a hazardous chemical and must be treated with care.

Considering its corrosiveness, direct contact with any form will create skin burns and is extremely destructive to mucous membranes, the upper respiratory tract, and the eyes. While being in direct contact with skin imparts a slippery feeling to touch due to NaOH transforming the skin's fats in a process like one used to make soaps (saponification). Its corrosiveness depends on the concentration of the solution and the duration of its contact with tissue. It will act locally, exerting a strong corrosive action that does not involve the coagulation of proteins to impede

¹. Roughly corresponding to the NaOH solution concentration made during the experiment.

penetration. Consequently, Sodium Hydroxide may not be immediately painful during skin penetration, producing severe and slow-healing burns with the degeneration of the tissue, causing severe burning, ulceration, and scarring. Deeper layers of the skin tend to be destroyed until NaOH is washed off, and the extent of injury depends on the length and amount of exposure. Eventually, its rapid absorption into the circulating system and distribution with the body water can occur. It is worth mentioning that NaOH is not metabolized. This chemical can also penetrate the eyes, even at low concentrations, to damage the cornea accompanied by clouding and loss of normal vision. Eye disorders like glaucoma, cataract, and permanent blindness can occur. Inhalation of dust, vapors, or fumes of Sodium Hydroxide is also toxic and irritating to the eyes and respiratory systems and can provoke lung damage (up to pulmonary edema).

Sodium Hydroxide can react violently with incompatible materials such as organic chemicals, strong acids, chlorinated solvents, oxidizing and reducing, peroxides, flammable liquids, Aluminium, and Zinc. Chemical incompatibilities can generate additional hazards, such as the release of flammable gas, toxic vapors or fumes, and strong exothermic reactions. Shock-sensitive explosive salts can also be generated in the presence of nitromethane and nitrophenols.

Handle with care! Careful precautions should always be taken when handling, making solutions, and disposing of this chemical. **Dissolution of NaOH solid in water is highly exothermic**, and caustic fumes/vapors can be released, or even splashes of the basic solution. **Also, do not touch NaOH with bare hands: in addition to its saponification properties, its hygroscopic features will be responsible for its quick liquefaction, a state that greatly improves the skin contact surface and penetrative properties.**

The solid can be purchased as pellets (the most common form) or flakes of mini pearls. Aqueous solutions at various concentrations (from 0.1M to 10M) are also commercially available. If not handled and disposed of properly, this chemical can pose a serious threat to the health and safety of laboratory personnel, emergency responders, and waste handlers. Consequently, it is essential to thoroughly understand the properties of this chemical and follow all safety protocols to store and handle it properly.

Summary of potential hazards/toxicity

- Corrosion hazards
- Skin burns and irreversible eye injuries / Irritation of mucous membrane
- Toxicity hazards
- Exothermic reactions (heat)
- Violent reactions with incompatible materials or chemicals
- Splash hazards

The user must also consider the ones that nanomaterials could generate during handling, storage, and waste procedures. As discussed in the [Nanomaterials Safety Guidelines](#) and in the *Safe Handling of Nanomaterials* EHS-safety training, the precautionary principle must apply at every step of the process.

6.2 Safe Handling:

The safety procedures outlined below are required by all research staff when working with the corrosive substances described above (in solid form or solution).

○ Administrative controls:

- 1) Anyone who handles those corrosive/toxic substances is required to review (a) this SOP, (b) the corresponding SDSs, and (c) the related documents and policies.
- 2) Anyone who handles those corrosive/toxic substances must have successfully completed the required safety training previously mentioned.
- 3) **Work with a solid form of those corrosive/toxic substances or with corresponding highly concentrated solutions ($\geq 0.5M$) should only be done during business hours** and when there is a second person cognizant of the related dangers available to assist with procedures and emergencies: a lab buddy system shall be required. **Do not work alone!**

○ Engineering controls:

- 1) All work involving those corrosive/toxic substances, including weighing and dissolution procedures, should be conducted **inside a certified chemical fume hood**. Make sure the fume hood has a warning sign indicating that corrosive/toxic substances with high concentrations are

currently being used and restrict other activities in the fume hood while operating. The sash opening should be minimized to prevent splashes.

2) Confirm that emergency eyewash and/or shower stations are located within the working area and have a current certification date. **Laboratory personnel must know their location and ensure that the emergency eyewash station properly works and is tested weekly. Users must all know the location of 1) the ABC extinguishers in the lab and on the floor and 2) the laboratory emergency exits.**

○ *Personal Protective Equipment:*

Considering the corrosiveness and toxicities associated with the chemicals involved in that experiment, **no skin exposure** must be followed.

1) Eye protection: **Chemical goggles, along with a face shield**, must be worn when handling any corrosive (acidic or basic) solutions. Safety glasses alone may not provide adequate eye protection. Safety glasses/goggles with side shields must be worn at all times when handling corrosive solids or solutions.

2) **Safety Goggles** (ANSI Z87.1-2015 and CSA Z94.3)

3) Face protection: A faceshield along with eye protection (suggested goggles, for instance) have to be worn at all times when handling corrosive solids or solutions. **Faceshields are available for users in H-007** (Shiyu Qin agreed to lend materials during the experiment) (Picture 1).



Fig. B1. Types of face shields available in H-007 for the experiment.

4) Gloves: Always consult the manufacturer's glove selection guide when selecting gloves for working with strong corrosives. **Doubled disposable nitrile gloves** will provide good resistance to corrosive solids and solutions. If the upper gloves become contaminated with a little amount of

solution, remove them immediately and replace them with new gloves. Also, wash hands and check for any sign of contamination. Thicker (10-20 mil) heavy-duty neoprene gloves with long cuffs worn over a pair of nitrile gloves can also be used, always ensuring suitable dexterity.

- ✓ Fisherbrand™ Nitrile gloves (Palm thickness: 3.5 mils; Finger thickness: 4.7 mils).

5) Protection clothing: The handling of strongly corrosive materials requires special protection equipment in addition to the standard laboratory clothing (lab coat). A corrosive-resistant neoprene apron or a smock **MUST** be worn on top of the lab coat. **No exposed skin is allowed!** Legs should also be covered (chemically resistant suit or long pants), and closed-toed shoes/boots must also be worn.

- ✓ Fisherbrand™ Labcoat with knit cuffs

- ✓ AlphaProTech NuTech™

- ✓ Fisher Scientific™ PVC Apron

6) Safe work practices

When preparing corrosive solutions, **use the general safe rule recommending the slow addition of the corrosive to water.** Therefore, DO NOT add water to the NaOH pellets or the chlorinated derivatives ($\text{Ni}(\text{Cl})_2$, $\text{Fe}(\text{Cl})_3$, or $\text{Zn}(\text{Cl})_2$). **Instead, SLOWLY ADD** the corrosive substance in the water (a few amounts at a time) with a gentle stirring. The increasing temperatures generated by the exothermic process can be controlled with the use of a large secondary bucket containing ice or cold water.

Ensure that glassware is free from chips and cracks before use to prevent leaks of corrosive solution or breakage of glass beaker provoked by the increased temperatures.

Due to the hazardous nature of the material, only minimal quantities of material should be used.

All excess of the solution must be treated as hazardous waste by applying the following procedures.

a. Storage considerations:

Corrosive substances containers must be stored in dedicated corrosive storage cabinets (bases compartment for sodium hydroxide, acids compartment for chlorinated derivatives) in a cool, dry, well-ventilated area away from incompatible substances: strong acids, water, metals, flammable liquids, or halogenated organic chemicals.

Due to their hygroscopic properties, those chemicals must be stored under an inert atmosphere (N_2).

b. Waste considerations:

Except for de-ionized water, all the material/chemicals/mixtures described in this SOP must be disposed of as hazardous waste. The precautions preventing hazards and direct contact with those strong corrosives can be extended to disposal procedures. **It is the researcher's responsibility to make sure that dedicated liquid and solid waste containers are used, clearly labeled, identified, and left in a safe area.** Hence, the hazardous waste labels must be properly completed, displaying the full chemical name, the concentration (for the liquid waste), the hazards related to the material, and the laboratory information. Hazardous liquid waste can be contained in 4L-plastic

jugs, 10L, or 20L-plastic containers with narrow lids. Solid chemical waste, including consumables such as contaminated disposable nitrile gloves, paper towels, and Pasteur pipettes, can be disposed of in 4L-plastic containers or 20L plastic pails with wide lids. Also, the liquid waste containers must be placed in a secondary spill tray to prevent any corrosive spill directly on the floor. The containers must be stored away from incompatible materials.

Contact EHS (hazardouswaste@concordia.ca) for hazardous waste containers and waste pick-ups.

c. Spill considerations:

Only employees trained in handling strongly corrosive solutions should clean up spills.

➤ *In the event of a small (**incidental**) spill* (small volumes $\leq 100\text{mL}$ of low or high concentrations $\geq 1\text{M}$, located in a fume hood):

1. Notify personnel from the immediate area to stay away from the area.
2. Wear appropriate PPE (fully buttoned lab coat, chemical splash goggles, thick gloves (butyl, neoprene, Viton)) to clean the spill.
3. A clear general protocol aiming to ensure efficient decontamination of the equipment and spaces, including the fume hood, must be considered:

✓ *Use neutralizing material such as diluted acidic solutions to neutralize a low-concentration NaOH solution spill. Diluted forms of citric acid, $<0.5\text{M HCl}_{aq}$, or commercially available vinegar solutions can be considered to neutralize minor spills. **Even with neutralization products, heat and gas will often evolve and can cause splattering.** The use of the proper precautions (PPE, slow addition of neutralizer working from edges of spill inward) is recommended.*

✓ *Use neutralizing material such as diluted basic solutions to neutralize a spill of HCl-containing solutions. Diluted forms of sodium (bi)carbonate solutions can be considered to neutralize minor spills. **Even with neutralization products, heat and gas will often evolve and can cause splattering.** The use of the proper precautions (PPE, slow addition of neutralizer working from edges of spill inward) is recommended.*

✓ *Test with litmus paper or color-indicating solution until the spilled material is within the neutral range of pH 6-8 to ensure effective neutralization and consider safe disposal.*

4. Clean the area by absorbing the neutralized spill and spraying the area lightly with water. Discard contaminated materials in dedicated solid hazardous waste containers, displaying labels and warnings described before.

5. Advise PI/supervisor and complete an incident/near-miss report.

6. **Consider the spill as an emergency one If:**

- ✓ **You do not feel comfortable doing the clean-up,**
- ✓ **You do not have in hand the necessary equipment, such as proper PPE, neutralizing materials, absorbent pads ...**
- ✓ **The spill meets the emergency spill criteria presented below.**

➤ *In the event of a large (**emergency**) spill* (and high concentration solutions >1M) located inside or outside a chemical fume hood, the procedure for NON-HAZMAT Team Members (students, lab technicians, workers) must be:

1. Advise and warn co-workers.
2. Evacuate and secure the area immediately.
3. Restrict access to the area.
4. Do not touch the hazardous material.

5. Call Security at **ext. 3717** or **514-848-3717**, providing them with the location of the spill, the name of the hazardous material, the quantity involved, the related health risks, and precautions to be taken. Provide them Safety Data Sheet (SDS) and appropriate documentation.

6. Please wait for the arrival of the Hazmat clean-up team; remain available to provide them with details about the spill.

All work involving corrosive solutions with high concentrations outside a fume hood should require area and risk assessment prior to being performed.

d. Emergency considerations:

a) Skin Contact:

1. Remove contaminated clothing and immediately wash the affected area with large amounts of water until all evidence of the chemical has been removed (approximately 15 minutes).
2. Call Security at **3717** for emergency medical assistance.

b) Eye Contact:

1. Immediately wash the affected eye with large amounts of water until all evidence of the chemical has been removed (approximately 15 minutes).
2. Do not allow the victim to rub or keep the eyes closed.
3. Call Security at **3717** for emergency medical assistance.

c) Inhalation:

1. Immediately move the victim to fresh air.
2. Call Security at **3717** and ask for medical assistance; seek medical attention in the event of respiratory irritation, cough, or tightness in the chest. *It may be hazardous to the person providing aid to give mouth-to-mouth resuscitation when the inhaled material is toxic, infectious, or corrosive.*

In all cases of exposure, a copy of the Safety Data Sheet (SDS) of the chemical must be brought to the emergency room as the treating physician might be unaware of the treatment measures for strongly corrosive substances and related solutions. All incidents (spill or exposure) must be reported to your supervisor and Environmental Health & Safety with the completion of an injury/near-miss report.

If you have any concerns about the use of NaOH at Concordia University, please contact EHS at ehs@concordia.ca.

7) Procedure / Proposed Experiment

General: All operations are carried out in a certified fume hood with the *sash* at the lowest level for convenient *operation* towards the best protection. The fume hood and the working area must be free of any incompatible materials.

Chemical Balance Equation



Chemical amounts used:

Balanced equation (left) <i>Stoichiometry in red</i>	Molecular Weight(g/mol)	Weight (g)
<i>0.5</i> NiCl ₂ ·6H ₂ O	237.69	2.86
<i>0.5</i> ZnCl ₂	136.30	1.64
<i>2</i> FeCl ₃	162.20	7.81
<i>8</i> NaOH	39.99	7.70

Material Used for the Experiment:

1. Magnetic stirrer and stir bars
2. pH meter
3. IR Thermometer
4. Chemical beakers Pyrex (6× 600 mL and 2× 2000 mL)
5. Ring Stand
6. Weighing Scale 50 g
7. Buchner Funnel Vacuum Filter
8. Filter Paper
9. Wash/squeeze bottle 500 mL containing DI Water
10. Chemical spatula
11. Plastic spoons are used after filtration to keep in a glass box.
12. Vials with closed lids
13. *PPE worn throughout the entirety of the procedure*

Co-Precipitation step:

During that step, PPE described above must be worn at all times. All the described processes (weighing, chemical handling, reaction setup, mixing ...) must be performed inside a certified fume hood.

NOTE: This procedure could be revised and adapted in the event the magnetic stirrer is not suitable with synthesized magnetic nano-ferrites.

1. All the beakers are cleaned with de-ionized water and dried using provided special paper towels at Lab H-007.

2. Based on the balanced equations, the amount of each chlorinated derivative is weighed separately in a vial with the help of a 50 g weighing scale (placed inside the fume hood). Typically, one beaker equipped with a stir bar is placed on top of the magnetic stirrer on which an ice-bath is already installed. 100 mL of deionized water is added inside the cold beaker, and the chlorinated chemical is slowly and carefully poured down to prevent exothermic reactions. Gentle but constant stirring is maintained during the addition to safely dissipate heat, paying attention to the formation of splashes. The chlorinated derivatives ($\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, FeCl_3 , or ZnCl_2) are used to form the acidic solutions where the amounts are 2.86g, 7.81g, and 1.64g, respectively.

At first, $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ is added to a 2L beaker containing 100 mL of deionized water while stirring it with a stir bar using the magnetic stirrer at a constant speed of 1500 RPM. The procedure is repeated with the two other chlorinated congeners (FeCl_3 and ZnCl_2) in two distinct 600 mL beakers to yield three acidic solutions. For identification purposes, chemical names were written on the beakers' external walls with markers. The regular spatula should be used to take out chemicals from the bottles and cleaned after each use to prevent corrosion. It is worth mentioning that while one acidic solution is stirring on top of the magnetic stirrer, the beakers accommodating the two other acidic solutions are safely kept in a clean part of the fume hood.

3. The pH of each acidic solution is checked with the help of a pH-meter (*pH Meter Digital Water Quality Tester, Testing Range 0.00-14.00 Ph Great for Household Drinking, Pool and Aquarium High Accuracy Pen Type PH Tester Digital for Water*) and registered.

4. The required amount of NaOH pellets (7.70g) is carefully weighed under the fume hood directly inside the vial (it must be quickly capped after measurement to prevent air moisture). One 600 mL beaker equipped with a stir bar is placed on top of the magnetic stirrer on which an ice-bath is already installed. 100 mL of deionized water is added inside the cold beaker, and the NaOH is slowly and carefully poured down to prevent exothermic reactions. The vial must be closed after each addition as sodium hydroxide's hygroscopic properties tend to liquefy the chemical. A gentle but constant stirring is maintained during the addition to safely dissipate heat, paying attention to the formation of splashes. The pH of the resulting NaOH solution (approx. 1.9M) is checked with the help of the pH-meter and registered.

5. **Once the dissolutions are completed, the large beaker is installed in an ice bath on top of the magnetic stirrer. During the following transfer processes, the stir bars are blocked in the original beaker by applying the long magnetic bar retriever along the external walls of the beakers.**

The two (2) other acidic solutions are then poured sequentially, one after the other, and slowly inside the 2L beaker. Subsequently, NaOH solution is slowly added by carefully pouring down small portions (approx. 5-10 mL/addition; 10 additions over a 50 min. period) inside the 2L beaker in a sequential procedure (e.g., addition every 5 minutes, after having checked the temperature of the solution with the IR-thermometer) applying a constant magnetic stirring. After 30 min.,² the expected ferrite powders are at the bottom of the beaker, and the mixture is stirred for another hour at room temperature. Concordia University's [Unattended Experiment Form](#) duly completed must be affixed to the fume hood's sash during the whole process [174].

Modifications of the present SOP will have to be done if higher temperatures are involved during the process. EHS must be contacted to adapt the present SOP.

6. *While ferrite nanopowders are forming, used beakers and stir bars are cleaned using first de-ionized water (3x 100mL cycles). The combined acidic rinsates must be disposed of in hazardous waste containers (4L, 10L, or 20L for liquids) provided by EHS and properly identified (e.g., "Aqueous solutions containing traces of iron chloride, zinc chloride, nickel chloride – CORROSIVE (acid) and TOXIC").*

². In the literature, some works report 30 min, 1h, even 12h stirring with the magnetic stirrer. In others, procedures involving heat around 70-150° C are applied [132]-[136].

The NaOH solution's rinsates must be segregated from acidic rinsates. 4L, 10L, or 20L Hazwaste containers provided by EHS must also be used and properly identified (e.g., Aqueous solution containing traces of sodium hydroxide – CORROSIVE).

Please ensure the continuous HazWaste containers' availability and make a request at hazardouswaste@concordia.ca when needed.

7. After 24 hours, the clear supernatant is very carefully discarded in a container by tilting the beaker and maintaining the stir bar with the help of a magnetic retriever applied to the external walls of the beaker. No ferrite nanoparticles should be lost during the transfer, even if small amounts of supernatant must remain in the reaction beaker. 500 mL of DI water is then added, and the magnetic stirring is resumed. The supernatant is changed daily for six (6) other days before the filtration process. This week-long-process will ensure a high saturation magnetization of the final material.

The multiple discarded supernatants must be accommodated in EHS liquid waste containers (4L or 10L) properly identified as “Aqueous solutions containing traces of iron chloride, zinc chloride, nickel chloride, sodium hydroxide, and ferrite nanoparticles – CORROSIVE and TOXIC). Those wastes should not be mixed with the ones generated in Step 6.

Filtration step:

During that step, PPE described above must be worn at all times. The entirety of the filtration procedure must be performed inside a certified fume hood.

1. After seven days of purifying the solution by changing the deionized water, the filtration process is performed. The obtained suspension of ferrite Nano-powders in water is finally filtrated using a vacuum filtration set. The system includes a Büchner funnel top equipped with filter paper (with suitable dimensions), a 1 or 2L-filtration (collecting) flask, a silicone/rubber stopper, and proper tubing to connect the setup to a vacuum pump. The setup is safely held to a stand retort (or fume hood scaffold) with the help of a clamp.³

2. The filtration is performed by pouring down the mixture very slowly into the funnel top while the vacuum pump is on. The beaker is rinsed with DI water (2× 50 mL) to ensure all the

³. A video of the filtration procedure (with a water-induced vacuum system):
<https://www.youtube.com/watch?v=U3a8mzJIKq8> (consulted on March 17, 2022).

material is inside the funnel top. Once the first cycle is done, **slowly** disconnect the tubing from the collecting flask, slowly remove the Büchner funnel from it and discard the rinses in the suitable hazardous waste container used to accommodate waste generated in Step 7. Once emptied, the collecting flask is re-installed under the Büchner funnel, and the tubing is reconnected (vacuum pump on) to ensure a more efficient drying process of the desired ferrite Nano-powder. Once the paste is considered dry enough, the tubing is slowly disconnected from the collecting flask, and the vacuum system is switched off. The Büchner funnel equipped with the filter paper is carefully removed from the collecting flask, and the magnetic solid is very gently transferred into a suitable resistant (chemically compatible with the nanoparticles) box with the help of a plastic spatula/spoon.

Heating and Baking Ferrite Nano-powders:

The procedures described below will not be performed in Concordia laboratories. Other facilities with suitable expertise in heating processes, X-Ray diffraction, emu/g calculations, and SEM analyses will be requested.

The next step is to bake/heat the powder at 1000° C temperature. In the literature, some experiments were done at 500-1200°C. The best performance is observed at 1000-1100° C temperature while baking it for 4 hours [136]-[137].

The ferrite paste/powder shipment will require EHS assistance as *Transportation of Dangerous Goods* regulations may apply (e.g., 1.19.1 TEST SAMPLES Exemption).

Getting the Magnetic Properties of the Ferrite Powder:

1. After getting the dry powder, the next step will allow investigations of the material's magnetic and structural properties. The ferrite powder must be verified using x-ray diffraction (XRD), which uses $\text{CuK}\alpha$ radiation. The size and morphology of the nanoparticles were characterized using scanning electron microscopy (SEM). From the energy-dispersive X-ray spectra (EDAX), the synthesized ferrite particle's elemental composition is mainly determined from the co-precipitation process, where we have mixed the chlorides with NaOH.

2. The next step will be to check the saturation magnetization value of the nanomaterial (M_s in emu/g). The composition is expected to give us a higher saturation magnetization. Higher saturation magnetization means it can support high-frequency applications. The saturation magnetization is measured using a vibration sample magnetometer (VSM), providing EMU results. Before inserting the powder in the VSM, it is required to weigh it in grams. Thus, the emu/g can be calculated by dividing the emu by the weight of the powder inserted. A certification of the results in EMU is shown on the next page. We aim to work beyond the 30 GHz frequency range, where a higher magnetization will be essential.

Making Ferrite Disks Using Hydraulic Press Machine:

After testing the powders, the next step is to find the right pellet to put the powders. A hydraulic press machine will be required to make the disk; a minimum of 2.5 tons is needed. The hydraulic press machine that was used for this work was purchased from Pike Technologies. Two available pellets, 3 and 7 mm, were purchased along with the hydraulic press machine for fabricating the disk.



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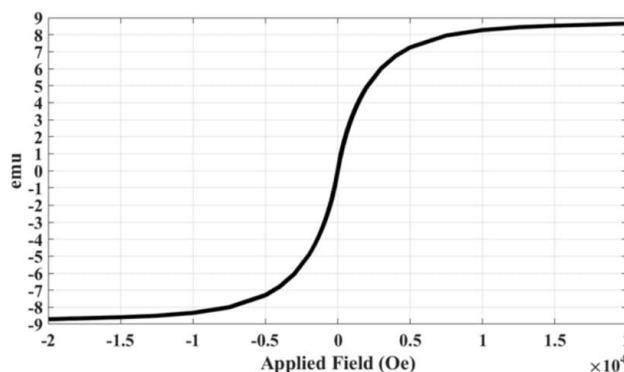
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École affiliée à
l'Université de Montréal

January 27, 2023

Vibrating Sample Magnetometry (VSM) at Polytechnique Montreal

This is to acknowledge that we performed several magnetometric measurements (hysteresis curves) on ferrite powders for M. Syed Sifat, student at Concordia University in Montreal. The measurements have been performed using our Vibrating Sample Magnetometer (VSM), Model EV9 from Microsense (formally ADE Technologies). The instrument provides a magnetic field of ± 2 T (or ± 20 kOe) and measures a magnetic moment with a resolution around 10^{-6} emu. An example of an hysteresis curve measured on the Concordia's ferrite samples is shown below.



The sample consisted of 59 mg of powder, which we were told is Ni-Zn ferrite. Every measurement session starts with a calibration of the moment scale using a calibration sample from NIST.

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- **S. M. Sifat**, M. M. M. Ali, S. I. Shams, and A. Sebak, "High Gain Bow-Tie Slot Antenna Array Loaded With Grooves Based on Printed Ridge Gap Waveguide Technology," *IEEE Access*, vol. 7, Mar. 2019.

Under Review Articles:

- **S. M. Sifat**, M. M. M. Ali, S. I. Shams, M. Elsaadany, and A. A. Kishk, "Beyond Magnetic Limits: Unveiling the Remarkable Magnetization of Ferrite Disk for Cutting-Edge Millimeter-wave Application," *Nature Materials*, 2023.

Patents

- **S. M. Sifat**, S. I. Shams, M. M. M. Ali, M. Elsaadany, and A. A. Kishk "Fabrication of Millimeter-wave High Magnetization Ferrite Disk Based on Nickel-Zinc Composition Using Chemical Co-Precipitation Method," *US Patent*, 2023. (Pending)

International Conferences and Symposiums

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