Design, Analysis and Implementation of wide-band antenna for IBFD Applications

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Dedication

I dedicate this work to my Family, my supervisor, Dr. Nosherwan Shoaib and to all those who have helped me throughout my thesis

.

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Abstract

This research work is conducted to design and analyze a novel antenna for In band full duplex communication. A metamaterial-based microstrip patch antenna is designed for wideband operation in IBFD systems. The design incorporates electromagnetic band-gap structures for improved isolation and bandwidth enhancement. Detailed mathematical modeling and full-wave simulation techniques are employed to optimize the antenna's performance. Designed antenna in the 4.9 GHz to 6.4 GHz range, with a focus on achieving high isolation (over 40 dB).Peak isolation is 55 dB and increased up to 67 dB with rat race coupler. Grid slotted patch antenna and thick substrate reduces the surface wave coupling and enhances the isolation. T structure feeds also enhances the DC isolation due to gap between the structure and radiating element. The simulation results show excellent isolation and impedance matching across the target frequency band.

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Chapter # 1.

Introduction

This chapter includes the introduction to Different types of communication, in band full duplex communication, advantages of in band full duplex communication, Objective of the presented research work, challenges in realization of in band full duplex systems, challenges in realization of microstrip antenna for wide band applications, and applications.

1.1. Types of Communication System:

Spectral Efficiency and channel throughput are two most significant parameters of communication systems. Spectral efficiency is data rate over a specified frequency range and channel throughput can be defined as the transmission rate of communication cannel. Both parameters are critical considerations in designing and optimizing communication systems. Based on the utilization of channel bandwidth, Communication is classified into three types explained below:

2.1.1 Simplex Communication:

In simplex communication, transmission is unidirectional. There is no way for feedback or contact to go back and forth. This simple way of saying things is often used when talking to someone is either not possible or not required. When radio and TV broadcasters want to get information to people without a direct feedback system, they often use single communication. A few examples of simplex communication include radio broadcasting and television broadcasting[1]

2.2.1 Half Duplex Communication:

Half-duplex communication can send and receive data in both directions, but it can only be used in one direction at a time. This is a type of two-way information-sharing method. In this method, entries take turns being the sender and the receiver. This makes sure that data is always sent from one end to the other. Because of the way this mode works, you need a sequential transmission technique to send data in this mode[2]. A few examples of half-duplex communication include intercom and two-way radio communication such as walkie-talkie and VHF radios.

2.3.1 Full Duplex Communication

Full-duplex communication allows data flow in both ways at the same time and in real-time, which makes bidirectional communication easier. This method makes conversation more efficient by allowing users to share and receive data on the same route. Frequency division duplex (FDD) and time division duplex (TDD) are the two main types of full-duplex transmission that are needed for many technologies. With FDD, communication, and reception can happen at the same time without any problems because each side of the chat uses its frequency band. Time-division multiplexing, or TDD, sends and receives data over a single frequency band with distinct time slots. In this way, time can be split up so that there is room for two-way communication. These methods, which are adapted to specific working needs and band conditions, are used by all modern communication networks[3].

Figure no 1[4] explains the three communication types. The arrows (a), (b), and (c) on these three graphs show three different ways that Users A and B can communicate to each other over time, based on the direction of the data flow. Time is presented horizontally in the simplex system (a), and data only moves from User A to User B. This is a one-way communication system. As per figure there is no data flow from person B to User A, it is illustrated that there is only transmission is unidirectional. The properties refer to a simplex communication system. The second image, Half-Duplex System (b), shows a system that allows data transmission between User A and User B, but not at the same time. the data transfers from User B to User A and then back to User B to User A in different time slots. The transmission process is completed with delay. The third picture is a Full-Duplex System. In this system, both User A and User B can transmit and receive data at the same time. In a full-duplex system, both users can give and receive data at the same time. This allows the data flow without any delays. The time is shown on the horizontal side of each figure. The contact events are shown by the dots, and the direction of the data flow is shown by the lines.

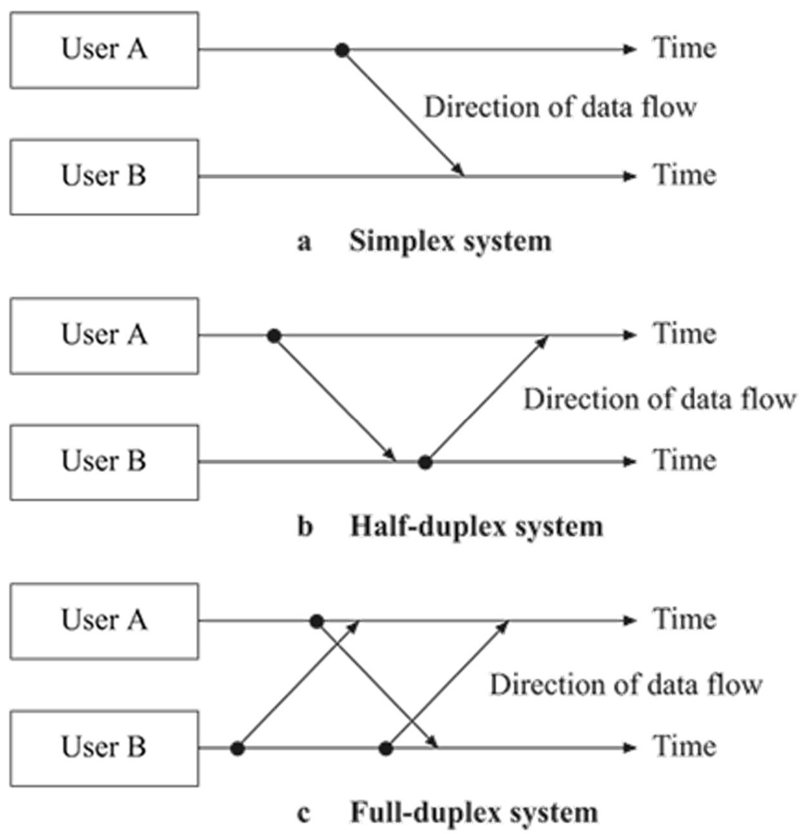

Figure 1.1-1 Types of Communication Systems

1.2. In-Band Full Duplex Communication:

A special type of full duplex communication is in-band full duplex communication that is area of interest of this publication. A technological advancement is in-band full-duplex (IBFD) communication. It allows for bidirectional data transfer on a single frequency band, eliminating the need for specific time slots or bands where devices may simultaneously send and receive data. In band full duplex communication devices are contributing a lot in the communications industry by ensuring the effective spectrum utilization. In band full duplex communication is playing significant role for systems that need a lot of bandwidth, like 5G new radio, because it makes it possible to use spectrum resources more effectively. This new technology is resolving the problems of half-duplex systems by making the system capable of sending and receiving the signal within the same frequency range can at the same time. But on the other hand, complex techniques for getting rid of self-interference are necessary for IBFD communication to work well. These steps are very important to lower the adverse effects of radio noise, which can affect the reception performance and make the communication link less reliable. This is essential to prevent receiver saturation and ensure optimal performance[5].

1.3. Challenges In realization of in-band full duplex communication

In band full-duplex communication is requirement of most of the systems due to its advantages. But realization of most efficient in-band full duplex communication system is a challenging task. The key challenge is mitigation of self-interference. Aforementioned challenge is a critical issue that can affect the transmission and reception process. Signal processing algorithm and advanced hardware designs plays significant role in cancelling the self-interference. SIC can facilitate the users to transmit and receive in same band without any interruption[6].

In in band full duplex system transmission and receiver are co-located. Transmitted power is more than that of the received signal. This problem can degrade the reception performance. the strong transmitted signal can saturate the receive that affects its performance. A level of isolation between the transmitter and receiver ports are required to achieve best results.

The promise of doubled spectral efficiency and reduced latency cannot be realized if the self-interference is not mitigated in in band full duplex communication systems. Self-interference changes with the environment, and variations in signal strength. Therefore, the IBFD system must continuously adapt to environmental variations to effectively cancel out the interference. Effective self-interference cancellation different techniques that are address in next few chapters

1.4. Advantages of In band Full Duplex Communication:

These IBFD is considered as a feasible and efficient technology for the future of wireless communications because it has offered many benefits including better speed, user experience, and economy. There are several advantages of IBFD communication systems. Few of them are listed below[7].

1. IBFD communication technology is offering double spectral efficiency by simultaneous transmit and receive operation on the same frequency band. Aforementioned system capability is not achievable by using traditional half duplex systems.

2. By enabling simultaneous sending and receiving of data, IBFD technology reduces latency.This improvement is plays major role for real-time applications including autonomous driving as well as telemedicine. Reduced latency is required in such systems to get immediate response in emergency situations

3. Enhance network capacity is another advantage of IBFD technology. Utilization of same bandwidth for data traffic enhances the network potential. That is considered to be a most significant aspect for heavy data applications.

4. Utilization of additional frequency band is also avoided by using the IBFD technology. Technology aims to provide the transmission in same band. This makes the system effective in terms of cost.

5. Because IBFD has a faster data transfer rate and less delay, users have a smoother and more efficient experience, especially when they are watching videos or playing games online.

1.5. Application of in band full duplex communication system:

Traditional half-duplex systems are being replaced by in band full duplex systems due to improved spectral efficiency and channel throughput. However, mitigation of self-interference is still a challenging task[8]. Few applications of in band full duplex in communication sectors are listed below:

1.5.1. Continuous wave radar:

Continuous wave radar requires the simultaneous transmission and reception process for target detection. Self-interference in radar domain is known as transmission leakage. A high isolation level is required between transmission and receiver end to avoid transmission leakage that can affect received signal. In case of bistatic systems, this is achieved by physical separation and integration of metamaterials. In case of monostatic systems, SIC is implemented by antenna designing and feeding mechanism.

1.5.2. Full Duplex Relaying (FDR) Systems:

Traditional relay systems uses half duplex mode with frequency or time domain multiplexing. In case of full duplex relaying, system is capable of simultaneous receive and transmit operation. In band full duplex communication systems can perform relaying by decoupling the incoming and outgoing links[2].

1.5.3. Other Wireless Systems:

Satellite communications, wireless LANs, and cellular networks are the domains that are using In-Band Full-Duplex (IBFD) technologies. The technology aims to make telecommunication sector much more productive and able to handle more work. In our linked world, the need for fast wireless communication is growing

Different research work has been conducted that aim to devise techniques for reducing the self-interference in monostatic and bistatic systems. Main goal of researchers is to focus advancing fifth-generation (5G) New Radio (NR) systems[9]. The key goal is efficient spectrum utilization. Enhanced spectral efficiency and channel throughput ensures the

1.6. Realization of Patch Antenna for wide band IBFD communication:

The realization of microstrip patch antennas for wideband in-band full-duplex (IBFD) communication faces several challenges. The main challenge is bandwidth limitation due to surface waves. Surface waves are electromagnetic waves that propagate along the surface of the dielectric substrate beneath the patch antenna. Emission of these waves reduces the bandwidth of antenna. This may also cause end fire radiation and higher cross polarization levels[10] .

When these surface waves are excited, higher modes are introduced that effects the bandwidth of antenna, due to surface waves, antenna operational bandwidth is divided into multiple narrow bands. Bandwidth enhancement without affecting the antenna performance is a challenging task. Surface waves can excite higher-order modes in the microstrip patch antenna. Figure no 2 is illustration of the propagation of electromagnetic waves in a microstrip patch antenna, highlighting two primary types of radiation: space-wave radiation and surface wave[11]

A. Space-Wave Radiation are the desired radiation for antenna operation, which propagates space. It is depicted with blue vertical arrows emerging upwards from the top of the antenna structure.
B. .Lateral Radiation are Indicated with red horizontal arrows on both sides of the antenna structure, lateral radiation is typically considered an undesired effect. It represents the electromagnetic energy radiating off the edges of the antenna, which can lead to efficiency losses and undesired interference.
C. Surface Wave are Represented by green wavy lines within the substrate of the antenna (the grey area between the top and bottom layers),.These are generally undesired as they can cause energy losses and affect the radiation pattern of the antenna.surface waves are also major cause of bandwidth reduction.

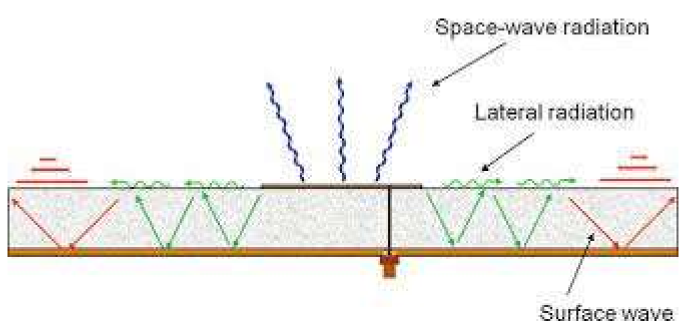

Figure 1.6-1 Different Types of waves

In case of different antenna architecture, element coupling between Tx and Rx antennas is a key challenge. However, for single antenna architecture achieving highest level of isolation between the transmitting and receiving ports of the antenna is required to mitigate self-interference. Designing multiport antennas to ensure this isolation without compromising the performance parameters of antenna is a complex task.

To overcome above mentioned challenges, advanced design techniques that includes multiple resonant elements, employing metamaterials, or integrating active components for impedance matching are mentioned in previous research work.

1.7. Thesis Objectives

The objective of this work is to design a wide band in band full duplex antenna system with single antenna configuration with improved isolation. The design is offering a high self-interference cancellation level in wide band. Aim of the design is to design a electromagnetic band gap three port antenna that ensures the higher isolation in wider band. Key objectives of the designed systems are listed below

- To design electromagnetic band gap antenna that operated in 4.9GHz to 6.4 GHz.
- To ensure the isolation over the band more than 40 dB and peak isolation up to 53 dB
- To achieve polarization diversity by implementing the Differential feed network

1.8. Significance of this research

The advantages of given thesis will be:

- High inter-port isolation
- Wide bandwidth
- Cost-effective in terms of fabrication

Moreover, this thesis project is relevant to national needs and can be utilized in following domains:

- C band radars
- 5G NR

1.9. Thesis Organization:

The organization of this dissertation is as follow:

- Chapter no 1 is introductory chapter that describes the in band full duplex systems, challenges, realization of microstrip patch antenna for specified operation

- Chapter no 2 is literature review that provides detailed review on architecture of IBFD system, on SIC techniques on architectural level in IBFD systems, Bandwidth enhancement techniques, previously implemented isolation enhancement techniques for IBFD systems particularly in propagation domain.
- Chapter no 3 is methodology that focuses on the design procedure an d simulation results
- Chapter no 4 provides the fabrication details and measurement of designed structure

Chapter # 2.

Literature Review

This chapter presents a detailed review on Architecture of IBFD system, SIC techniques on architectural level in IBFD systems, Bandwidth enhancement techniques, previously implemented isolation enhancement techniques for IBFD systems particularly in propagation domain.

2.1. Background

In the present era, advancement in wireless communication is observed by implementation of in band full duplex technology. The key objective of researchers is efficient utilization of spectrum and doubling the channel throughput. Several advantages of the technology encourage the researchers and innovators to introduce the technology in latest wireless communication systems[12].

2.2. Architecture of IBFD systems

IBFD system can be categorized in three domains based on the architecture as depicted in figure no 4. Three domains are named as analog, digital, and propagation domains. The key challenge is self-interference, that contribute in performance deterioration at each stage. Self-interference in transceiver domains — analog, digital, and propagation — are caused because of various factors. Each domain has its own distinct challenges[12].

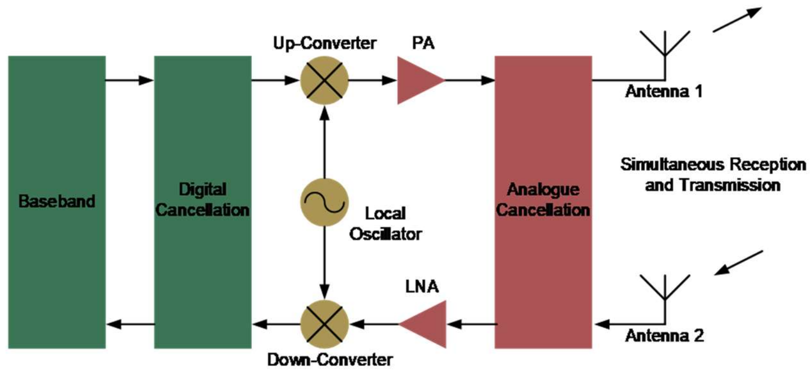

Figure 2.2-1 IBFD Architecture

2.2.1. Digital Domain:

In digital domain, advancements with respect ot in band full duplex technology are also observed. Digital signal processing handle modulation and demodulation through mathematical algorithms. Major process that casue Self interference are listed below

- Symbol Interference: In digital systems, symbol interference, also known as Inter Symbol Interference (ISI), occurs when symbols merge together that leads to errors in decoding.
- Quantization Noise arises from the quantization process in analog-to-digital conversion (ADC), that is considered as self-interference. it can also affect the performance of system
- Clock Jitter: Variability in timing (jitter) of the digital clock can cause errors in timing of the signal processing, leading to degradation of the signal.

2.2.2. Analog Domain

In the analog domain, transceivers chain consists up of oscillators, mixers, amplifiers, and filters. These components perform modulation and demodulation of signals for conversion between radio frequencies and baseband. Factors affecting the performance in analog domain are listed below

- Non-linearities are introduced due to analog components such as amplifiers or mixers. These devices may operate in non-linear regions in case of high-power conditions. This can generate harmonics as well as intermodulation distortion. Non linearities are also referred as forms of self-interference.

- Oscillator Phase Noise is also major cause of self-interference. Oscillators used in frequency synthesis can contribute to phase noise.
- Impedance Mismatches in impedance can lead to reflections of the signal within the circuit, causing interference with the original signal.

2.2.3. Propagation domain

In the propagation domain, antenna radiation travels through different types of mediums. Primary purpose of antenna is to radiate and receive electromagnetic waves. Four important properties of transmission are refraction, diffraction, attenuation, and reflection. If you understand these processes well, you can place and optimize antennas in a way that improves both signal transfer and receiving while also making interference with the main signal stronger.

- Multipath Propagation: Because signals reflect, a phenomenon known as multipath transmission can happen. This is when multiple copies of the signal reach the receiver at different times. Interference occurs due to this desired or undesired propagations
- Doppler Shift: Relative movement between the transmitter, receiver, or environment can cause a frequency shift in the signal, leading to interference.
- Antenna Radiation Pattern: Imperfections in the antenna design or placement can lead to unintended radiation patterns, causing self-interference.

Self-interference mitigation techniques can be deployed at each transceiver stage to ensure optimal performance of the receiver. Some of the SIC techniques are tabulated below[13]:

Table 1 SIC Techniques in Three Domain

Digital domain	Analog domain	Propagation domain
• Digital Beam Forming • Advance Signal Filtering • Adaptive Equalizers • Error Correction coding • Machine Learning	• RF Cancellation[14] • Adaptive analog Cancellation[15]	• Antenna Design and Antenna Placement • Separation between radiating elements • Polarization diversity • Phase control

		• Integration of coupling elements • Surface Treatment • Circulators

2.3.Bandwidth Enhancement Techniques:

Implementation of IBFD systems for wideband applications is the key goal of this publication. As it is explained earlier that realization of patch antennas for wide band applications is a challenging task due to emission of surface waves. However, suppression of surface waves can enhance the bandwidth of antenna. Few bandwidth enhancement techniques are tabulated below[16]:

Table 2 : Bandwidth Enhancement Techniques

Technique	Description
Substrate with High dielectric material	Surface wave are confined closer to copper patch and reduced emission results in less fringing effect. This enhances the bandwidth of system
Photonic band Gap (PBG)	PBG filters the surface waves and allow propagation is specified band
Electromagnetic band gap (EBG)	EBG also reduces the fringing effect due to discontinuity in the systems
Defected Ground Structure	DGS is implemented by designing discontinuities in ground plane. This can also suppress the surface waves
Use of parasitic elements	Parasitic elements can absorb the surface waves.
Slotted Patch antenna	Slots in patch antenna adds meta-material properties to the structure. discontinues act as parasitic capacitance and enhance the bandwidth and isolation of design

Different feeding mechanism	Feeding techniques also affect the bandwidth of the systems. Aperture coupling and EM coupling can enhance the bandwidth of the system

This research work utilizes the Slotted patch antenna technique and mentioned feed mechanism to ensure targeted isolation and bandwidth.

2.4.Previously Implemented Antennas for IBFD applications:

Researchers aim to implement self-interference cancellation techniques in propagation domain n Some previously implemented antennas for IBFD application are mentioned in this section. In this domain, there are two types of architecture, Single antenna and multiple antenna architecture.

R.Hafezifard et.al , Presented a novel antenna design in 2015. It discusses a Bistatic Multilayered Passive Self-Interference Cancellation (SIC) device with Defected Ground Structure (DGS), Figure illustrate the antenna design . figure no reveals that the designed structure is operating at 5.4 GHz with a bandwidth of 790 MHz and peak isolation of 46 dB. Maximum reported gain of this work is 6.5 dB. SIC is achieved by placing EBG structure between radiating elements[17]

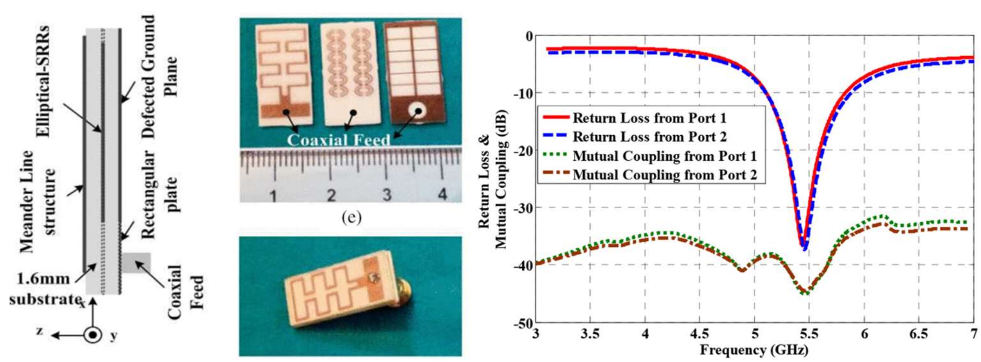

Figure 2.4-1 Bistatic device with Defected Ground Structure

A compact proximity fed monostatic patch antennas is presented in figure. H.Nawaz et-al, proposed this design in 2020.the figure illustrates the proposed design operates at 2.4 GHz with the Bandwidth of 90 MHz. the isolation of the proposed design is more than 60 dB over the operating band.peak isolation is 87 dB and gain of the proposed desin is 4.5 dB[18]

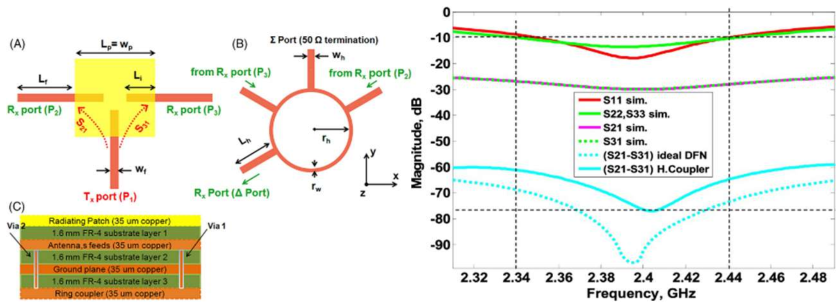

Figure 2.4-2 Compact Proximity feed Antenna

Another Publication by Dr. Haq Nawaz presented a dual polarized slot coupled mono static patch antenna. A dual-polarized, slot-coupled monostatic antenna designed for high isolation is shownin figure. The results reveals that the design offers a 45Mhz of bandwidth and isolation, with an emphasis on minimizing interference (95 dB isolation). Differntial feed network is applied to implement SIC[19].

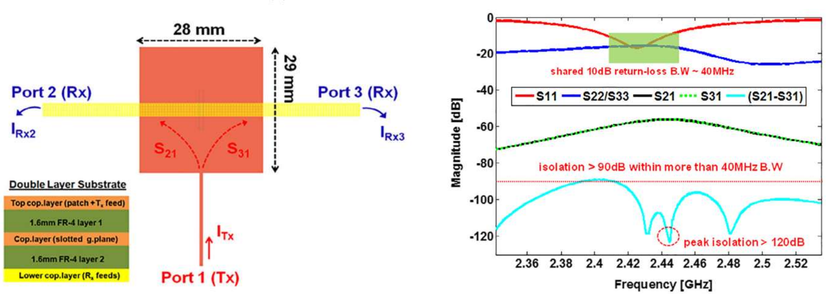

Figure 2.4-3 Dual Polarized Slot Coupled Antenna

A compact, bistatic antenna system, also a Patch-Multiple Antenna, provides even higher isolation (105 dB), suitable for applications where minimizing signal crossover is critical, though with slightly reduced bandwidth. Bandwidth is 105 MHz. The antenna shown in fig is based on two closely spaced radiator and a 3dB rat race coupler for DFN at receiver end. Figure reveals that the interport isolation is 90 dB and 95 dB within the bandwidth o 60 Mhz and 40 Mhz repectively[20].

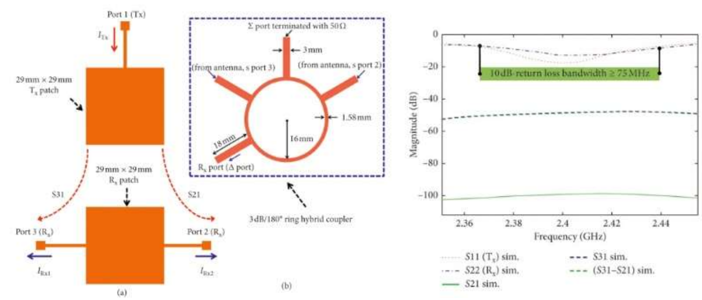

Figure 2.4-4 Compact bistatic Antenna

A stacked patch antenna as shown in figure 5, categorized as a Patch Antenna Shared. Fig reveals that antenna resonate at 2.45 GHz with a wider impedance bandwidth (100 MHz), with a notable high interport isolation equals to 88 dB, beneficial for versatile communication needs[21].

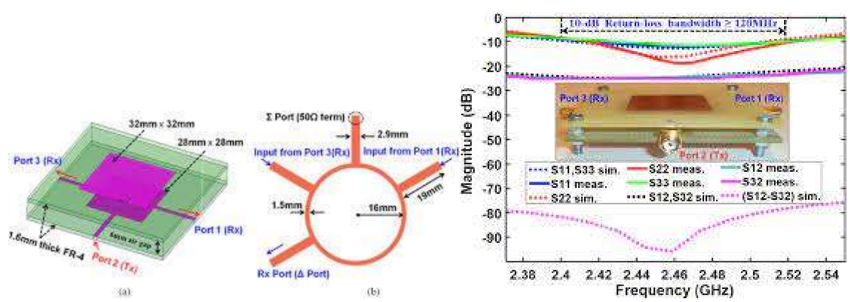

Figure 2.4-5 Stacked Patch Antenna

Yu-Zhong et.al conducted research work on wideband co-polarized stacked patch antenna. Antenna operates from 3.23 to 4.26 GHz but isolation level is low up to 20 dB[22].

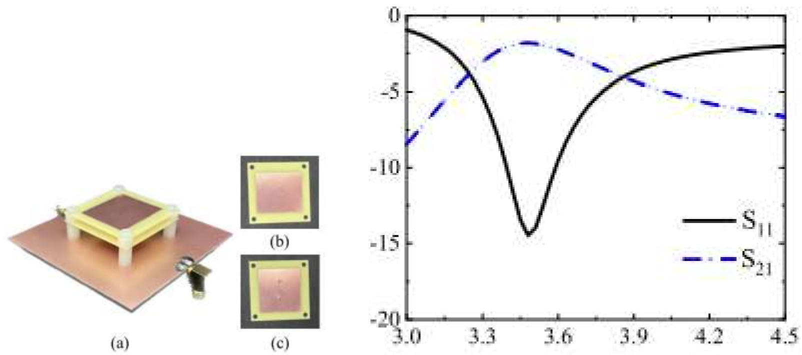

Figure 2.4-6 Wide-Band co-polarized Stacked Antenna

In 2023,another conducted researchwork presented a dual layer Metamaterial antenna that offers high isolation up to 49.5 dB but the bandwidth is 250 MHz.[23].

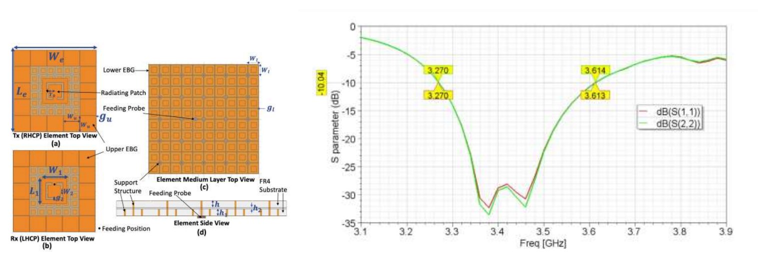

Figure 2.4-7 Metamaterial array

Literature Review Table

Table 3: Literature Review Table

Ref no	Technique	Antenna Type	BW MHz	Isolation (dB)	Remarks
[17]	Mutual Coupling Reduction for Two Closely Spaced Meander Line Antennas Using Metamaterial Substrate	Bistatic Multilayered Passive SIC with DGS	130	54	Lower BW and isolation
[18]	High isolation, proximity-fed monostatic patch antennas with integrated self-interference cancellation-taps for ISM band full duplex applications	Patch Antenna Shared	100	74	Lower bandwidth
[19]	Dual polarized, slot coupled monostatic antenna with high isolation for 2.4 GHz full duplex applications	Patch- Shared Antenna	45	95	Lower Bandwidth higher Isolation
[20]	A Compact, Bistatic Antenna System with Very High Interport Isolation for 2.4 GHz In-Band Full Duplex Applications	Patch-Multiple Antenna	60	105	Lower Bandwidth Higher Isolation
[21]	Stacked patch antenna with wider impedance bandwidth and high interport isolation for 2.4 GHz IBFD transceiver	Patch Antenna Shared	100	88	Lower Bandwidth
[22]	Wideband Co-Polarized Stacked Patch Antenna for In-Band Full-Duplex Application	Patch Antenna Shared	1030	20	Higher Bandwidth Low Isolation
[22]	Dual-Layer Metamaterial Rectangular Antenna Arrays for In-Band Full-Duplex Massive MIMO	electromagnetic bandgap slotted circularly polarized patch	250	49.5	Better Isolation Lower Bandwidth Polarization diversity is used

Characteristics of previously implemented antennas for in band full duplex communication are tabulated in table no 3. It can be seen that the rat race coupler can be used as self-interference cancelation. It is observed that wide band and high isolation is a challenging task.

Chapter # 3.

Design Procedure

This chapter provides design and simulation details of the proposed three-port metamaterial antenna which deployed. The proposed antenna provides polarization diversity. In this chapter, design reviews based on fabrication challenges are also discussed, and simulated results are provided.

3.1.1. Introduction:

A stepwise methodology has been adopted to design the system to cancel SI in propagation domain. The aim of the conducted research work is to design a monostatic In-band full-duplex antenna with excellent isolation in the propagation domain. The design utilized the polarization diversity as well as high impedance surface technique to achieve wider bandwidth and enhanced isolation. In the realm of IBFD Transceivers featuring a single antenna architecture, numerous reported antenna systems employ polarization diversity coupled with Self-Interference (SI) cancellation techniques for decoupling the transmit and receive ports. Diverging from these conventional designs, this section introduces a novel dual-port, linear co-polarized single microstrip patch antenna. This antenna utilizes a three-port microstrip patch design, integrated with a 3-dB Ring Hybrid Coupler acting as the Self-Interference Cancellation (SIC) circuit, thereby achieving superior inter-port isolation.

3.2.Antenna Design and Feeding Mechanism

In proposed design, the Electromagnetic gap patch antenna is aperture-coupled. Dual polarization is achieved through differential excitation of two side ports using a ring hybrid coupler. Two sides of the patch antenna are excited by two T-shaped Microstrip lines through EM coupling. The antenna is designed on the RO4003 substrate the stack-up details of the substrate can be depicted in figure no. Based on the stack up detail design analysis can be divided into to following sections:

- Top side: The top side of the design consists of radiated EBG patches and two MS-T ports.
- Middle Layer: Ground plane with a slot for aperture coupling
- Bottom layer: Feed line for Tx port

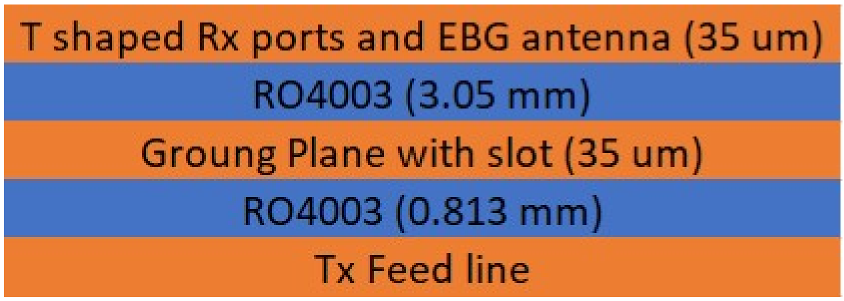

Figure 3.2-1: Stacked layer Details

Ports arrangement contributes in isolation enhancement by reducing the direct coupling. Thick substrate also reduces the surface wave coupling. EM coupled T shaped ports also offers DC isolation for next stages in transceiver. Polarization diversity is also achieved due to port positions.

3.2.1. Mathematical Modelling of Metamaterial Antenna

The proposed metamaterial-based grid-slotted patch antenna is shown in Fig. 1. This antenna consists of a three-layer structure with upper and lower dielectric substrates made of Rogers RO4003C material. The substrates have a relative permittivity of 3.38, a loss tangent of 0.0027, and thicknesses h and h0. The design features a rectangular microstrip patch (dimensions $Lp \times Wp$) on the top layer of the upper substrate (dimensions $GL \times GW$). This patch is characterized by a uniform grid of slots, with varying numbers and widths in different directions: (nx, gx) and (ny, gy) for resonant and non-resonant directions respectively. The grid-slotted patch can be seen as a two-dimensional periodic structure, composed of capacitor-loaded patch unit cells. The specifics of this structure include numbers, periods, and patch widths of (mx, px, wx) and (my, py, wy) along the x- and y-axes. The relationships between these parameters are defined as $mx = nx + 1$, $my = ny + 1$, $px = wx + gx$, $py = wy + gy$, $Lp = mxpx - gx$, and $Wp = mypy - gy$.Finally, the antenna is center-fed by a 50-Ω microstrip line through an aperture cut in the ground plane, with the slot number nx being odd to align the coupling aperture to the center grid slot.

Table 4: Parameter values

Lp (mm)	Wp(mm)	Ls(mm)	Ws(mm)	nx	ny	W_feed(mm)	gx(mm)	gy(mm)
39	39	59	84	4	4	2.3	1	1

$$\beta_u p_x/\pi = \frac{1-2\beta_e \Delta/\pi}{m_x/2},\ antiphase\ TM_{20}\ mode \quad (1)$$

$$\beta_e = 2\pi f\sqrt{\varepsilon_{re}}/c \quad (2)$$

$$\beta_u p_x/\pi = \frac{1-2\beta_e \Delta/\pi}{m_x}, TM_{10}\ mode \quad (3)$$

$$\varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}(1+12h/W_p)^{-1/2} \quad (4)$$

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{re}+0.3)(W_p/h+0.262)}{(\varepsilon_{re}-0.258)(W_p/h+0.813)} \quad (5)$$

The whole patch is cut into a 4 × 4 patch array with three radiating slots and three non-radiating slots. The corresponding antenna performance is to be analyzed by considering the dispersion property of the capacitor-loaded patch unit cell. The aperture coupled grid-slotted patch sustains TM10 and antiphase TM20 modes closely spaced at the RH dispersion branch as well. The transmission-line model is still applicable to the mode analysis of the vialess grid slotted patch antenna.

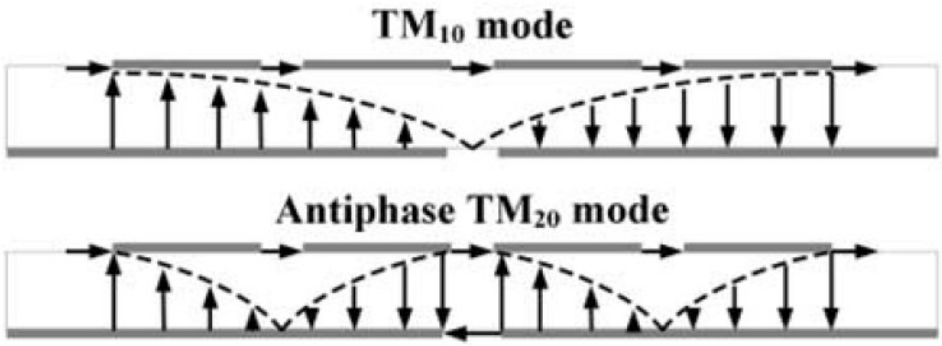

Figure 3.2-2 TE and TM modes

3.2.2. Impedance Transformation using microstrip T:

The gap between the patch and the microstrip-T junction is set at a fixed distance of 0.3mm, while the width of the microstrip-T arm measures 7.5. Initially, the dimensions of the Microstrip-T were selected to be λ/2 (wavelength/2).

However, these dimensions were later fine-tuned through an optimization process using CST. Following the optimization, and the width (T) of the transmission line was set at 7.5mm. To achieve a port impedance of 50 Ohms.

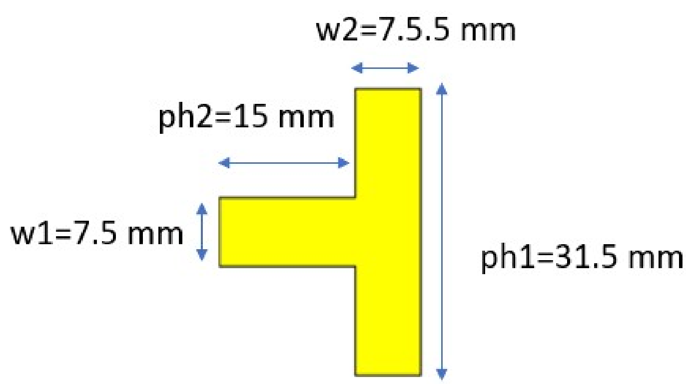

Figure 3.2-3: T optimization

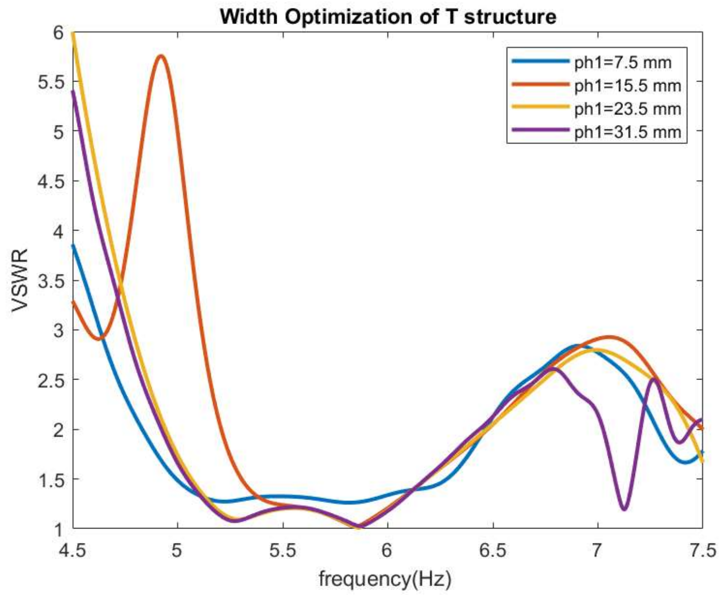

Figure 3.2-4: VSWR (Parameter Sweep results)

Optimized width of T arms is 31.5mm for excellent VSWR of T ports.

Furthermore, the bandwidth achieved by this electromagnetically coupled dual-polarized patch antenna is significantly broader than that attained using other coupling methods like probe-fed, proximity-coupled, or aperture coupling .

3.3.Full Wave simulation:

An antenna has designed by using CST Studio Suite, a comprehensive software tool for electromagnetic simulation. The entirety of the design is delineated in Figure No. _, which showcases the detailed structure and configuration of the antenna elements. Figure 14 presents the top side of the antenna that consist up of EBG 4 x 4 square radiating patches to ensure the higher bandwidth of antenna as mentioned in section . Two T shaped ports are for Rx operation that feed the antenna from two parallel sides. The parameters of the T feeds are optimized in section. Figure 15 presents the middle ground plane with slot that is used to excite the antenna in Tx operation. Figure 16 presents the bottom side of antenna that consist of feed on RO4003 substrate of thickness equals to 0.813 mm.

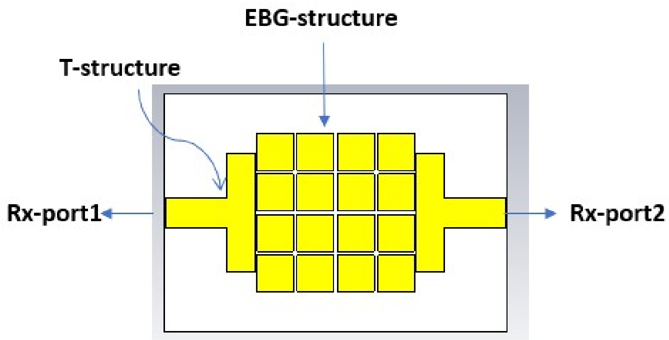

Figure 3.3-1 Top Layer

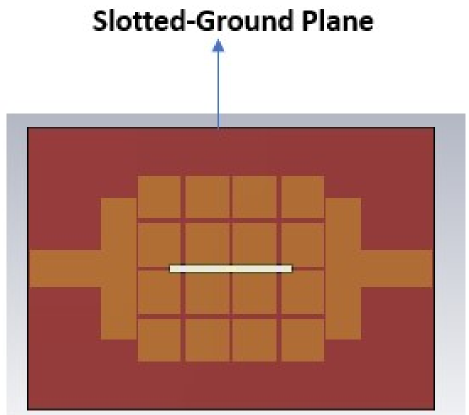

Figure 3.3-2 Ground Plane

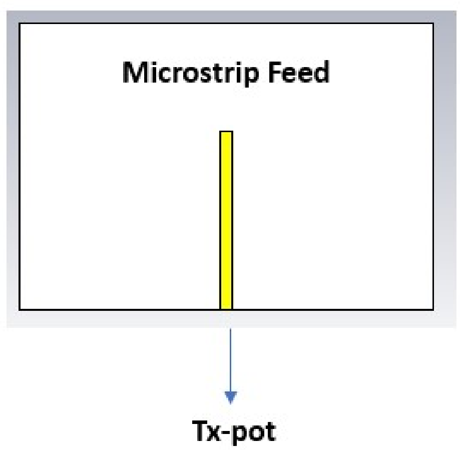

Figure 3.3-3 Bottom Layer

The Full wave simulations results are illustrated in figure no 17 S11 S22 and S33 Parameters: These represent the reflection coefficients at ports 1 2and 3, respectively. Technically, they indicate how much of the incident power is reflected back at the input ports, which is a measure of impedance mismatch. Values closer to 0 dB imply a perfect match, while values below -10 dB are typically considered acceptable in antenna design, indicating that 90% of the incident power is accepted by the antenna and only 10% is reflected. S21 and S31 are the isolation. It is observed that, the system operates over a bandwidth of 1.5 GHz, within which the antenna is designed to perform optimally according to predefined criteria. The isolation, which measures the degree of decoupling between ports, is greater than 37 dB across the operational bandwidth. Isolation is crucial in multi-port systems to prevent port-to-port interference which can degrade the performance of the system. The maximum observed isolation is 55 dB, which suggests an excellent level of decoupling at a specific frequency, ensuring minimal signal leakage between the ports. The frequency range displayed on the x-axis spans from 4.5 GHz to 7.5 GHz, covering the upper C-band and extending into the X-band, which are common for applications such as satellite communications and radar. The y-axis shows the magnitude of the S-parameters in decibels (dB), where the dynamic range of the plot indicates the antenna's performance over a significant portion of the microwave band.

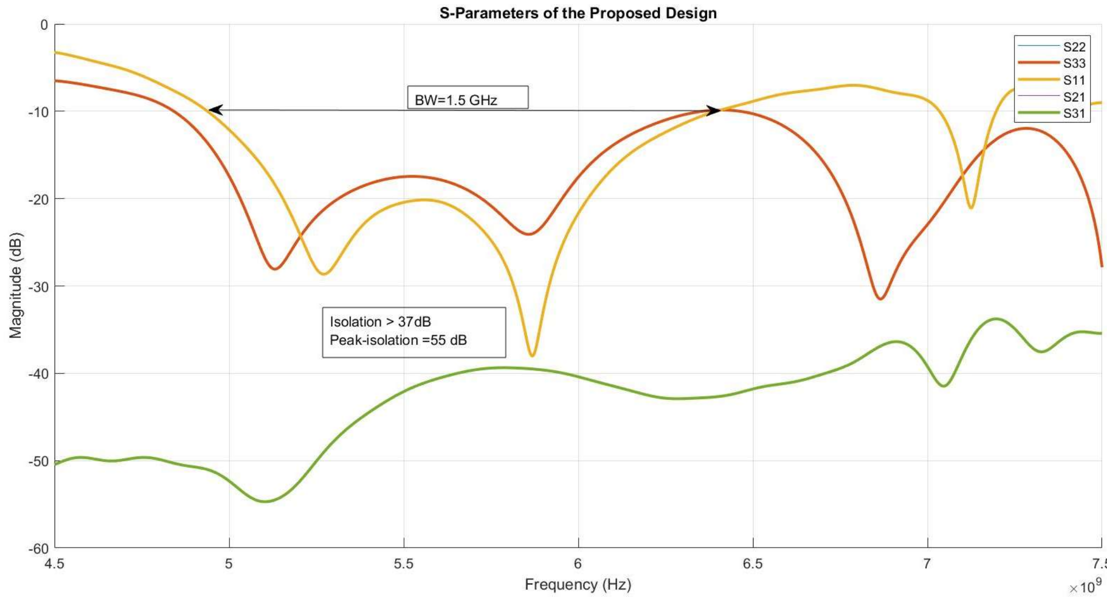

Figure 3.3-4: S-parameter of three port Antenna

3.3.1. Simulation with Rat Race coupler:

Unlike the external loop method for self-interference suppression, the ring hybrid coupler in this design effectively cancels self-interference across a broader bandwidth. This leads to enhanced inter-port isolation over an extensive frequency range. The design features a three-port microstrip antenna that utilizes differential excitation for dual polarization and self-interference cancellation, with two Rx ports symmetrically positioned relative to the central Tx port. A rat race coupler is designed using ADS and antenna results are presented in figure no 19.

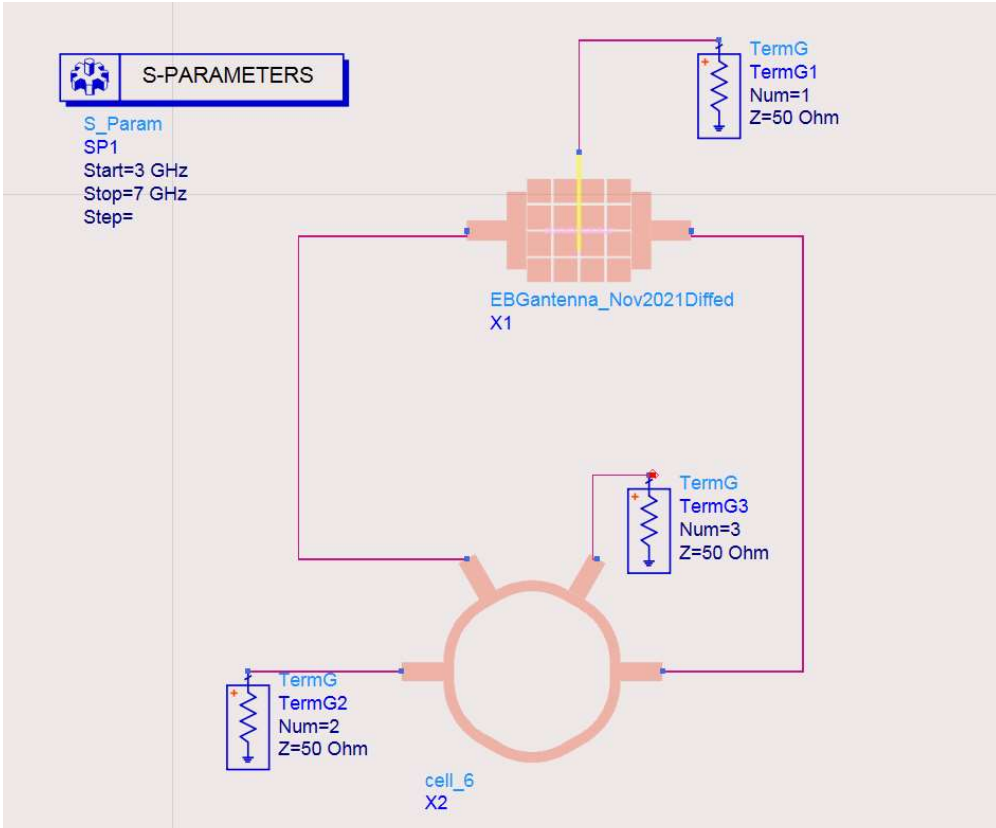

Figure 3.3-5: ADS Schematic of Antenna simulation with rat race coupler

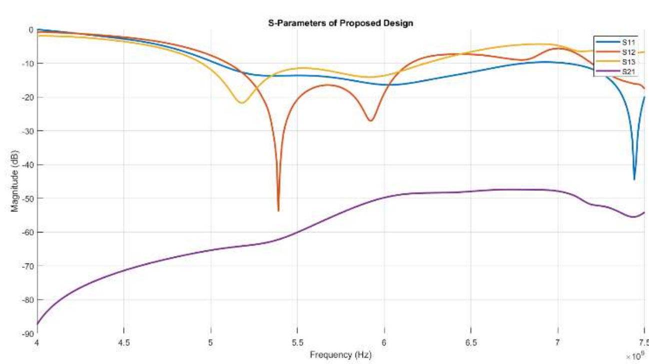

Figure 3.3-6:S-parameters for Antenna with Rat race coupler

3.4.Far Field Simulation:

CST is used to simulate the design for radiation pattern measurement. Tx port is excited first and radiation pattern at 5 GHz, 5.4 GHz, 5.8 GHz and 6.2 GHz are analysed. Maximum observed gain is 10 dB and maximum cross polarization level is 30 dB. Simultaneous excitation for Rx ports is used to analyse the radiation pattern radiation pattern at 5 GHz, 5.4 GHz, and 5.8 GHz are analysed. The Simulated results are presented in fabrication section.

3.5.Design Review Based on Fabrication:

The design and fabrication of this antenna pose significant challenges due to the sandwiched configuration of the ground plane between two rigid substrates. This configuration introduces the potential issue of air gaps forming between the boards when they are stacked together. These air gaps have the potential to adversely affect the performance of the two Rx ports. To mitigate this, we have implemented a double-layer ground plane between the two boards. Additionally, we have incorporated slots to accommodate connectors for mounting, and extensive antenna simulations have been conducted with these connectors in place. Our intended assembly method involves stacking the boards using solder paste. Below, we present the results obtained from these efforts.

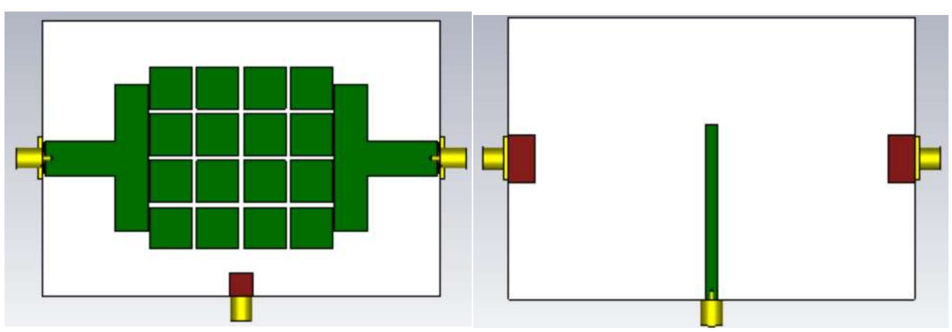

Figure 3.5-1: Fabrication based CST design

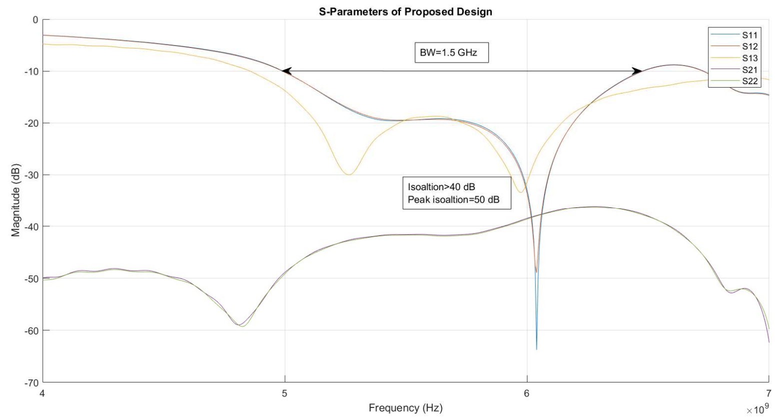

Figure 3.5-2: S parameter results of modified Design

Chapter # 4. Fabrication and Measurements

This chapter provides the fabrication details of the design and hardware testing. It is observed the results are similar to the simulation results.

4.1.Fabrication Details

Three port EBG antenna is designed on Roger 4003 boards of thickness 3.05 mm and 0.813 mm. Rogers boards were provided by Rogers corporations as complementary for research purpose.

Antenna presented in figure no 22 is fabricated by smart PCB. Gerber files were exported from the CST. Drill file was also provided to the Smart PCB. Four holes at the corners were used to align two boards. Perfect alignment during stacking of the board is a important step as it can affect the performance of aperture coupling. Smart PCB used the photolithographic method for antenna fabrication and holes were drilled by using milling machine.

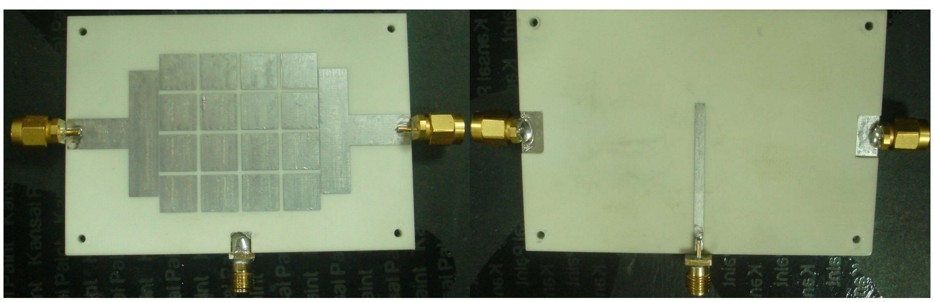

Figure 4.1-1: Fabricated Design

4.2.Antenna Measurement:

RIMMS lab facilitate the student to test the antenna in lab. VNA for S-parameter measurement and anechoic chamber for radiation pattern measurement is also available in lab. Testing plan is provides as below:

- S-parameter measurement of Antenna
- S-parameter measurement of Antenna with rat race coupler
- Radiation pattern Measurement by exciting Tx port
- Radiation pattern Measurement by exciting rat race delta port
- S-parameter measurement of three port antenna

4.2.1. S parameters measurement of Antenna

S-parameters were measured using VNA, the test set up is illustrated in figure no 23. VNA is calibrated for 4 to 7 GHz. VNA is a two-port equipment that is why it facilitate measurement of two ports at a time. Rx port 1 and Tx port are connected to VNA. Rx port is terminated to 50 ohms.

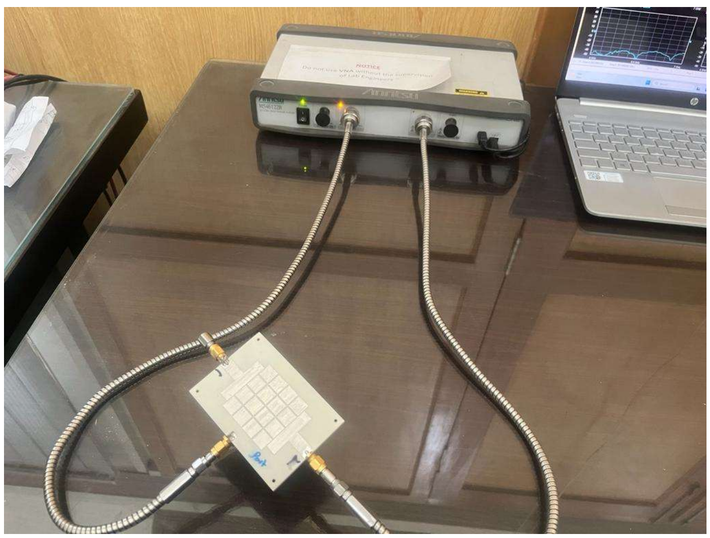

Figure 4.2-1: Test Set up

Output file is saved in csv format. MATLAB is used to plot data of three ports. Reflection coefficients of three ports are measured. Isolation between Tx and two Rx ports is also measured. The measured results are similar to the simulated results.

Figure no 24 illustrate that the 10 dB impedance bandwidth of the device under test is approximately 1.4 GHz. simulated bandwidth of antenna is 1.5 GHz. Peak isolation is 55 dB and isolation is more than 38 dB in frequency band 4.9 to 6.35 GHz.

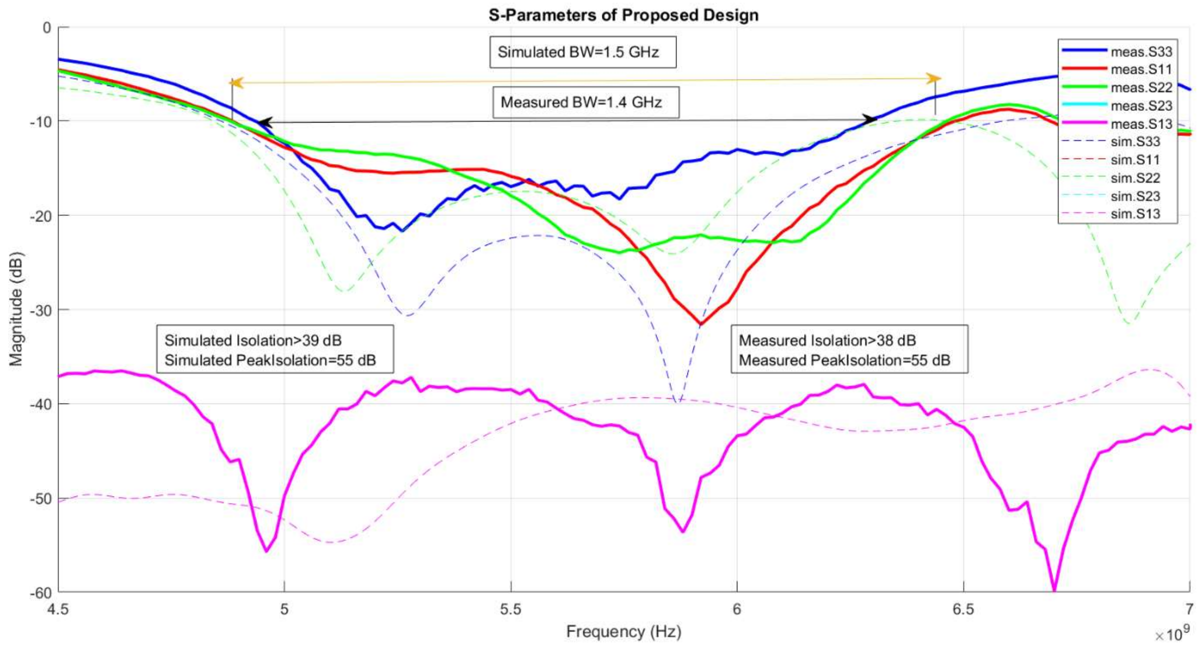

Figure 4.2-2 S-parameter Three port antenna

4.2.2. Antenna Simulation with rat race coupler:

Rat race coupler is used for differential. Rat race coupler is four port device that is used to ensure maximum isolation between the antenna ports. Delta port of rat race coupler is designated as Rx port of the antenna. Two rx ports are connected to input ports of rat race coupler and sum port is terminated. Port 1 of VNA is connected to tx port and port 2 is connected to delta port of rat race coupler, test set up is provided in figure no 25.

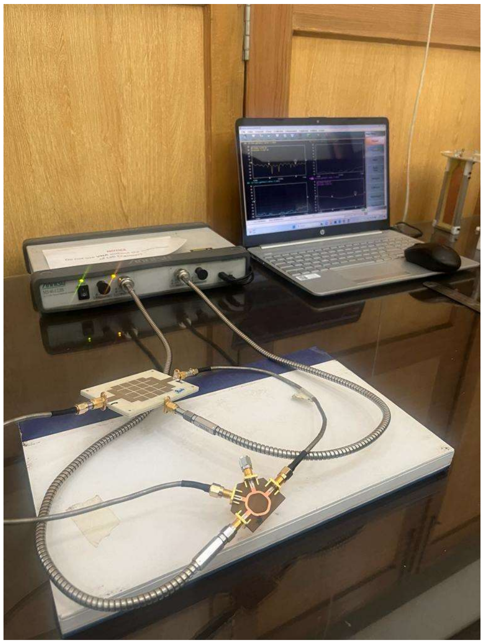

Figure 4.2-3: Test setup of antenna with rat race coupler

Figure no 4.2-3 presents the ss-parameter results of DUT. Smooth curving is applied to minimize the fluctuations due to cable. Isolation is improved to above 60 dB and peak isolation is 67 dB.

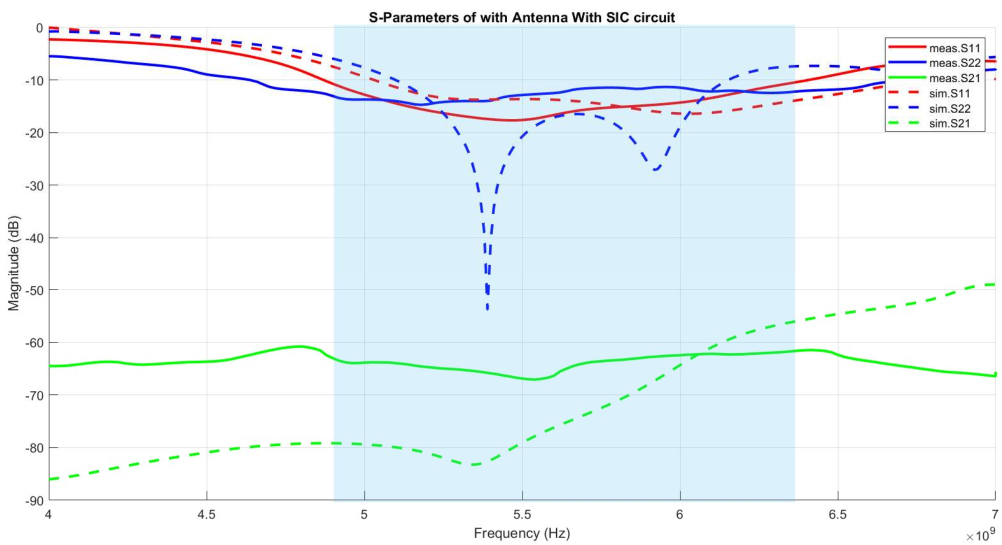

Figure 4.2-4: S-parameter (hardware Testing)

4.2.3. Far Field radiation measurement

Anechoic chamber facility for radiation pattern measurement is available in RIMMS. An anechoic chamber is a specialized room designed to entirely absorb reflections of sound or electromagnetic waves. They are typically used to conduct experiments in acoustics or electromagnetic radiation, such as antenna testing or sound recording, where external interference and reflections must be minimized. The walls, ceiling, and floor of these chambers are covered with sound-absorbing material, often in the form of pyramid-shaped foam, to create a space that simulates a completely open environment with no sound or signal reflections. The term "anechoic" means "no echo," which describes the chamber's primary characteristic of preventing echoes and reverberations. anechoic chambers are critical in testing electronic devices and components, such as radios, radars, and antennas, to ensure they perform correctly without external electromagnetic interference. Test setup for radiation pattern measurement is presented in figure no 4.2-3.

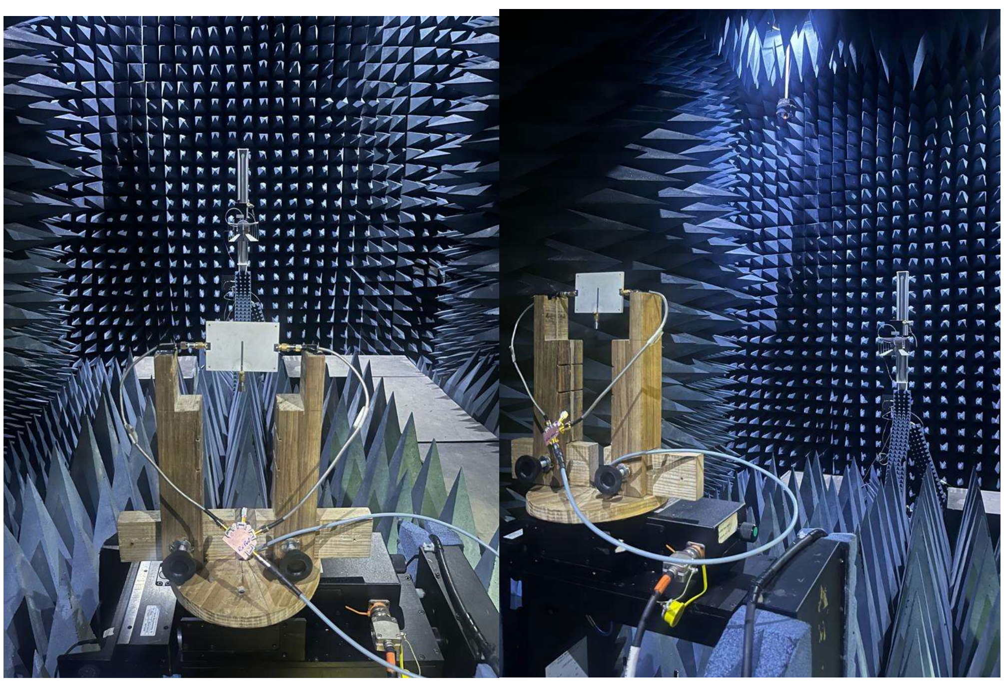

Figure 4.2-5: Test set up for radiation pattern Measurement

Gain is measured at three frequencies 5 GHz, 5.4 GHz and 5.8 GHz. For Tx and Rx port.

Gain plot for co and cross polarization at 5 GHz are presented in figure no 4.2.1-6. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

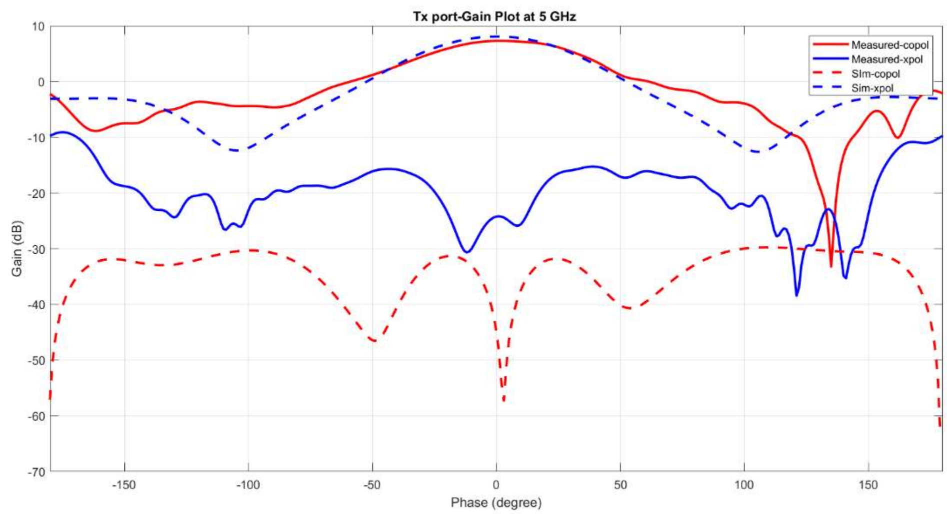

Figure 4.2-6 Tx port gain plot at 5GHz

For co-polarization, the maximum gain is equals to 8 dB. For x-polarization, the maximum gain seems to be around -10 dB and occurs at multiple phase points.

Gain plot for co and cross polarization at 5.4 GHz are presented in figure no 4.2-1-7. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

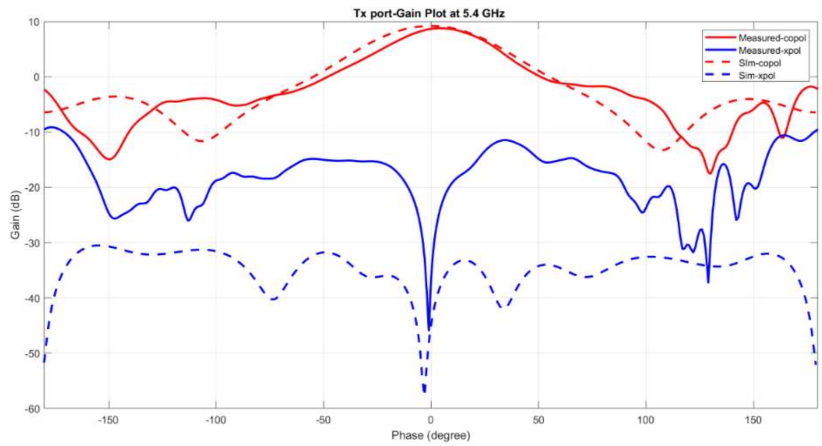

Figure 4.2-7 Tx port gain plot at 5.4 GHz

For co-polarization, the maximum gain is equals to 8 dB. For x-polarization, the maximum level around -10 dB and minimum level -47 dB is obtained

Gain plot for co and cross polarization at 5.8 GHz are presented in figure no 4.2.1-8. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

For co-polarization, the maximum gain is equals to 8 dB. For x-polarization, the maximum level around -10 dB and minimum level -47 dB is obtained

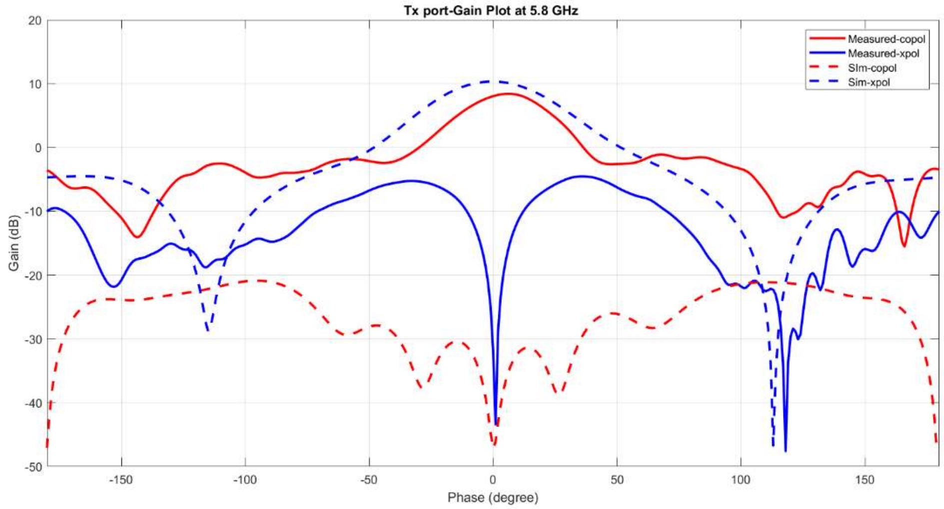

Figure 4.2-8 Tx port gain plot at 5.8 GHz

Gain plot for co and cross polarization at 5.4 GHz are presented in figure no 4.2.1-9. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

For co-polarization, the maximum gain is equals to 4 dB. For x-polarization, the maximum level around -10 dB and minimum level -40 dB is obtained

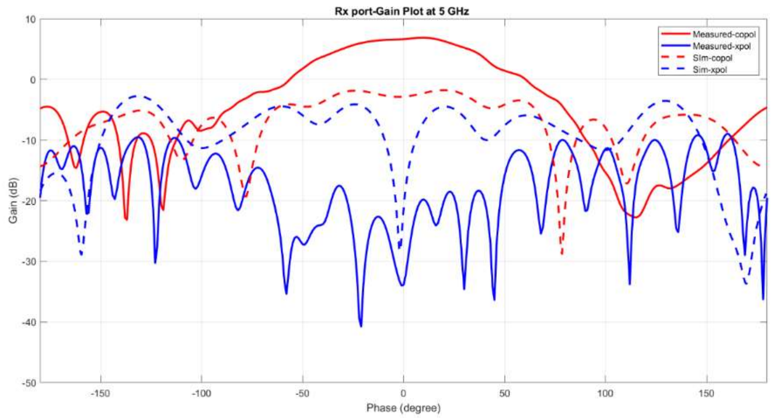

Figure 4.2-9 Rx port gain plot at 5 GHz

Gain plot for co and cross polarization at 5.4 GHz are presented in figure no 4.2-7. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

For co-polarization, the maximum gain is equals to 4 dB. For x-polarization, the maximum level around -10 dB and minimum level -40 dB is obtained

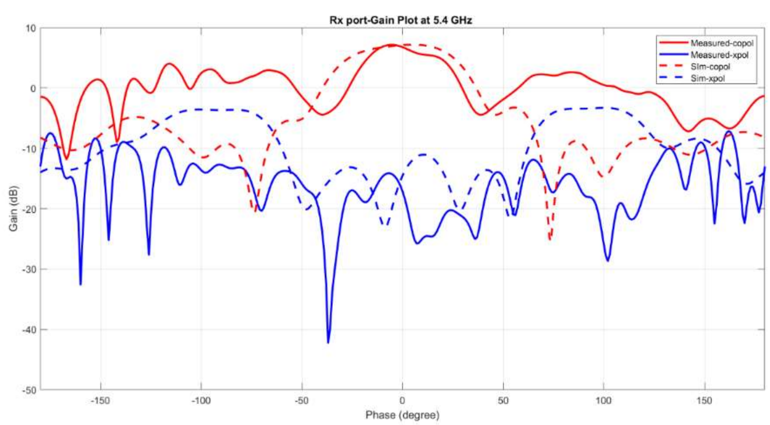

Figure 4.2-10 Rx port gain plot at 5.4 GHz

Gain plot for co and cross polarization at 5.8 GHz are presented in figure no 4.2-8. Figure is depicting the gain of an antenna system across various phases measured in degrees. In the graph, there are two lines representing two different types of polarization:

- Co-polarization (in blue)
- X-polarization (also known as cross-polarization, in orange)

For co-polarization, the maximum gain is equals to 4dB. For x-polarization, the maximum level around -10 dB and minimum level -40 dB is obtained

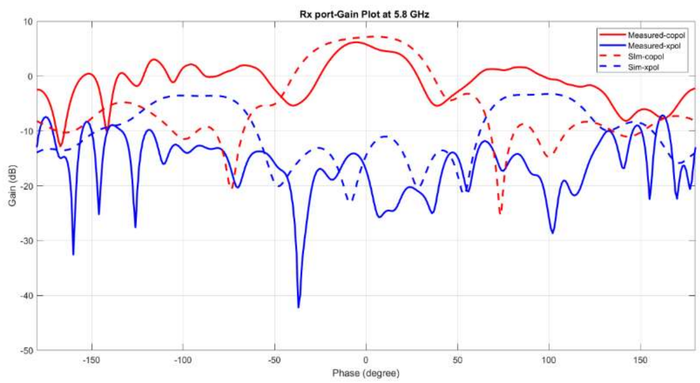

Figure 4.2-11 Rx port gain plot at 5.8 GHz

Table 5 Comparison b/w proposed and previous designs

Ref	SIC technique	Bandwidth (MHz)	Isolation/BW (dB)	Peak Isolation
[18]	Polarization Diversity	90	>60	87
[19]	Polarization Diversity	45	>90	120
[21]	Polarization Diversity	100	>80	87
[22]	Decoupling effect of metamaterial antenna	1030	>20	35
Prop-Design	Feed Positions (polarization diversity), EBG radiating element (Decouplind effect)	1400	>39	57

CONCLUSIONS AND FUTURE RECOMMENDATION

The research successfully addresses the key challenges in designing an efficient antenna for IBFD communication systems. The metamaterial-based microstrip patch antenna developed in this study demonstrates high isolation, wide bandwidth, and effective self-interference cancellation, making it a promising solution for advanced wireless communication systems.

The antenna is designed for operation in the 4.9 GHz to 6.4 GHz range, with a focus on achieving high isolation (over 40 dB) and polarization diversity. The design incorporates advanced techniques such as aperture coupling and uses a differential feed network. The antenna is fabricated and subjected to comprehensive hardware testing, including measurements of S-parameters and radiation patterns. The results from these tests are in close agreement with the simulation predictions.

The design can be further optimized according to fabrication point of view. The connectors pad for the bottom feed. This will provide more strength to the connector. Rat race coupler with improved parameters can be designed to achieve better results. Wide SIC band circuit can be designed for achieving better performance.

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APPENDIX A

Table 6 Abbreviations and their Acronyms

IBFD	In band Full Duplex Communication
RP	Reflected Path
Tx	Transmitter
Rx	Receiver
SI	Self-Interference
SIC	Self-interference cancellation
EBG	Electromagnetic Band Gap
DP	Direct Path
AR	Antenna Reflection
DFN	Differential Feed Network
HIS	High Impedance Surface
PBG	Photonic Band Gap
LP	Linear Polarization
VNA	Vector Network Analyzer
DUT	Device Under Test