# A Compact Ultra-Wideband MIMO/Diversity Antenna with Band-Rejection Capability

By

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# Approval

It is certified that the contents and form of the thesis entitled "A Compact Ultra-Wideband MIMO/Diversity Antenna with Band-Rejection Capability" submitted by Farah Latif have been found satisfactory for the requirement of the degree.

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# Abstract

In recent years, ultra-wideband (UWB) technology has attracted the devotion of researchers due to its unlimited advantages. These advantages include higher channel capacity, better wall-through imaging, localization, medical imaging and reliable transmissions. Along with all these advantages, UWB technology suffers from some limitations. Major limitation of this technology is very low spectral mask i.e. -41.3dBm/MHz. Due to its very low power level, it undergoes severe multipath fading in highly scattering environment. The solution to manage this fading effect is MIMO (multiple-input-multiple-output) technology. UWB-MIMO systems mitigate multipath fading very effectively. Furthermore, such systems offer more channel capacities as compared to narrowband systems. However, on the other side, increasing trend of miniaturization of portable devices leads to increased mutual coupling among MIMO antenna elements. In order to enhance isolation level, distance among MIMO elements has to be increased by compromising design compactness. So, designing an UWB-MIMO antenna with compact size and minimum isolation achieved is a very exciting challenge. Moreover, UWB suffers from interference with already existing communication standards i.e. wireless local area network (WLAN) (5.15–5.825 GHz). So, we have to introduce the band-rejection capability in MIMO systems to castoff the interfering bands.

This thesis focuses on the study of UWB-MIMO antenna design for wireless communications systems. Two different designs have been proposed in this research work. In first design, semi-circular annular slot antenna is used for entire UWB coverage (3.1-10.6 GHz). These slots are symmetric- ally fed by orthogonally placed 50Ω micro-strip transmission lines. Uniform radiation patterns and better polarization characteristics are achieved by symmetric feeding. Two small stubs are used on both sides of microstrip lines for better impedance matching at higher frequencies. Furthermore, for most of the band, isolation better than 20dB is achieved by inserting two slots in between two antenna elements. Vertical slot helps in reduction in coupling at lower frequencies i.e. 3-5.5 GHz while horizontal slot enhances isolation at higher frequencies i.e. 5.5-10.6GHz. For band-rejection at the WLAN (5.15–5.825 GHz), an inverted U-shaped slot is etched in the feeding transmission line. The overall antenna size is $58 \times 27mm^2$.

Second design is a compact ultra-wide band antenna with enhanced isolation and band-rejection capability that is presented for portable devices. Rectangular stepped slots are etched on the back side of antenna to cover entire ultra-wide band. These slots are off-centered fed by 50Ω micro-strip transmission lines so there is no need of stub matching. Use of inverted T-shaped slot near upper edge of ground plane maintains isolation level better than 24.5dB in the lower band i.e. 3-5GHz. A z-shaped slot is inserted on the back side of antenna to reject WLAN. Proposed antenna size is $26 \times 23mm^2$ with planar geometry. Both designs have achieved better impedance matching, minimum isolation among the ports and stable radiation patterns. Good agreement among measured and simulated results makes both proposed designs promising for UWB applications.

To my family and friends.

# Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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# List of Acronyms

| | |
|---|---|
| FCC | Federal Communications Commission |
| UWB | Ultra-wide Band |
| MIMO | Multiple Input, Multiple Output |
| WLAN | Wireless Local Area Network |
| PIFA | Planar Inverted F Antenna |
| CST | Computer Simulation Technology |
| OFDMA | Orthogonal Frequency-Division Multiple Access |
| LNA | Low Noise Amplifier |
| LAN | Local area Network |
| QSCA | Quasi-self-complementary Antenna |
| CPW | Coplanar Waveguide |
| ECC | Envelope Correlation Coefficient |

# Chapter 1

# Introduction

## 1.1 Overview of UWB-MIMO Technology

Ultra-wideband (UWB) technology is indeed not a latest theory; however it has attracted a lot more attention and focus of researchers in past few years. More development and research in this technology is due to its exceptional advantages over other communication standards i.e. wireless local area network (WLAN), Bluetooth etc. It has radical way to improvement as well as implementation in the wireless world. In 1960's, the idea of UWB initiated, when more study was done in impulse measurement techniques required for wideband antenna designing. Short pulse radar systems were developed as a result of initial research. 'Baseband' or 'impulse' technology was also a term used for UWB. After this, many techniques were developed due to advancement in this technology. Once UWB technology became mature, it started being utilized in many applications i.e. medical imaging, radars, short distance applications, anti-jamming systems and other communication devices.

Concept of Multiple-Input-Multiple-Output (MIMO) is employed in latest smart technologies to get better data rates and reliable signals through wireless medium. Different copies of same signal are sent to receiver from different paths. All diverse paths are independent from each other. So signals from different paths are not equally faded. Rather, healthier signal is received from one of all available diverse paths. In this way, extra power and bandwidth are not wasted to get healthier signal. Along with all other advantages of ultra-wideband technology, it also suffers from severe multipath fading due to its very low spectral mask. This limitation can be overcome by using concept of MIMO along with UWB technology. Use of MIMO brings diversity that increases channel capacity as well as link performance. So, UWB-MIMO antenna is suitable candidate to overcome multipath fading and signal degradation in the wireless environment.

## 1.2 Research Motivation

Researchers have focused more on the concept of Ultra-wideband as compare to other traditional wireless technologies such as Bluetooth, wireless LAN etc. This is due to its advantages of high-speed data rates with available spectrum and low power consumption. The increasing trend of employing UWB technology in key areas has made a remarkable change in present era.

Recently, some industrial surveys have shown the need of simple antenna designs at RF front ends. Transceiver designs have become much more complex with increase in digital processing in it. There is intense need of reduction in complexity level without compromising design compactness.

Designing a compact UWB-MIMO antenna with desired performance parameters is very challenging task. These challenges provided by UWB technology have provoked keen interest in researchers. The most important challenge is the increase in isolation level among ports while keeping the antenna size as small as possible. Some other challenges include broadband performance, impedance matching and stable radiation patterns. Some Broadband antenna techniques must be employed in designing UWB-MIMO antenna so that it can behave desirably for entire band of operation i.e. 3.1-10.6 GHz. To make antenna’s radiation efficiency better, its return loss must be greater than 10dB that means only

10% of total incident power is reflected back and 90% of total incident power is radiated in the desired directions.

Miniaturization is one of the most important factors that must be taken into account while designing any antenna. There is always a trade-off between antenna size and other performance parameters. So, miniaturization has to be done without compromising antenna performance. Hence, it is one of the biggest challenges in designing phase. Planar structures are better than that of 3D structures because of space constraints. Additionally, planar antenna designs are very easy to fabricate with lesser fabrication cost. They can be easily integrated in RF circuits. For radars and medical imaging devices, very compact size is not required. That’s why; proposed design is compatible for particular applications.

Another limitation of UWB technology is its interference with already existing wireless communication standards i.e. WLAN, WiMax etc. Different filtering techniques have been reported in literature to overcome this issue. These techniques include use of slots, stubs and strips to bring band-notched characteristics. Addition of such structures also results in enhanced coupling among antenna elements. Therefore, such design challenges have accelerated keen interest and motivation for researchers to design a novel UWB-MIMO antenna for industrial operations and applications.

## 1.3 State of the Art

Research shows that mostly two or four antennas have been used in literature to bring spatial or pattern diversity. Number of antennas cannot be increased beyond certain level because of space limitation and requirement of miniaturization in modern communication devices. From last decade, most of the research was done on PIFA and monopole antennas [1]-[3] but use of slot antennas has increased in latest research due to its inherent directional properties and compactness [6], [20], [21], [25]. Mutual coupling is one of the most important issues that badly affect the efficiency of UWB-MIMO antennas. Several techniques are employed in literature to reduce mutual coupling among antenna elements [4]-[14]. These techniques include use of decoupling structures, use of dual polarized antennas, use of T-shaped slots or stubs in the ground plane etc. Two different types of antennas are employed to bring pattern diversity for better isolation in [4]. In [5], slanting rectangular slot is used to decrease coupling between two antenna elements. In [6], combination of slanting slot and stub is used to isolate both ports from each other. In [7]-[9], dual polarized antenna systems are used which bring polarization diversity to enhance isolation among MIMO elements. But, achieving better isolation by keeping antennas in same polarization is the true challenge. In [10], single polarized antenna is used with decoupling structure in between antenna elements to reduce mutual coupling. In [11], four quasi-self-complementary (QSC) antennas are employed to make UWB-MIMO antenna. All antennas are used in same polarization but its size is $60 \times 41$ $mm^2$ that is comparatively large. In [12], an UWB-MIMO antenna is suggested for the applications of radar and imaging devices. Slot antenna is used as main antenna element but with dual polarization. Isolation is achieved by dual-polarization. Size of this antenna is also large that is 66.25mm × 66.25mm. In [13], tree like structure and in [14], floating parasitic structure is employed to isolate both antenna elements. These structures make the overall design very complex.

Furthermore, over the last decade, researchers have focused more on UWB-MIMO antennas with band rejection capability to avoid interference [15]-[20]. In [15] and [16], stubs on ground plane are used to reject WLAN. A slot like structure is employed in radiating part of antenna to minimize radiations in WLAN frequency band in [17]. In [18], another filtering slot in L shape has been etched in the ground plane of antenna to bring WLAN band rejection In [19], a slot in the shape of arc behaves as the band-stop filter to reject entire WLAN while in [20], addition of split ring resonator slot in the radiator acts as band-stop filter.

Table 1.1: Comparison of different UWB-MIMO Antennas from literature H, W and T stands for the height, width and thickness of the antenna dimensions.

| **UWB-MIMO Antennas** | **Dimensions (W×H×T)** | **Isolation at lower band (3 - 5GHz)** |
|---|---|---|
| TAP-2013 [1] | $40\times26\times0.8$ mm$^3$ | -15dB |
| AWPL-2014 [2] | $40\times30\times0.8$ mm$^3$ | -20dB |
| EL-2015 [3] | $39.8\times23\times0.8$ mm$^3$ | -18dB |
| AWPL-2014 [4] | $38\times26\times0.8$ mm$^3$ | -22dB |
| AWPL-2014 [5] | $32\times32\times0.8$ mm$^3$ | -18dB |
| AWPL-2016 [6] | $66.25\times66.25\times0.8$ mm$^3$ | -18dB |
| TAP-2013 [15] | $37\times27\times0.8$ mm$^3$ | -15dB |
| TAP-2015 [16] | $22\times36\times0.8$ mm$^3$ | -15dB |
| AWPL-2015 [17] | $45\times45\times0.8$ mm$^3$ | -17dB |
| AWPL-2015 [18] | $38.5\times38.5\times0.8$ mm$^3$ | -21dB |
| Proposed Antenna | $27\times22\times0.8$ mm$^3$ | -24.5dB |

## 1.4 Problem Statement

From above state of art, some key areas in the research of UWB-MIMO antennas are highlighted. To design a compact and novel UWB-MIMO antenna with rejected WLAN band is needed.

## 1.5 Methodology

From extensive literature review, increasing research trend in UWB-MIMO antenna is quite obvious. In recent few years, researchers have preferred slot antennas more as compare to planar inverted F antenna (PIFA) or monopoles. This is because of compactness and inherent directional behavior of slot antennas. By using CST Microwave Studio, already published single circular slot antenna is simulated and its dimensions are optimized to make it two element MIMO design. Circular slot is changed into semi-circular keeping its radiation patterns unchanged. Desired level for impedance matching is achieved over the complete wide band by optimizing radiating slot dimensions. Isolation techniques are incorporated in between both antenna elements to reduce mutual coupling. After achieving desired level for isolation, band rejection techniques are incorporated in the design keeping its isolation level unchanged. After optimized simulated results achieved, its prototype is fabricated and measured. Both Results are compared with detailed parametric analysis.

## 1.6 Thesis Contribution

### 1.6.1 An Ultra-Wideband MIMO Antenna Design for Radar and Imaging Devices

In this thesis, an ultra-wideband MIMO antenna design is presented for radar and imaging devices. Semi-circular slot antenna is used as a main radiating element. The radiating slots are fed by 50Ω micro-strip transmission lines. Two stubs are loaded with feeding line for better impedance matching at higher UWB. Moreover, two slot like structures are inserted on the back side of antenna to enhance isolation level among MIMO elements. Vertical slot is responsible for isolation at lower UWB while horizontal slot maintains good isolation at higher UWB. In addition to that, an inverted U-shaped slot is introduced inside micro-strip transmission line to reject complete WLAN. This slot behaves as band-stop filter and rejects complete WLAN. Overall antenna size is 27 ×58 $mm^2$. Proposed design has attained stable radiation patterns, better impedance matching and better isolation level among ports. Good agreement in simulated and measured results makes this design suitable for UWB applications.

### 1.6.2 A Compact Ultra-Wideband MIMO Antenna with Enhanced Isolation and Band-Rejection Capability

An UWB-MIMO antenna design with compact size, enhanced isolation and band-rejection capability is the second design. This design is proposed especially for portable devices where enhanced mutual coupling is the biggest challenge. In this design, rectangular slot antenna is used as a main radiator. The radiating slots are fed by 50Ω micro-strip transmission lines. It covers complete ultra-wideband from 3.1-10.6 GHz. Two isolating slots are etched on the back side of antenna. Inverted T-shaped slot enhances isolation at higher UWB (5-10.6 GHz) while vertical slot reduces coupling at lower UWB (3.1-5 GHz). A stepped z-shaped slot is inserted under radiating slots to filter out complete WLAN frequency band.

## 1.7 Thesis Organization

The continuing part of the thesis is organized as follows:

- **Chapter 2** includes extensive literature review of UWB-MIMO antennas. Different antenna types, isolation techniques and filtering techniques have been discussed.
- **Chapter 3 & 4** include the description of two proposed designs of UWB-MIMO antenna. Simulated and measured results are compared to evaluate antenna performance.
- **Chapter 5** gives brief conclusion along with recommendations.

# Chapter 2

# Literature Review

## 2.1 UWB-MIMO Antennas

### 2.1.1 Introduction

Due to significant progress in wireless communication systems, demand for extra bandwidth, higher data rates and link reliability has been increased. In modern communication systems, UWB technology has been extensively used as compare to narrowband systems i.e. long term evolution (LTE), universal mobile telecommunication systems (UMTS) and wireless local area network (WLAN) etc. This is because UWB offers desired advantages i.e. high data rates, low cost, precise localization, medical imaging and higher channel capacities. Furthermore, due to wide band coverage, it is less prone to passive interference.

As an essential component of UWB communication, design of UWB antenna has gained more attention in latest research trend. Single UWB antenna undergoes severe multipath fading in dense and scattering environment due to its very low power level. A signal with such a low power needs some kind of diversity to reliably cover desired distance. Hence, concept of MIMO along with

UWB makes it suitable for use in modern wireless technologies. MIMO reduces multipath fading of signal by using different diversity schemes that include polarization diversity, spatial diversity etc. Different types of antennas have been used in literature for better impedance matching over entire ultra-wideband.

### 2.1.2 Types of UWB_MIMO Antennas

Several types of UWB_MIMO antennas are presented in this section.

Monopole Antenna

Monopole antennas have been widely used in literature to design UWB-MIMO antennas. This type of antenna has truncated ground plane instead of complete ground plane on the back side of antenna. This truncated ground plane helps in achieving better impedance matching over complete ultra-wideband. Gap between ground plane and monopole radiator has major influence on attaining broadband function. In [11] two semi-circular monopole antennas are used as shown in Fig. 2.1. This design has covered complete UWB. Isolation better than-20dB has been achieved due to orthogonal placement of antenna elements. Achieved size is 27 × 52mm$^2$. No band rejection technique is introduced in this design. It is fed by CPW (co-planar waveguide) port.

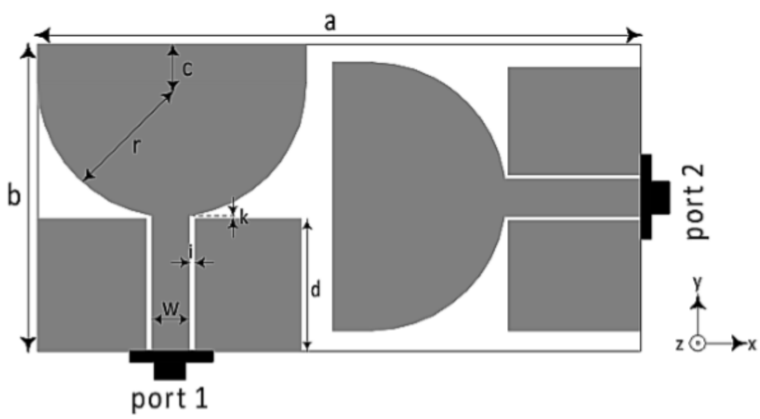



Figure 2.1: CPW-Fed UWB-MIMO antenna using monopole radiators [11]

In [24], four monopole radiators are used with common ground plane to cover complete UWB as shown in Fig. 2.2. These monopoles are placed in orthogonal position to each other to bring polarization diversity and reduce mutual coupling among 4 ports. Filtering technique is added in this design at the back side of antenna. This band-stop design acts as LC band stop filter that rejects WLAN frequency band. Achieved size is 50×39.8 mm$^2$. Isolation level over the entire UWB is better than 17dB.

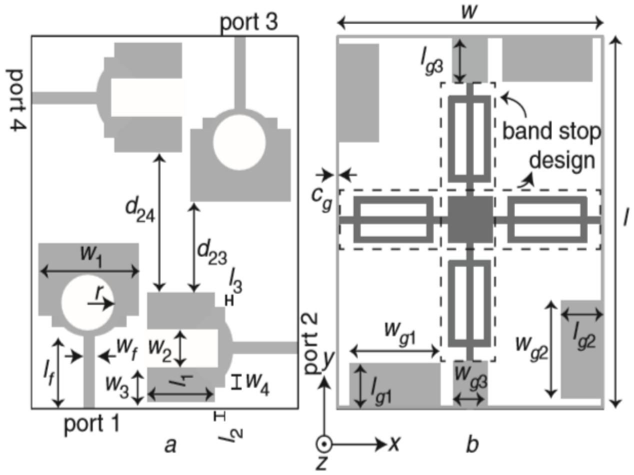



Figure 2.2: Geometry of UWB diversity antenna using four monopole radiators [24]

## Slot Antenna

Slot antennas are focused more in latest research because of its bi-directional radiation patterns as well as compact size. Radiating element of slot antenna is etched on the back side of antenna. Size of slot determines the lower cut-off frequency of operational band. Slot antennas are proximity fed by microstrip transmission lines. Position of feeding line has a major role in achieving covering complete band. In [25], slot antenna is employed as a main radiating element that is fed by microstrip transmission line as shown in Fig. 2.3. This design is smallest possible design reported in the literature for UWB applications. Inherent directional properties of slot antennas help in maintain better isolation level keeping the overall size very compact.

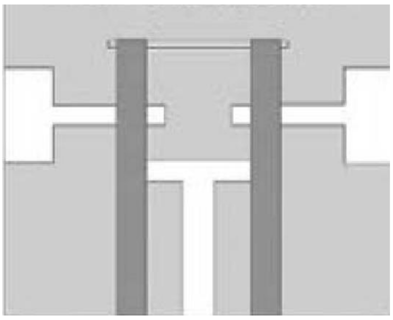


Figure 2.3: Geometry of UWB-MIMO antenna using stepped sot antennas [25]

In [21], four slot antennas are used to realize an UWB-MIMO antenna as shown in Fig. 2.4. Each slot if fed by 50Ω micro-strip line. Slots are inserted on the back side of antenna. These slots and feeding transmission lines are stepped to get better reflection coefficient over the entire band. Size of this antenna is 42 mm × 25 mm. but this design has not incorporated any band rejection technique. Furthermore, no isolation technique is used because of inherent directional properties of slot antennas. Distance between slots define isolation level among four elements.

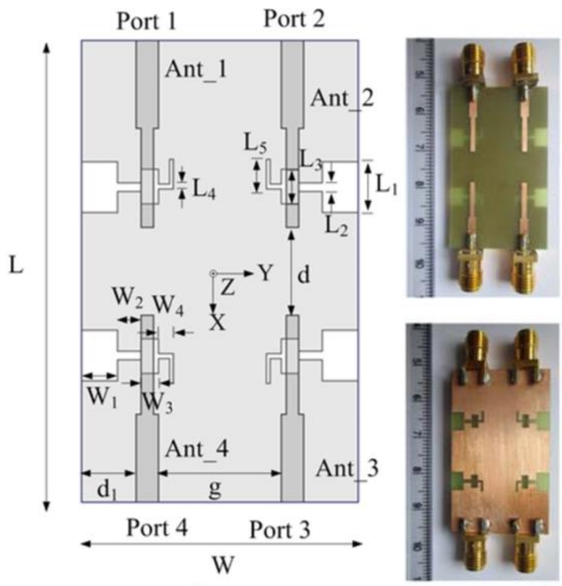



Figure 2.4.: Geometry of UWB-MIMO antenna using stepped sot antennas [21]

Kotch Fractal Antenna

Another important type of antenna is kotch fractal antenna. Fractalling of main radiating element helps in achieving broadband function but overall size becomes relatively large. Moreover, addition of decoupling structures results in increase in antenna size. In [9], four kotch fractal antenna elements are used. As shown in Fig. 2.5. Kotch fractal geometry is used to cover entire wideband with stable radiation patterns and better impedance matching. Grounded stubs are used for isolation over the whole band. Additionally, orthogonal placement of antennas, gives polarization diversity that helps in reduction in mutual coupling. Achieved size is 45mm ×45 mm. filtering technique for WLAN rejection is added in this design. A slot like structure in C shape is introduced in the radiating part of antenna to castoff interference with WLAN.

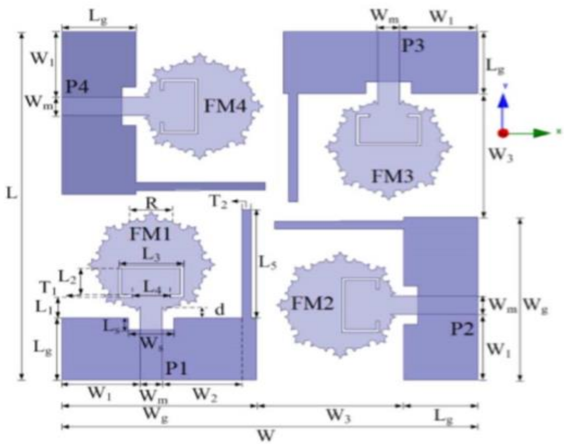



Figure 2.5: Kotch fractal UWB-MIMO antenna [9]

Planar Inverted F Antenna

In [22], two planar inverted antennas (PIFA) are used to cover complete ultra-wideband as shown in Fig. 2.6. T-shaped structure is used for better isolation and reduced coupling between both ports. This approach has proposed 3D design geometry. Achieved size is 50×90×7.5 mm$^3$. This size is quite large for portable devices. They have achieved isolation better than -20 dB for complete UWB.

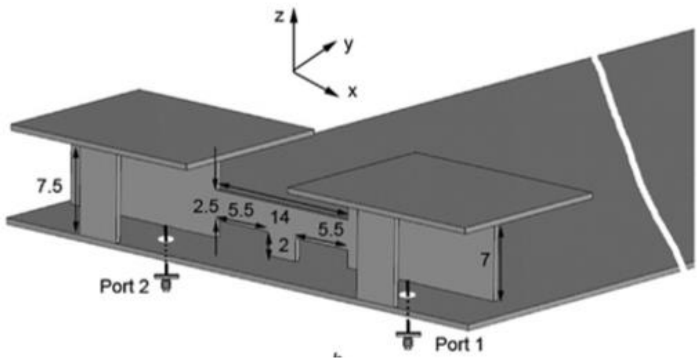



Figure 2.6: An UWB-MIMO antenna using planar inverted antennas (PIFA) [22]

Comparison

Monopole and slot antennas are widely used in designing UWB-MIMO antennas. Both types of antennas are simple and easy to fabricate. Keeping in view compactness, slot antennas have gained more attention in designing compact UWB-MIMO antennas for portable devices. Furthermore, some designs do not need any decoupling structures because of inherent directional properties of slot antennas. Brief comparison of all types of antennas with respect to their compactness and radiation characteristics is given in Table 2.1

Table 2.1: Comparison of UWB-MIMO antenna types

| Antenna Type | Radiation Pattern Type | Compactness |
|---|---|---|
| Monopole | Omnidirectional | Medium |
| Slot | Bi-Directional | High |
| Kotch Fractal | Omnidirectional | Medium |
| PIFA | Omnidirectional | Medium |

### 2.1.4 Filtering Techniques for UWB-MIMO antennas

Slot Technique

Slot technique is one of the most important filtering techniques to reject any un-desired band. Slot like structures are inserted in radiating elements, ground planes and feeding transmission lines. Length of filtering slot determines center frequency of rejected band while width determines bandwidth of rejected band. In [15], two quasi-self-complementary (QSC) antennas are used to design novel UWB-MIMO antenna as shown in Fig. 2.7. A slot like structure is inserted in the radiating element. This slot helps in rejection of complete WLAN. Polarization diversity is also employed in this design. Orthogonal placement of antennas make it isolate from each other. No additional decoupling structure is added in between both ports because of inherent property of QSC.

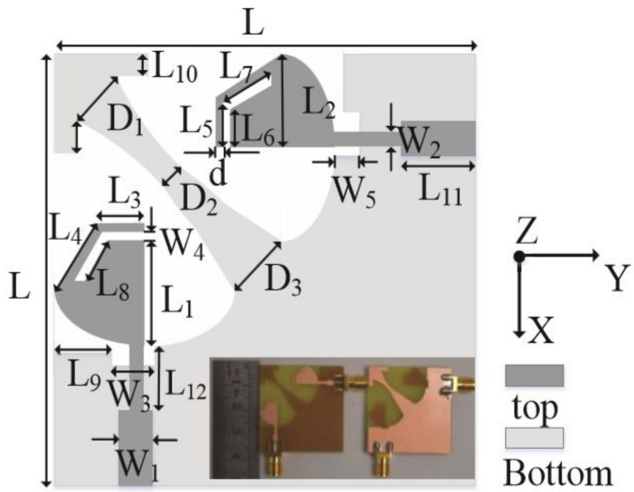



Figure 2.7: Geometry of quasi-self-complementary diversity antenna system [15]

Stub Technique

Another important filtering technique is stub technique. Stubs are introduced mostly on the back side of antenna to cancel out maximum possible current at un-desired band of operation. Cancellation of maximum current brings deep notch in rejected band. In [8]**,** stubs on ground plane are employed to reject complete WLAN as shown in Fig. 2.8.

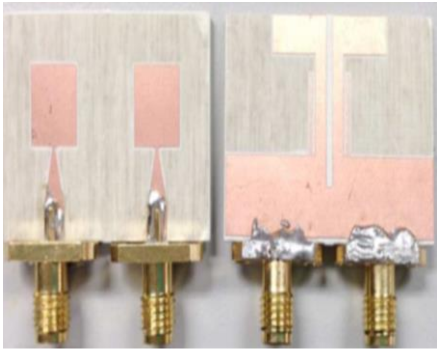


Figure 2.8: Geometry of monopole diversity antenna system with WLAN band-rejection [8]

### 2.1.5 Isolation Techniques for UWB-MIMO antennas

Pattern Diversity

In [4], two different types of antennas are used for pattern diversity as shown in Fig. 2.9. One antenna is tapered step slot antenna, other one is a monopole antenna. Both radiators are fed by 50**Ω** micro-strip feed lines. For reflection coefficient less then -10dB over the whole band, tapering is done at the corners of rectangular slot antenna. Furthermore, both antennas are placed in orthogonal position to get polarization diversity. H-shaped slot is etched in monopole radiator and H-shaped conducting path in tapered slot antenna on the back side of antenna are for impedance matching over the whole band. This design with size $26 \times 38mm^2$ has achieved better isolation but without any band notching characteristic.

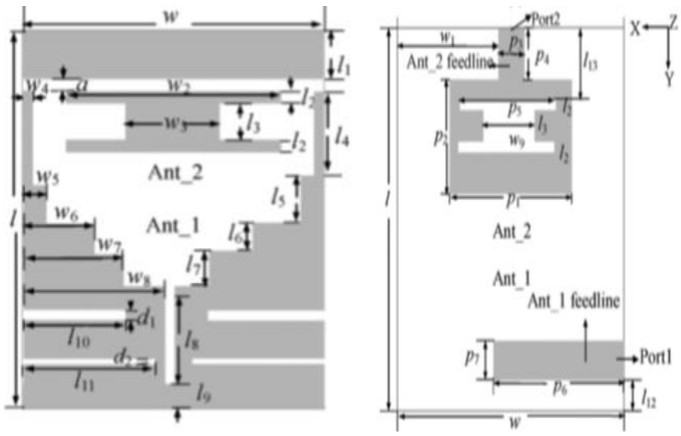



Figure 2.9: Tapered slot and monopole UWB-MIMO antenna [4]

T-shape Slot

In most of the antenna designs, T-shaped slot is employed on the back side of antenna to isolate both ports. This T-shaped slot helps in reducing coupling among antenna elements by providing different paths to current. Use of T-shaped slot among antenna elements keeps overall antenna size very compact. In [12], two compact co-radiator antennas are used in it as shown in Fig. 2.10. One radiator is being shared by two ports to make UWB-MIMO antenna size compact. T-shaped slot is introduced in radiating part on front side of antenna. An extended copper branch from ground plane on the back side of antenna is also there. Both of them are for reduction in mutual coupling. No band rejection technique has been used in this design. Achieved size is $40\times40\times0.8$ $mm^3$. Isolation of -15dB at lower frequency is achieved.

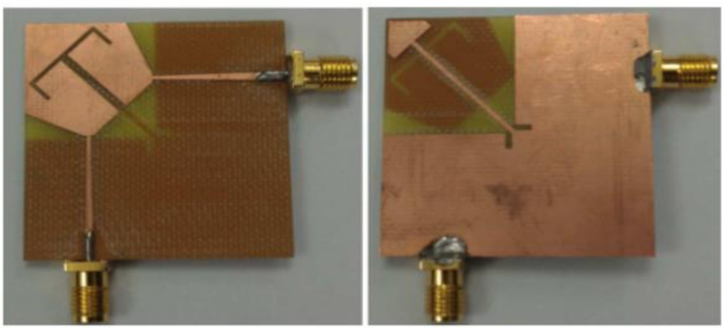


Figure 2.10: Co-radiator UWB-MIMO antenna [12]

Tree like structure

In [19], tree like structure is used on the back side of antenna to isolate both antenna elements as displayed in Fig. 2.11. No current is produced on non-excited antenna element because of excited antenna element because of this tree-like structure. This isolating structure makes the design very complex and relatively large in size.

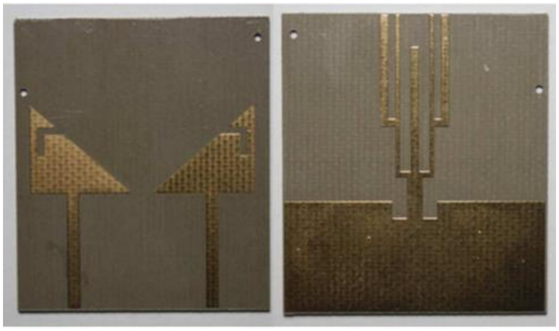


Figure 2.11: Geometry of monopole UWB-MIMO antenna with tree-like structure [13]

Comparison

Different isolation techniques have been reported in literature. Every technique has its own advantages and limitations. Some decoupling structures and neutralization lines result in designs with relatively large size and increased complexity. From all listed techniques, T-shaped slot among antenna elements enhances isolation level without compromising compactness of design. So, use of slot antennas with T-shaped slot in the ground plane is considered one of the most appropriate solutions for compact designs.

# Chapter 3

# An Ultra-Wideband MIMO Antenna for Radar and Imaging Devices with Band-Rejection Capability

In this chapter, detailed design procedure of UWB-MIMO antenna using annular slot antennas has been discussed and elaborated. This design is majorly proposed for radars and imaging devices. Furthermore, simulated and measured results are compared. Figures for Surface current distribution, radiation efficiency, effective correlation co-efficient, impedance matching and isolation over entire UWB have been shown and discussed with parametric analysis.

## 3.1 Design Process

Antenna is designed in 3 major steps to fulfill all the essential requirements of UWB-MIMO antenna design that include better impedance matching over the whole band, desirable isolation level and band notch characteristic. Figure 3.1(a-d) displays the step by step designing of the antenna.

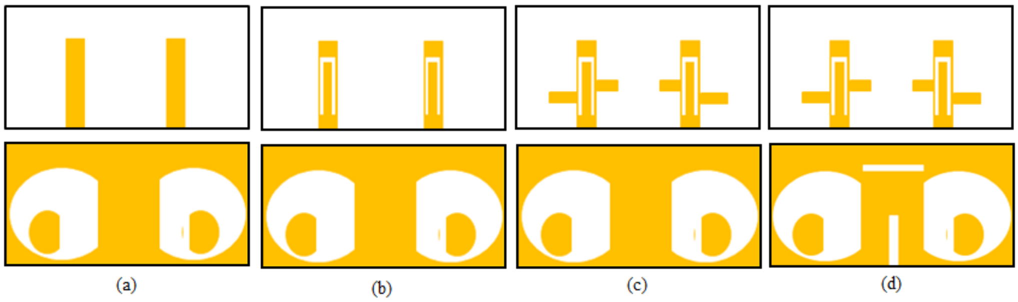



Figure 3.1: (a) Step1: the driven semi-circular slot only (b) Step2: the driven semi-circular slot and filtering inverted U-shaped slot in transmission line (c) Step3: the driven semi-circular slot and filtering inverted U-shaped slot in transmission line

### 3.1.1 Design of Radiating Element

In step1, two semi-circular annular slots are etched on the back side of antenna. These slots are fed at the center by 50Ω micro-strip feed lines. This feeding mechanism bring better radiation patterns but poor impedance matching at upper band of frequencies as shown in Fig. 3.2. Length and width of both feed lines are optimized for perfect matching. Radiating patches inside slots help in covering complete ultra-wideband.

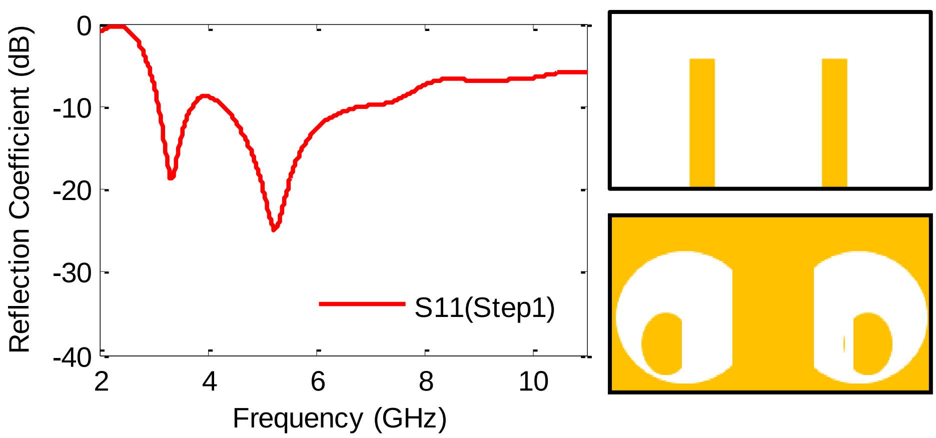



Figure 3.2(a) Simulated reflection coefficients for step1

### 3.1.2 Design of Filtering Technique

This step involves introduction of some filtering technique to reject WLAN frequency band. This band causes interference with existing UWB devices, so there is intense need of rejecting this band. In proposed design, some filtering technique is introduced in feed-line of slot antenna. An inverted U-shaped slot is incorporated in feed line as displayed in Fig. 3.2(b). Length of this slot defines center frequency of rejected band and position of slot inside feed line defines the level of reflection coefficient achieved. This level must fall below -4dB but we has achieved around -2.6dB to suppress undesired radiation in this specific band of operation.

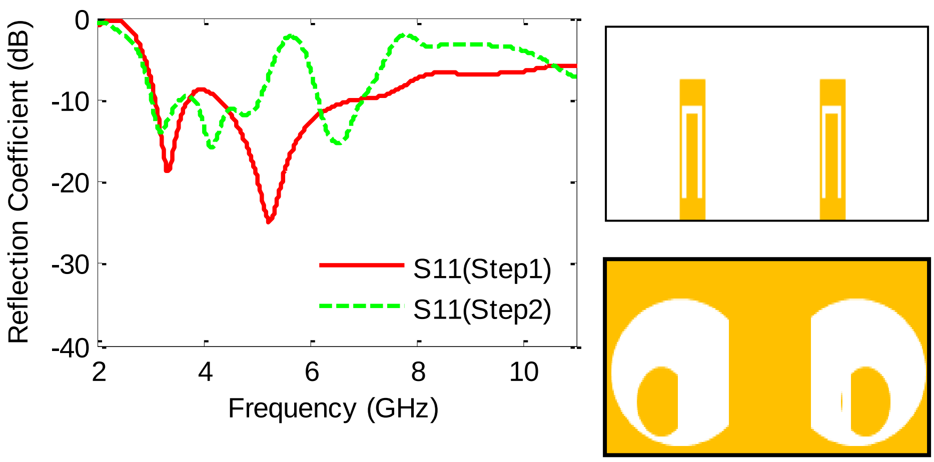



Figure 1Figure 3.2(b): Simulated reflection coefficients for step2

### 3.1.3 Improvement in Impedance Matching

This step includes improvement in impedance matching at higher frequencies as presented in Fig. 3.2(c). Due to central feeding mechanism of slots, impedance matching at higher frequencies is affected badly due to higher radiation resistance. There are 3 different micro-strip feeding mechanisms to improve impedance matching and reducing radiation resistance. First one is to use **off-center feeding**. Second one is to use center feeding but with **use**

**of stubs along with feed line**. These stubs bring reactive loading to antenna, hence changing its input impedance. Third method is to use center fed mechanism but the **slot must be inclined**. In this dissertation, we have employed second method to get desired results. Position on stubs has greater impact over impedance matching as compare to widths of stubs.

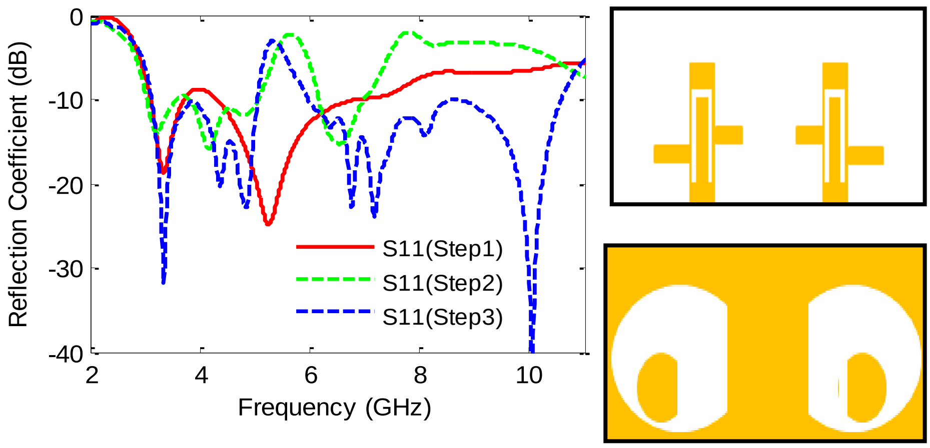



Figure 3.2(c): Simulated reflection coefficients for step3

### 3.1.4 Isolation Technique

This final design step4 is solely for improvement in isolation between both antennas and their ports while above 3 steps were majorly done for improvement in impedance matching with band notching characteristic. Two slots are etched in between both radiating slots as shown in Fig. 3.2(d). One is placed vertically that improves isolation at lower frequencies. While the other one is placed horizontally near upper edge of ground plane for isolation improvement at higher frequencies. Fig shows clear impact of both slots on isolation.

### 3.1.5 Final Design

An UWB-MIMO antenna is designed for radar and imaging devices. Annular slot antenna is preferred for antenna element of MIMO system due to its

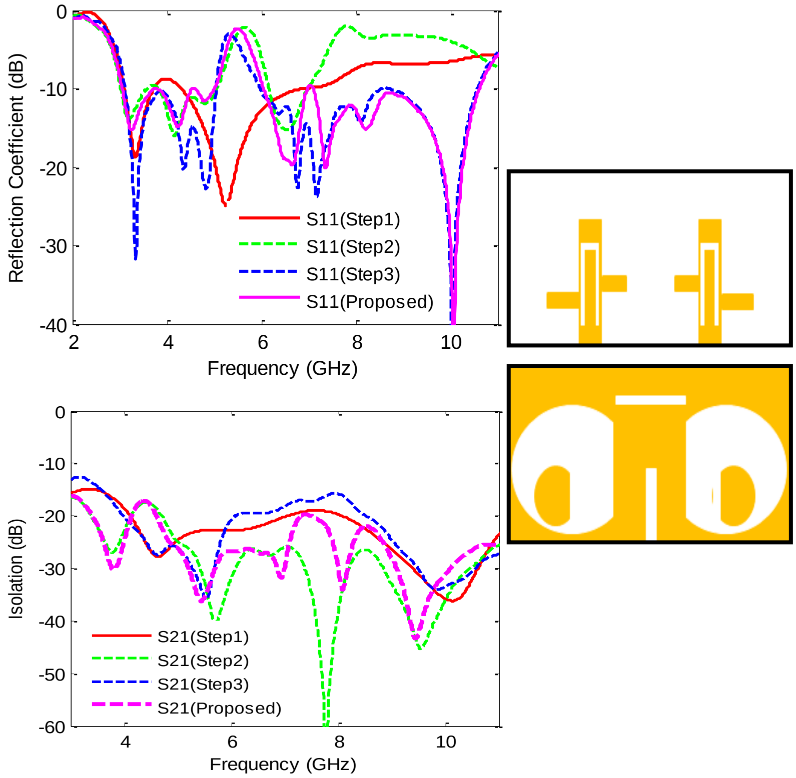



Figure 3.2(d): Simulated reflection coefficients for step1, 2, 3 and 4

bidirectional radiation properties. Each antenna has radiating patch to radiate efficiently in desired band of frequencies. Distance between lower edges of patch and slot has greater impact on impedance matching. Furthermore, stubs are added along with feed lines to improve impedance bandwidth. This design has achieved radiation efficiency up to 98%. Introduction of an inverted U-shaped slot inside feed line behaves as band-stop filter. It rejects WLAN frequency

TABLE 3.1

VALUES OF ANTENNA DIMENSIONS (IN MILLIMETER)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Parameters | L | W | L1 | L2 | L3 | L4 | L5 |
| Values | 27 | 58 | 14.75 | 7.2 | 11.5 | 10 | 11.5 |
| Parameters | L6 | w1 | w2 | w3 | w4 | w5 | w6 |
| Values | 8 | 2.7 | 1.3 | 1.1 | 0.4 | 0.4 | 1 |
| Parameters | d1 | d2 | d3 | d4 | d5 | d6 | R1 |
| Values | 2.7 | 6.5 | 9.7 | 8.7 | 2.1 | 23.5 | 10.4 |
| Parameters | R2 | r3 | r4 | s1 | s2 | g1 | g2 |
| Values | 12 | 5 | 5 | 3.68 | 3.18 | 1.7 | 4.75 |

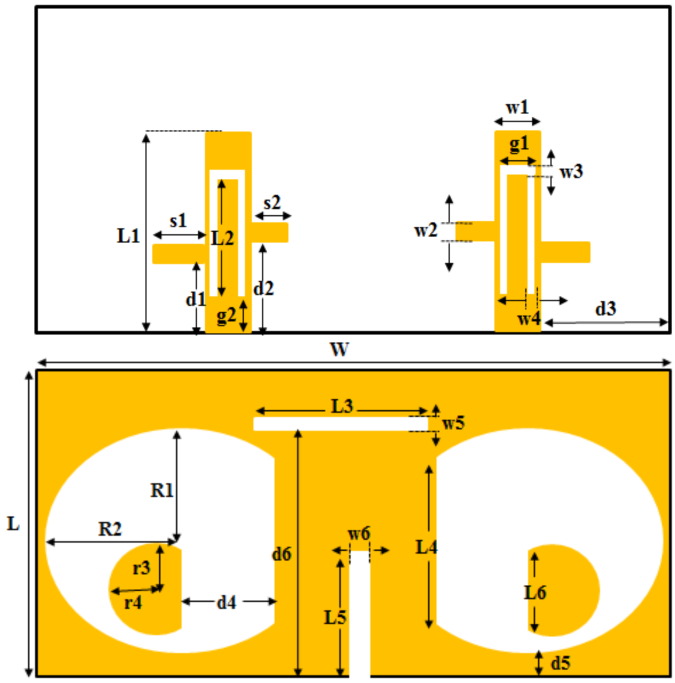



Figure 3.3: Final and detailed geometry of proposed UWB-MIMO antenna.

band efficiently with radiation efficiency of 16% that helps in suppressing undesired radiations in complete WLAN frequency band. Two rectangular slots are added for reduction in coupling between both ports. These slots have brought isolation level better than 16.5dB.

## 3.2 Parametric Analysis

This section gives clear view of dependence of some antenna dimensions on desired results.

### 3.2.1 Effect of Stubs

Position of stubs greatly affects the impedance matching at higher frequencies. Fig. 3.4(a) shows the impact of stub position on reflection coefficient at higher frequencies. Impedance matching at lower frequencies remains unchanged by these stubs. These stubs help in achieving better impedance matching over entire ultra-wide band.

## 3.2.2 Effect of Vertical and Horizontal Slots

These slots help in reduction in mutual coupling between antenna elements. Length of vertical slot has greater impact on isolation at lower frequencies as shown in Fig. 3.4(b). Similarly, position of horizontal slot also affects coupling at higher frequencies. These slots have very negligible effect on reflection coefficient of design. Comparison of curves shows strong dependency of isolation on horizontal slot at higher ultra-wideband.

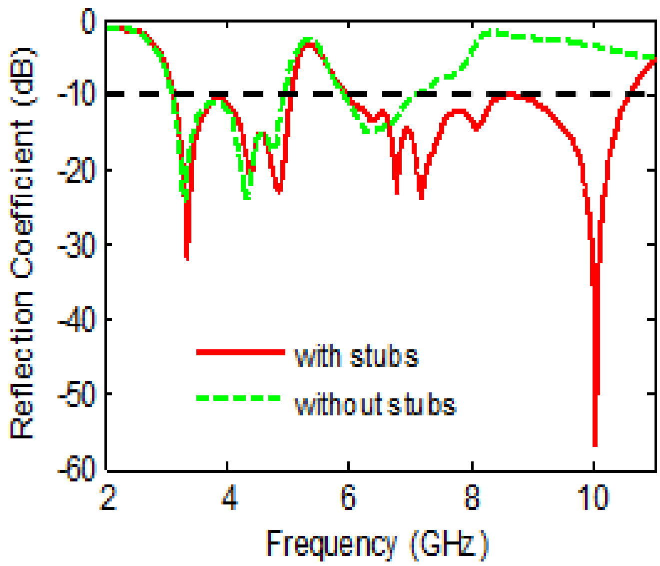



Figure 3.4(a): Reflection coefficient with and without matching stubs.

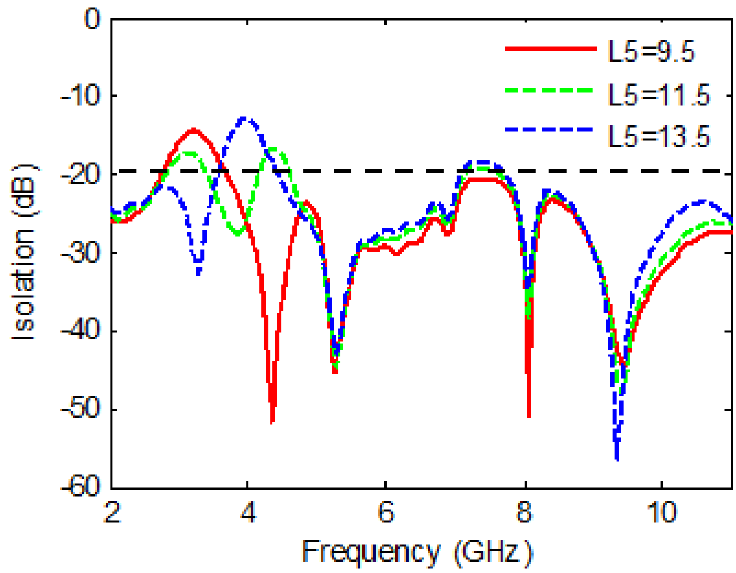



Figure 3.4(b): Reflection coefficient for different lengths of vertical slot.

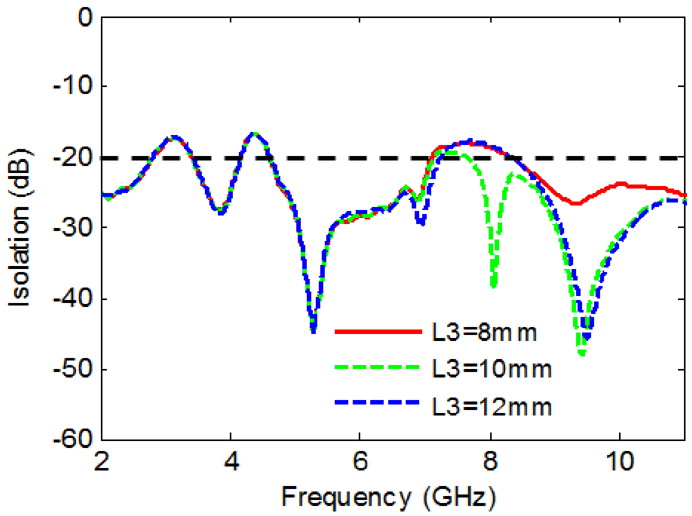



Figure 3.4(c): Reflection coefficient for different lengths of horizontal slot.

### 3.2.2 Effect of Filtering Slot

This slot is totally behaving as band stop filter. Its length determines center of frequency of rejected band i.e. WLAN as shown in Fig. 3.4(d) and its width determines the bandwidth of rejected band as shown in Fig. 3.4(e). This slot has nothing to do with isolation or impedance matching in remaining band of operation i.e. 3.1-5GHz.

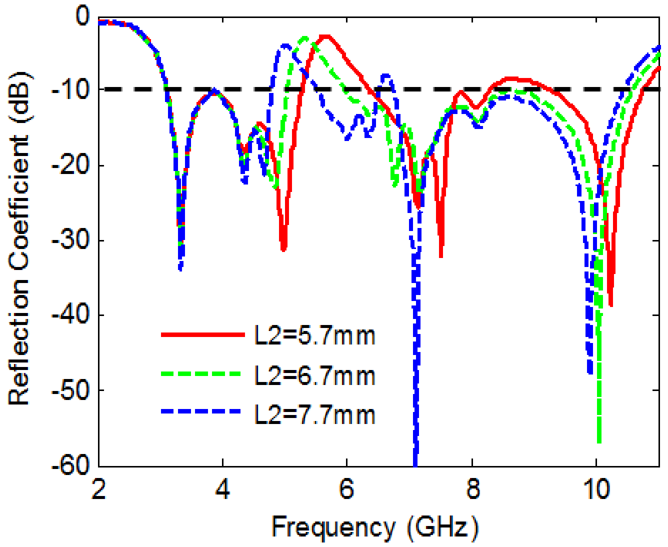



Figure 3.4(d): Reflection coefficient for different lengths of filtering slot.

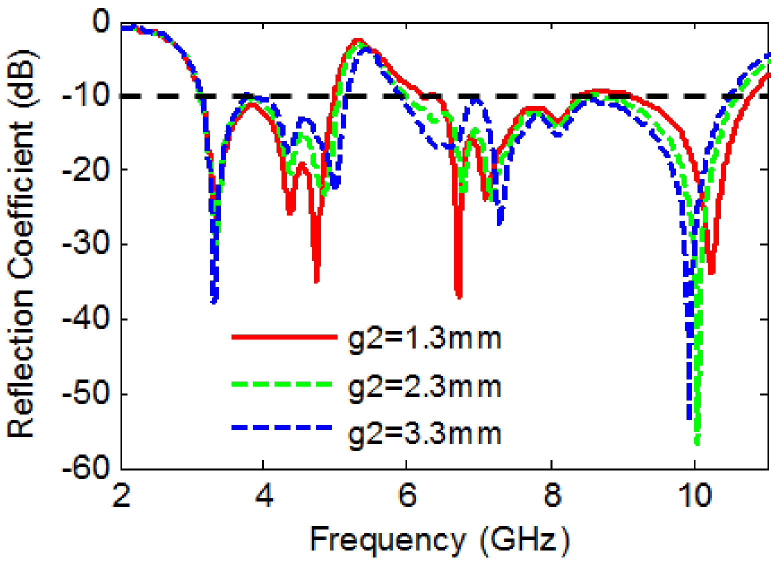



Figure 3.4(e): Reflection coefficient for different positions of filtering slot.

## 3.3 Results and Discussions

The antenna prototype is effectively fabricated for radar and imaging devices. FR-4 substrate ($\varepsilon_r$=4.4, tanδ = 0.02) with a thickness of 0.8 mm is used as a substrate. Achieved antenna size is 58×27mm² with uni-planar geometry that is acceptable for radars and imaging devices. Both slots are fed by 50Ω micro-strip line made on top side of FR4 substrate. The fabricated prototype of the antenna is presented in Fig. 3.5.

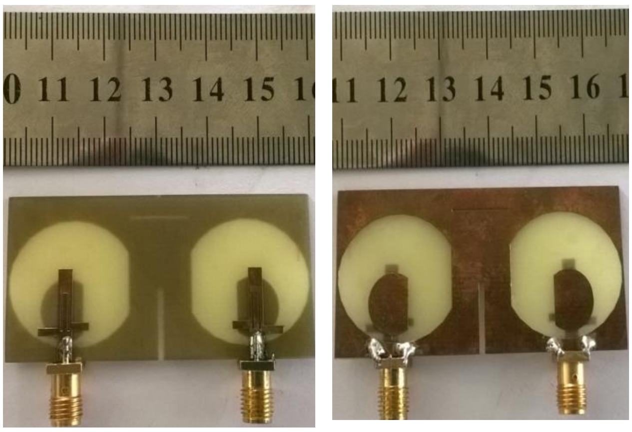



Figure 3.5: Photo of the fabricated UWB-MIMO Antenna

## 3.3.1 Scattering Parameters

Agilent E8362B vector network analyzer is used to get measured results of fabricated antenna. Fig. 3.6 and Fig. 3.7 show comparison of simulated results with measured ones for S11 and S21. Both results are close to each other. This difference is due to SMA connectors. This antenna design has covered complete UWB with better impedance matching over entire Ultra-wideband.

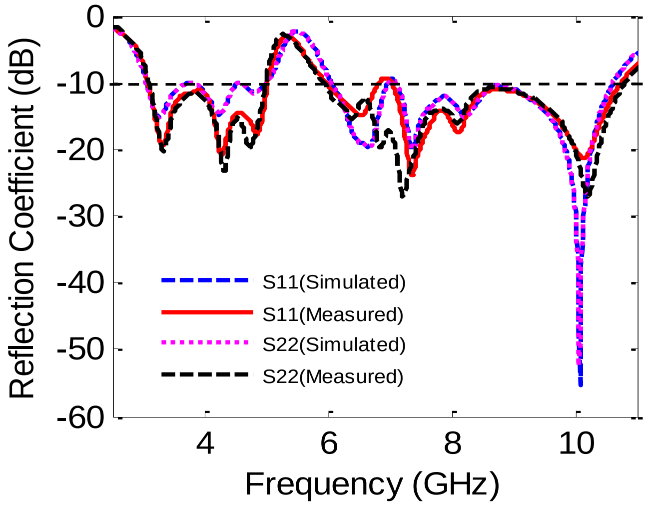



Figure 3.6: Simulated and measured S11, S22 for proposed design.

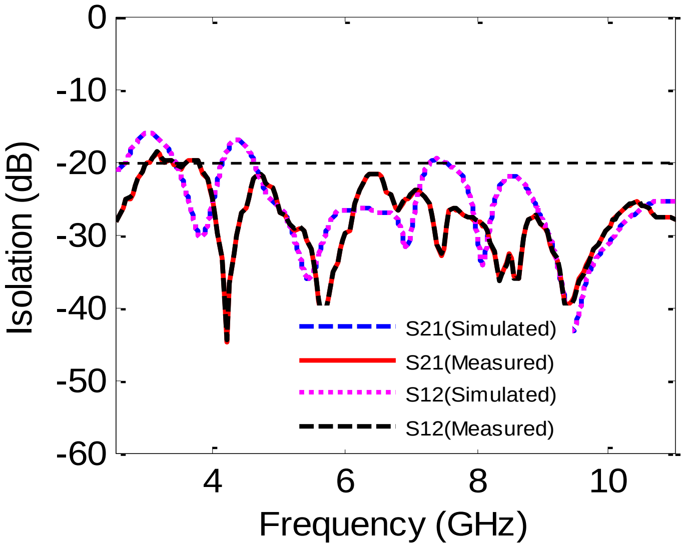



Figure 3.7: Simulated and measured S12, S21 for proposed design.

## 3.3.2 Surface Current Distribution

Surface current distribution analysis helps in better understanding of antenna design. Fig. 3.8 shows current distribution at different frequencies i.e. 4GHz, 5.49GHz, 6GHz, 9GHz for port1 excited and port2 terminated with 50Ω resistive load. At all frequencies, it is clear that surface current of one antenna element is not disturbing other antenna element. That means that both ports are highly isolated from each other that is the most important requirement of MIMO antenna design. Surface current distribution at notched frequency i.e. 5.49GHz is evidently displaying that current at this frequency is highly cancelled out because of better placement of filtering slot. This cancellation of current density brings suppression in radiation at desired band of frequency.

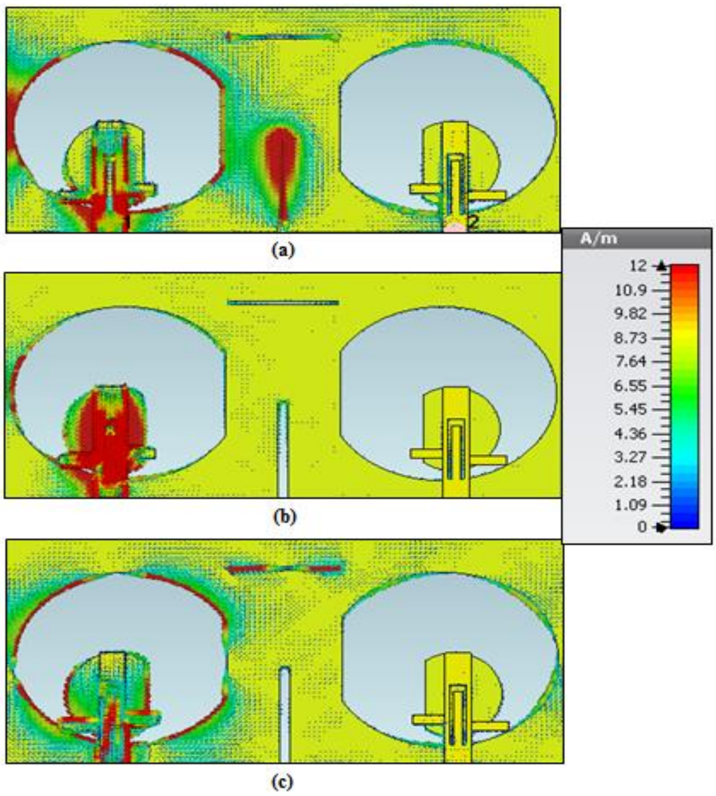



Figure 3.4: Surface current distribution at (a) 4GHz, (b) 5.4 GHz, (c) 9GHz.

### 3.3.3 Radiation Patterns

Fig. 3.9 and Fig. 3.10 show E-plane and H-plane of proposed design and radiation patterns of co-pol and cross-pol for both ports to show symmetry of proposed design. Radiation patterns for port1 are obtained with port1 excited and port2 terminated with a 50-Ω load and vice versa for port2.

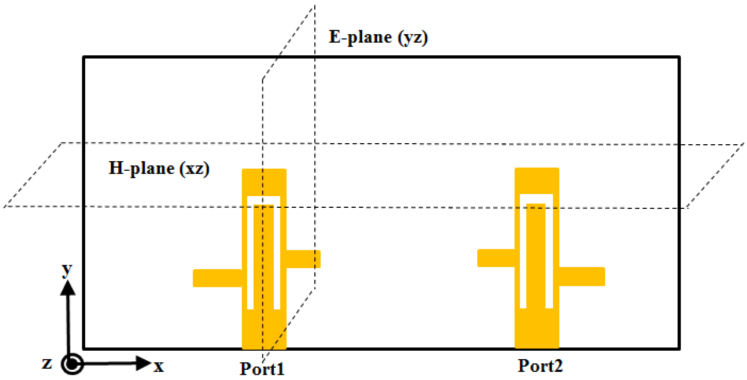
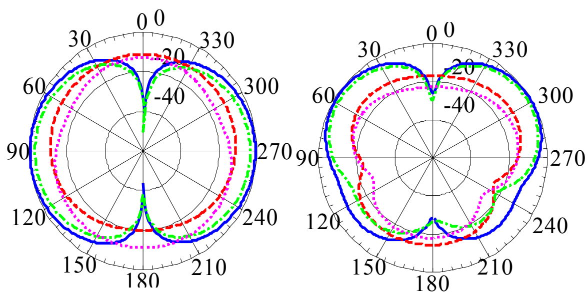
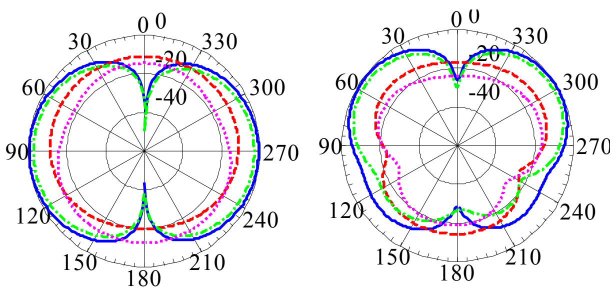



Figure 3.9: E and H-Planes of proposed design.

PORT 1, H- PLANE (XZ PLANE)



PORT 2, H- PLANE (XZ PLANE)



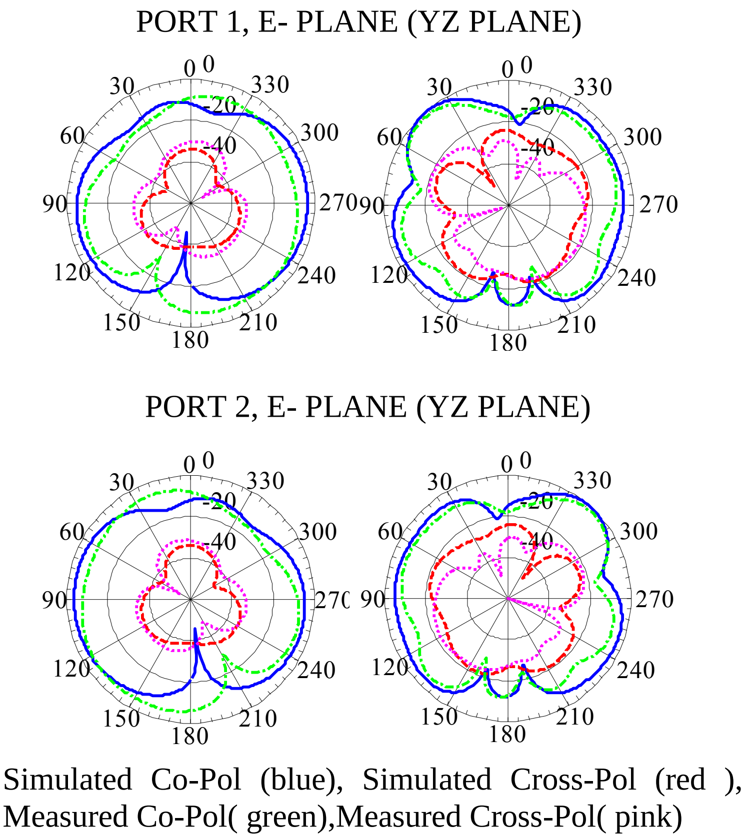



Figure 3.10: Simulated and measured radiation patterns at 4GHz (Column 1) and 8GHz (Column2)

It is quite obvious from these polar plots that radiation patterns for both ports are quite similar but mirror images along the y-z plane. Radiation patterns are Omni-directional but slightly directional towards $\theta = 270°$ . Furthermore, comparison of co-pol and cross-pol gains shows cross polar difference around -20dB.

## 3.3.4 Radiation Efficiency

Fig. 3.11 presents the radiation efficiency of the proposed design. For entire ultra-wideband, an antenna to work efficiently, its radiation efficiency must be greater than 70%. This proposed design has achieved maximum radiation efficiency of about 98%. At notched frequency, its efficiency must fall below 25% to suppress undesired radiation but this design has achieved radiation efficiency of 16% at notched frequency band that means its filtering technique is better for band rejection.

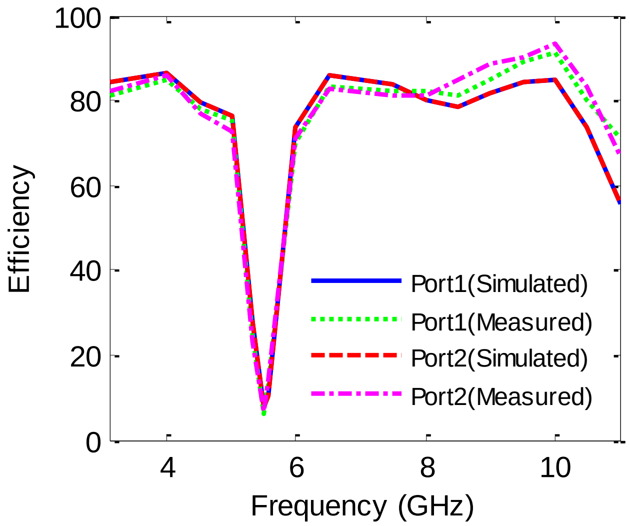



Figure 3.11: Simulated and measured antenna efficiency for both ports

## 3.3.5 Envelope Correlation Coefficient

Fig. 3.12 shows envelope correlation coefficient (ECC) that is most significant factor for design of any diversity antenna. This performance parameter tells about correlation among radiation patterns of MIMO elements. Radiation pattern of one antenna element should not disturb radiation pattern of other one. Level of correlation must be very less i.e. ECC $\leq 0.3$ for better MIMO performance. This antenna design has achieved ECC lower than 0.3 for whole ultra-wide band.

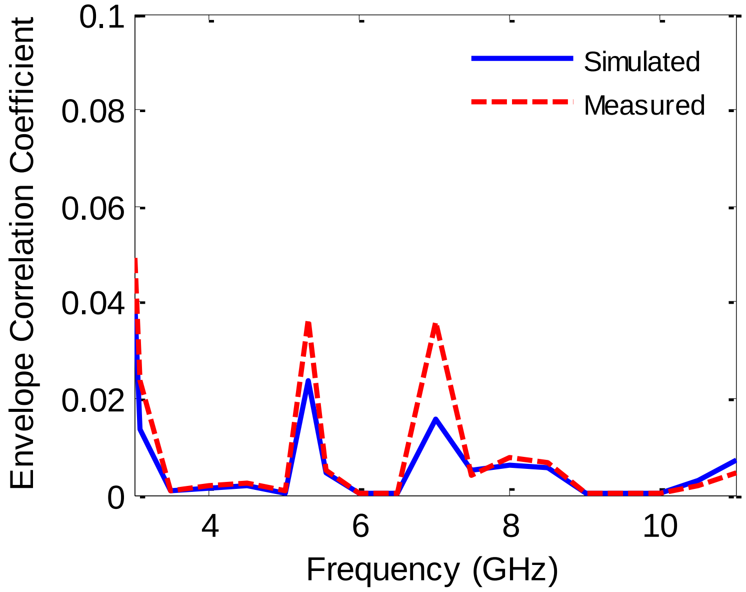



Figure 3.12: Simulated and measured envelope correlation coefficient

# Chapter 4

# A Compact UWB Diversity Antenna with Enhanced Isolation and Band-Rejection Capability

This chapter discusses the detailed design of an ultra-wide band MIMO antenna with compact size for portable devices. Major achievement in this design is to castoff electromagnetic interference among antenna elements at lower frequencies i.e. 3.1 – 4.8 GHz with a very compact size that is the true challenge I this research domain. Some important performance factors of UWB-MIMO antenna including simulated and measured reflection coefficients, isolation among ports, antenna efficiency along with envelope correlation coefficient and radiation patterns are also discussed in this chapter.

## 4.1 Design Process

### 4.1.1 Design of Radiating Element

In step1, two slot antennas are used on the back side of design as main radiating elements as shown in Figure 4.1(a). Rectangular stepped slots are etched on the back side of antenna to cover entire UWB. These slots are off-centered fed by 50Ω micro-strip lines so there is no need of stub matching. It is printed on 0.8mm thick FR4 substrate, loss tangent of 0.02 and relative permittivity of 4.4.

Each slot has two sharp steps. Broader slot is for radiating efficiently and narrower slot is for better impedance matching with feed line. While small steps in slots are for improvement in impedance matching. Slot antennas can be used in any shape i.e. circular, elliptical, annular or rectangular. Shape of slot doesn't make big difference but size of slot majorly affects the bandwidth of covered UWB. At this stage, better impedance matching over entire UWB is achieved

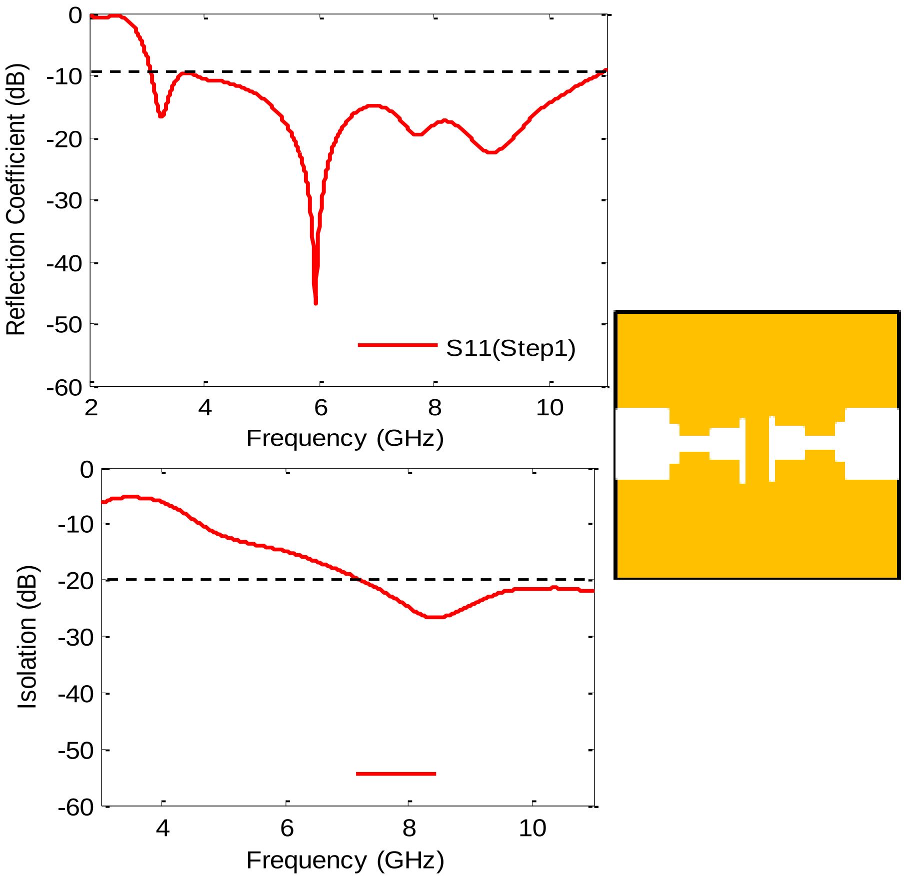



Figure 4.1(a): Reflection coefficient(S11, S22) and isolation (S21, S12) for step 1.

### 4.1.2 Design of Filtering Technique

In step2, a stepped z-shaped slot is cut under main radiating slot on back side as presented in Figure 4.1(b). It acts as band stop filter for WLAN frequency band. This stepped z-shaped slot generates the resonance at WLAN (5.15-5.85 GHz) and creates a notch to suppress radiations in desired band (WLAN).

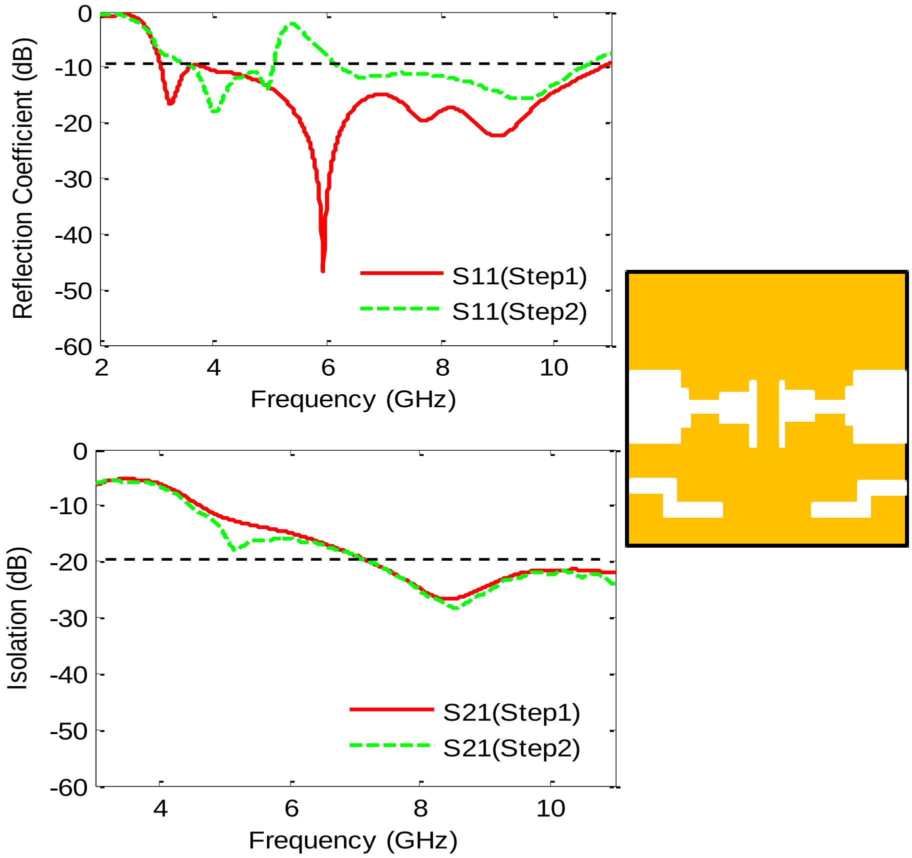



Figure 4.1(b): Reflection coefficient(S11, S22) and isolation (S21, S12) for step 2.

### 4.1.3 Isolation Technique

In final design step3, an inverted T-shaped slot is employed on back side of antenna near upper edge of antenna geometry. This slot helps in reduction in mutual coupling at lower frequencies. Another rectangular slot is placed vertically between both antenna elements to reduce coupling at higher frequencies. Figure 4.1(c) displays the simulated S11 for the reference antennas and the proposed antenna.

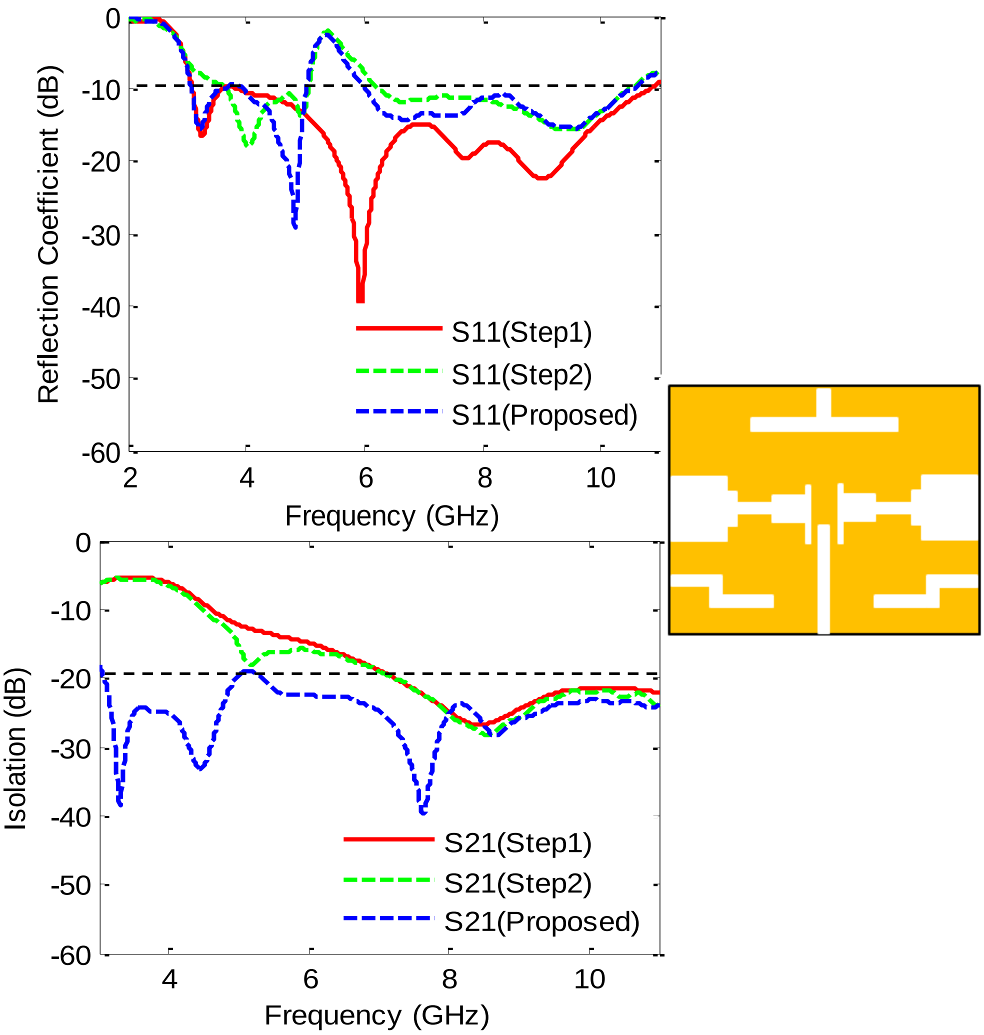



Figure 4.1(c): Reflection coefficient(S11, S22) and isolation (S21, S12) for step 3.

### 4.1.4 Final Design

Geometry of UWB-MIMO antenna is presented in Fig. 4.2 with optimized dimensions given in Table 4.1. The antenna has a uniplanar structure with dimensions of 27×22mm². The antenna design consists of stepped rectangular slots whish act as main radiating elements of UWB-MIMO antenna. These radiating slots are fed by stepped micro-strip transmission lines. Radiating slot size matters a lot for better impedance matching over frequency decreases and total bandwidth covered increases. The reason behind decrease in lower cut-off frequency is that the larger the slot whole ultra-wide band. By increasing the size of slot, longer current paths will result in resonance at lowest possible frequency and vice versa. So, increase in slot size has a limitation because of coupling issue in limited available size. Z-shaped slot is inserted for band rejection at WLAN band. Vertical slot in the middle of two antenna elements is introduced to isolate both elements. It maintains good isolation at higher band of frequency i.e. 5-10.6 GHz while an inverted T-shaped slot on the upper edge of ground plane reduces coupling at lower band of frequency i.e. 3-5GHz.

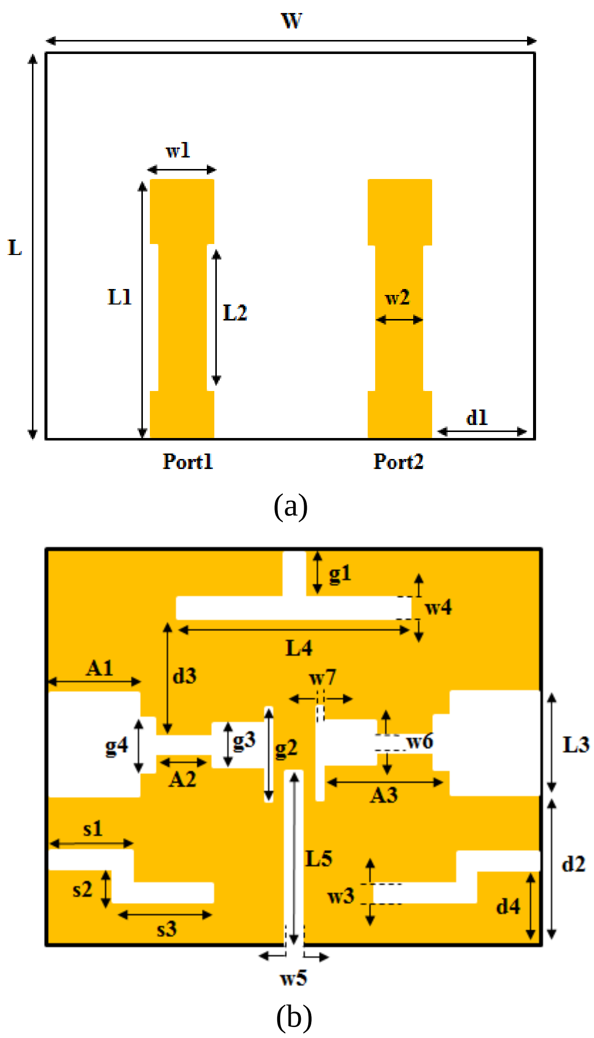



Figure 4.2: Final geometry of proposed UWB-MIMO antenna (a) Top View (b) Bottom View

TABLE 4.1
VALUES OF ANTENNA DIMENSIONS (IN MILLIMETERS)

| Parameters | L | W | L1 | L2 | L3 | L4 | L5 |
|---|---|---|---|---|---|---|---|
| Values | 23 | 22 | 14.75 | 8 | 5 | 12 | 10.7 |
| Parameters | w1 | w2 | w3 | w4 | w5 | w6 | w7 |
| Values | 2 | 1.4 | 0.4 | 0.4 | 0.7 | 1 | 0.3 |
| Parameters | d1 | d2 | d3 | d4 | A1 | A2 | A3 |
| Values | 8 | 8.5 | 10.5 | 7 | 3.2 | 3.5 | 7.25 |
| Parameters | s1 | s2 | s3 | g1 | g2 | g3 | g4 |
| Values | 2.5 | 2.05 | 5 | 0.6 | 4 | 1.4 | 3 |

## 4.2 Parametric analysis

Effects of inverted T-shaped slot, stepped z-shaped slot and vertical slot are given below.

### 4.2.1 Effect of Inverted T-shaped Slot

A filtering slot in T shape cut in the ground plane of antenna is solely for isolation enhancement at lower band of frequencies that is 3-5GHz. This band of UWB is the most crucial one for impedance matching as well as isolation among ports for those scenarios where we encounter space limitation. An Inverted T-shaped slot helps in keeping the overall size of antenna compact. Position of placement of this slot has greater impact on isolation level as compare to its other dimensions. Fig. 4.4(a) shows the impact of slot position that is the clear proof of importance of its placement. Exact positioning of this slot has brought isolation level better than 25dB that has not been achieved so far.

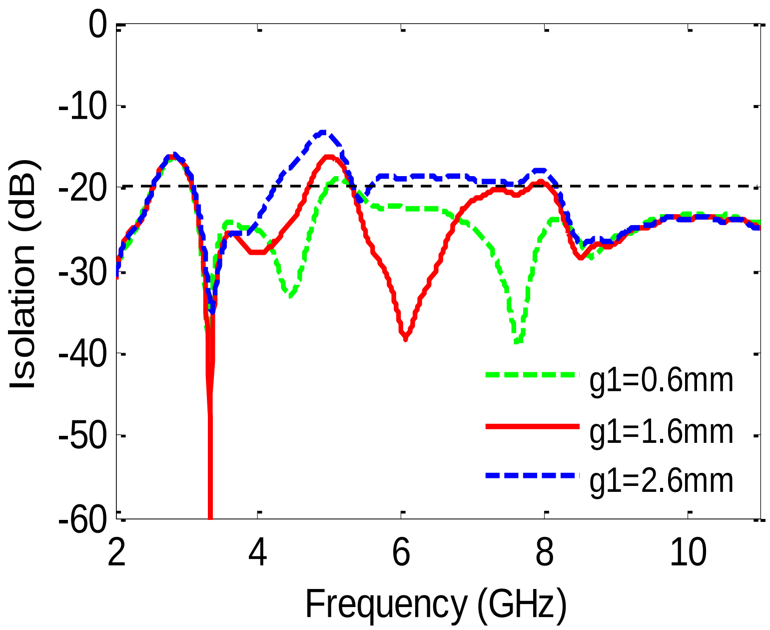



Figure 4.4 (a): Isolation as a function of inverted T-shaped slot position.

## 4.2.2 Effect of Stepped Z-shaped Slot

Stepped z-shaped slot is etched right below main radiating stepped slots in ground plane. Band stop filtering technique is incorporated in ground plane of antenna to reject complete WLAN frequency band. Its vertical length has greater impact on center frequency of rejected band. Its resonant length is measured by following formula:

$$L_{slot} = s1 + s2 + s3 = \frac{c}{2f_c\sqrt{\varepsilon_{eff}}}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}$$

Here, $L_{slot}$ = 2.5mm + 2.05mm + 5mm = 9.55mm which is almost equal to $\lambda/4$ where $\lambda$ is guided wavelength. In above mentioned equation, $f_c$ is the center frequency of Notched band and $\varepsilon_{eff}$ is variable for substrate effective permittivity. As the length increases from its resonant length, center frequency shifts to lower values and vice versa. It has major effect on impedance matching only at rejected band of frequencies as shown in Fig. 4.4(b), but isolation level remains unchanged by changing its length.

### 4.2.3 Effect of Vertical Slot

Vertical slot in between two antenna elements is for isolation improvement at higher band of frequencies. Its length has more effect on isolation as compare to its width. Change in isolation level with change in vertical slot length is shown in Fig. 4.4(c). This slot has very minor impact on impedance matching over the whole band. Due to symmetry of antenna, S11 and S21 are same as S22 and S12. So, graph for S11 and S21 is shown here for parametric analysis of different dimensions.

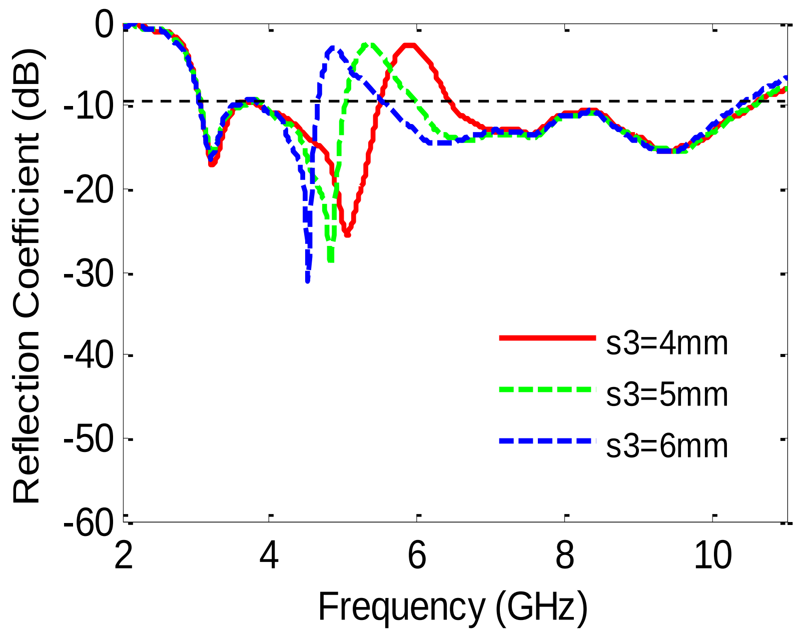



Figure 4.4 (b): Reflection coefficient as a function of z-shaped slot length.

## 4.3 Results and Discussion

The proposed design is effectively fabricated for portable devices. Fabricated prototype is presented in Fig. 4.5. The antenna is made on 0.8mm thick FR-4 substrate ($\varepsilon r$=4.4, tan$\delta$ = 0.02) with overall size of 26×23mm².

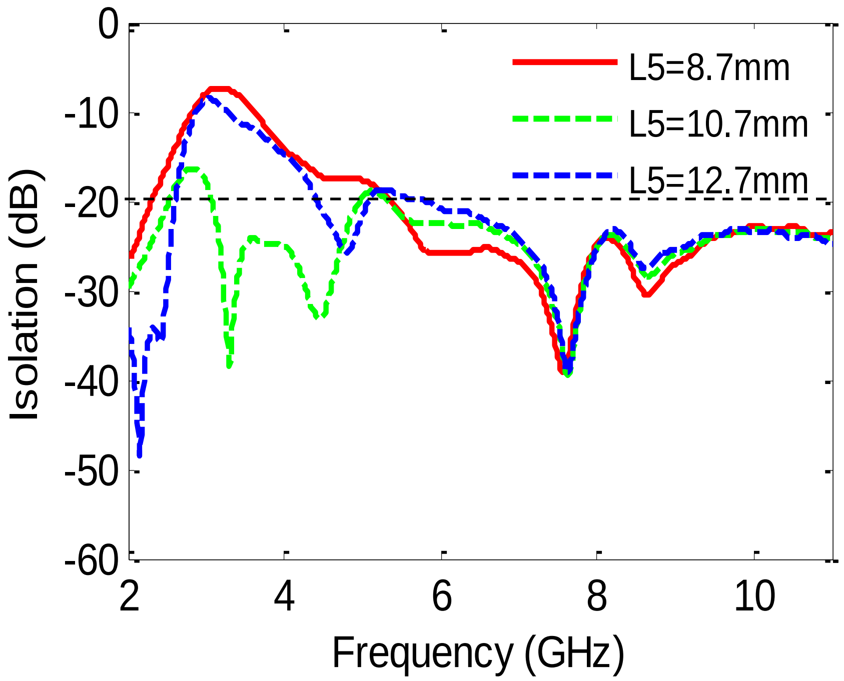



Figure 4.4 (c): Isolation as a function of vertical slot length.

### 4.3.1 Scattering Parameters

Vector network analyzer (Agilent E8362B) is used to measure scattering parameters of proposed design. Measured and simulated results of S11 and S21 are shown in Fig. 4.6. Both show little deviation from each other because of manufacturing tolerance, feeding cables used and SMA connectors. S11 and S22 of proposed design are given in Fig. 4.6a while isolation level among antenna elements is shown in Fig. 4.6b. It is clear from the graph that radiating slots have covered complete ultra-wide band with band stop filtering effect at WLAN. This band notching is introduced by adding stepped z-shaped slot in ground plane. Reflection coefficient less than -10dB and isolation better than 25dB at lower band of frequencies make it suitable candidate for devices using complete FCC UWB.

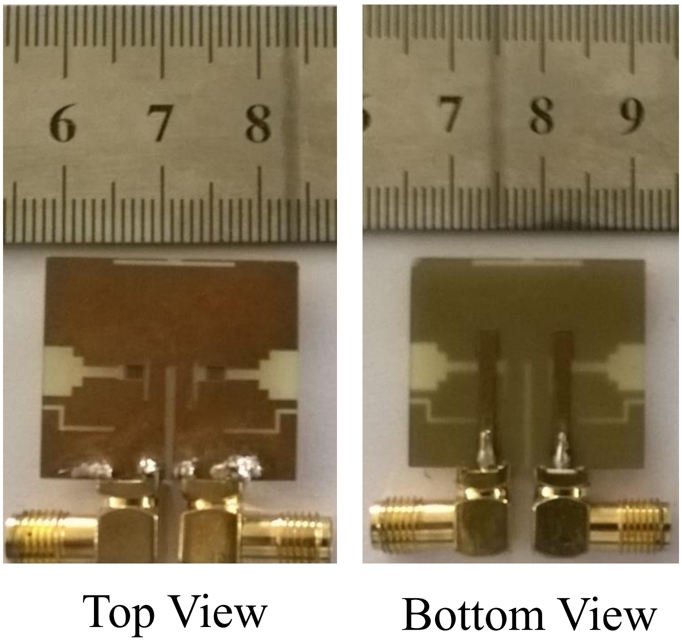



Figure 4.5 Fabricated Prototype of proposed design.

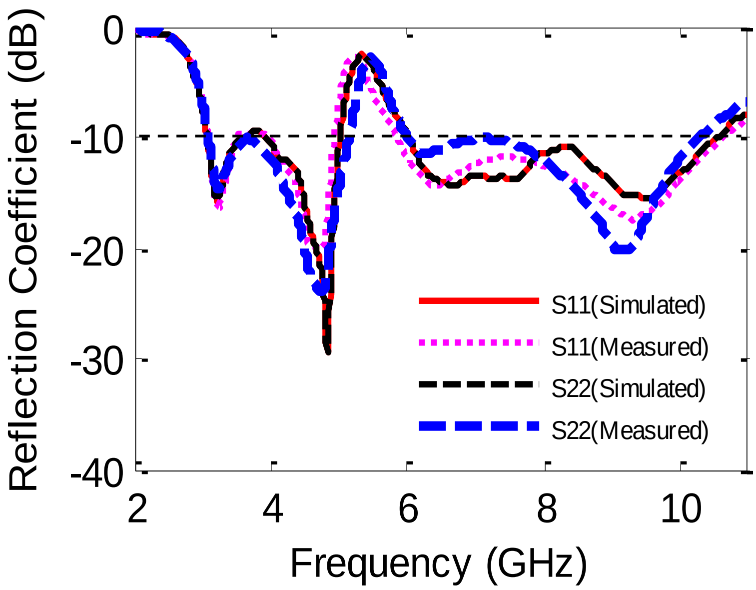



Figure 4.6a: Simulated along with measured reflection coefficients for both ports.

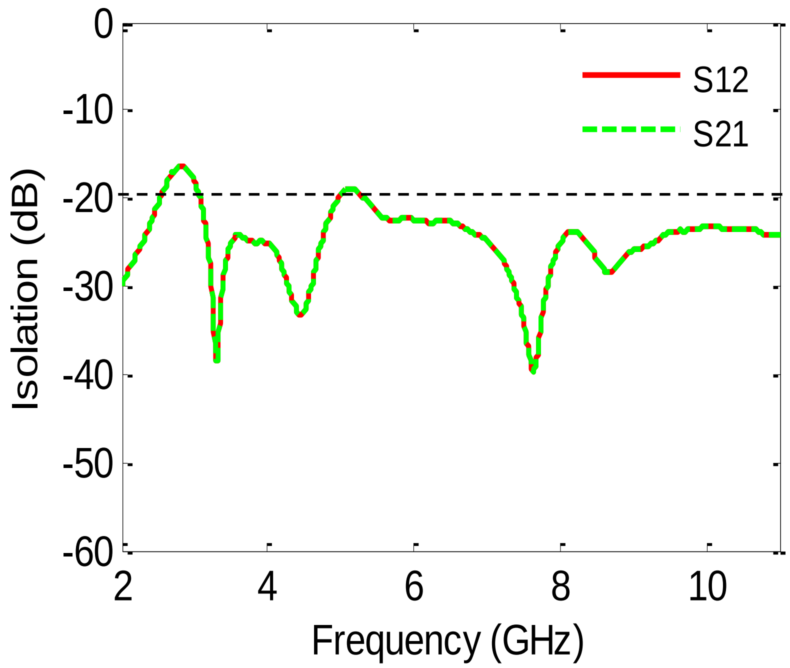



Figure 4.6b: Simulated isolation for both ports.

### 4.3.2 Surface Current Distribution

Surface current distribution is the most important parameter to see if the isolation technique is sufficient enough to reduce coupling among antenna elements or not. Furthermore, it tells about the placement of band rejecting slot. If more current is concentrated along slot, which means that slot is placed on the right place to cancel out more current. Fig. 4.7 shows current distribution before and after inverted T-shaped slot at 5.4GHz frequency when port1 is connected and port2 is non-excited. This is clear indication of importance of this slot. With slot, high density current is concentrated on first antenna and no current is developed on second antenna due to first antenna, which means that both are highly isolated especially at lower frequencies. Without slot, some current is also developed on the surface of other antenna element.

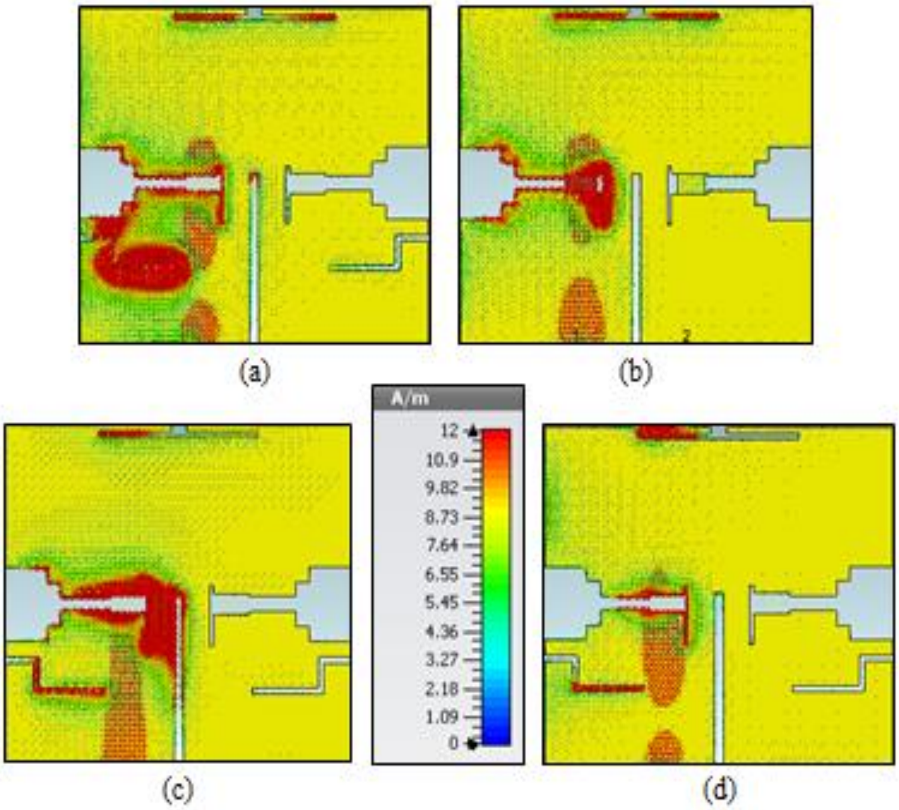



Figure 4.7: Current distribution at (a) 5.4 GHz (with z-shapped slot) (b) 5.4 GHz (without z-shapped slot), (c) 4 GHz and (d) 9 GHz

### 4.3.3 Radiation Patterns

The radiation patterns are evaluated in NSI far-field anechoic chamber at 4GHz and 7GHz with port1 excited and other terminated. E and H-planes are given in Fig. 4.8 while radiation patterns in Fig. 4.9. Radiation patterns measured with port2 excited and port1 terminated are mirror images of first ones along x-z plane because of symmetric antenna structure. Radiation patterns at different frequency show that proposed antenna design has almost stable radiation pattern at different frequencies except notched frequency. At notched frequency band, radiation pattern is much smaller as compare to other, which shows that antenna doesn’t radiate efficiently in the rejected band.

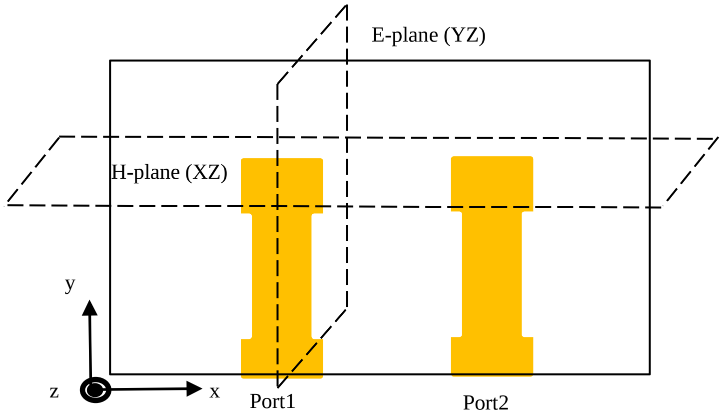
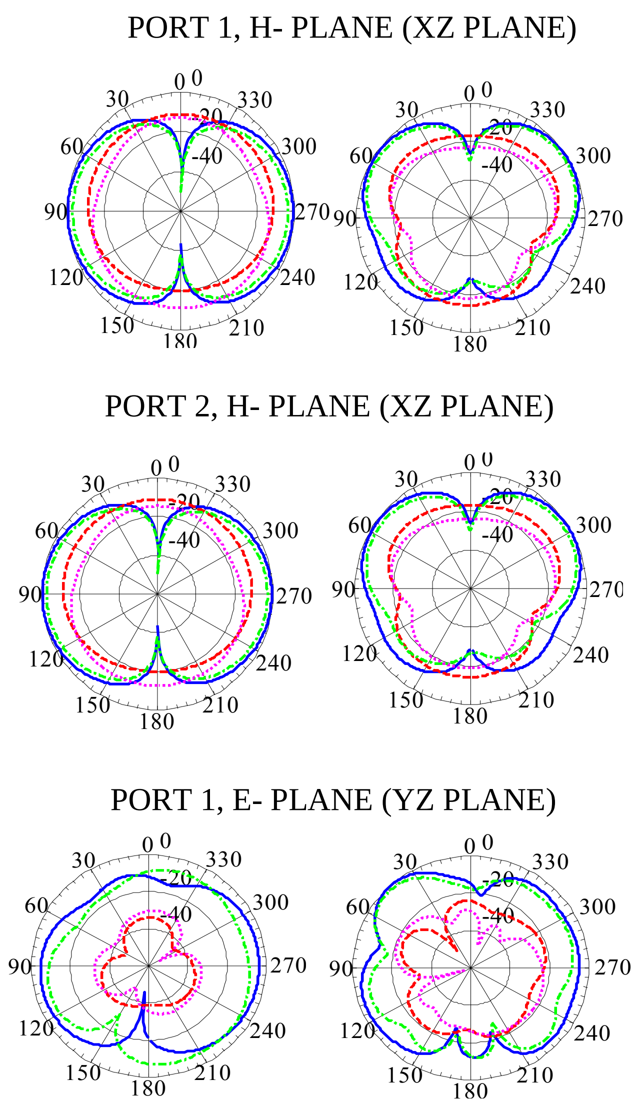
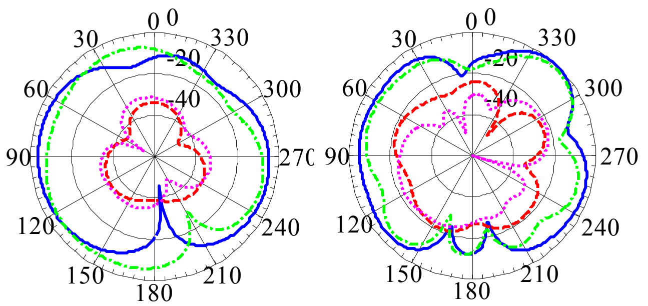



Figure 4.8: Front view of proposed antenna with E and H-planes.



PORT 2, E- PLANE (YZ PLANE)




Simulated Co-Pol (blue), Simulated Cross-Pol (red), Measured Co-Pol( green),Measured Cross Polarization( pink)

Figure 4.9: E,H-planes of proposed design at 4GHz (1st column) and 8GHz (2nd column)

## 4.3.4 Radiation Efficiency

Fig. 4.10 shows comparison of simulated and measured efficiency over the entire UWB. This graph shows that antenna has achieved efficiency up to 80%. At notched frequency, its efficiency falls down significantly. Antenna becomes non-responsive at this rejected band due to this deep-drop in efficiency and nothing radiates.

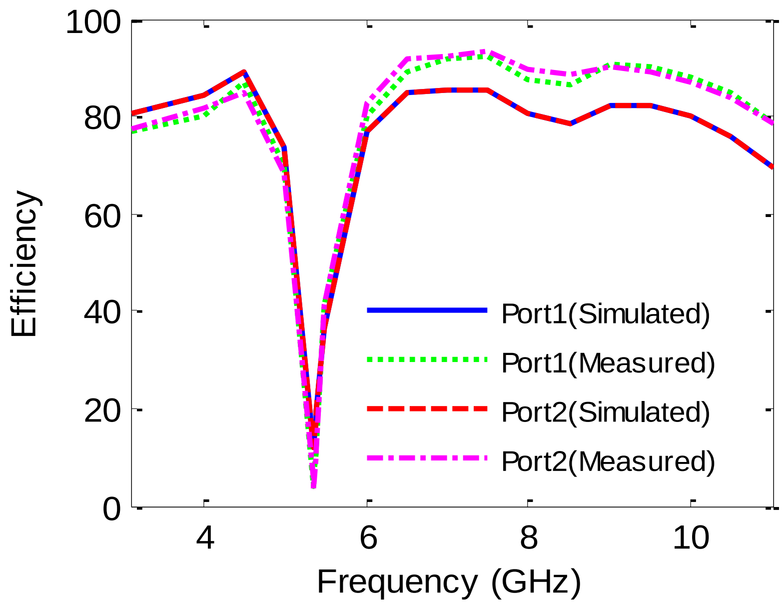



Figure 4.10: Simulated along with measured Efficiency of proposed design for both ports.

### 4.3.5 Envelope Correlation Coefficient

For best diversity performance, envelope correlation coefficient (ECC) is considered most significant important performance parameter. In this paper, 3-D radiation patterns of antenna are utilized to calculate exact ECC. So, ECC basically tells about correlation among the radiation patterns of MIMO elements at specific frequencies. Its level must be less than 0.3 for better MIMO performance. Fig. 4.11 shows graph for ECC that is clearly less than marked level that means its MIMO performance is better.

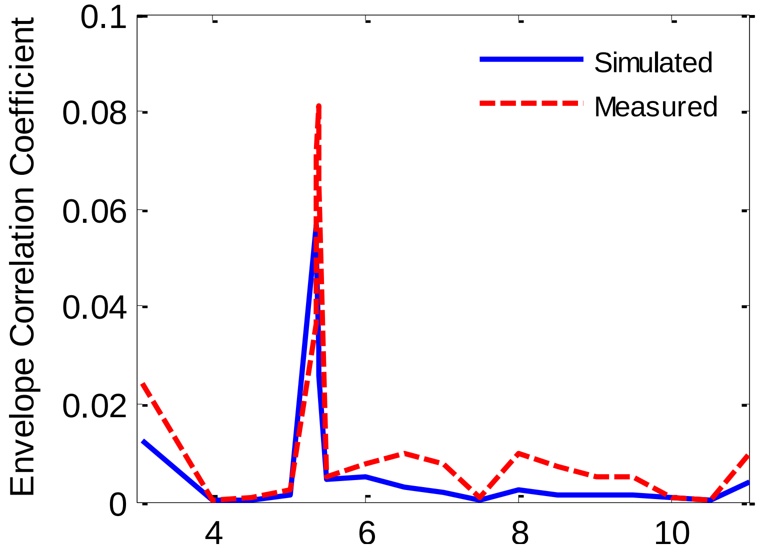



Figure 4.11: Measured along with simulated envelope correlation coefficient of proposed design.

# Chapter 5

# Conclusion and Future Work

With the increasing demand of higher channel capacities without wasting extra bandwidth and transmission power, MIMO concept along with ultra-wide band (UWB) has drawn intense focus. Different antenna types have been used in literature to cover complete ultra-wide band. Amongst all types of antennas, printed antennas are considered the most suitable ones for planar UWB-MIMO antenna designs. By comparing all types of printed antennas, slot antenna is considered the most suitable candidate due to its prominent features. These features include compactness, ease of fabrication, low cost and inherent directional properties. For UWB-MIMO antennas, isolation enhancement and band-rejection capability along with compact size are the key parameters that have to be considered more in designing stage. With the advancement in recent research trend in MIMO-UWB antennas, isolation enhancement among ports has become a center of motivation. Different isolation techniques have been reported in literature for isolation enhancement. Furthermore, due to interference issue of UWB with other existing technologies, different filtering techniques have been incorporated in literature.

In this thesis, two novel designs of UWB-MIMO antenna with simple configuration are realized with all important performance parameters. These parameters include better impedance matching, stable radiation patterns and minimum isolation level among ports. First design has overall size of 58×27mm². It is fabricated on 0.8mm thick FR4 substrate. Semi-circular slots help in achieving better impedance matching over entire ultra-wide band. WLAN rejection is achieved by inserting slots in the micro-strip transmission lines. Another antenna design is proposed for portable devices. This design is also fabricated on same substrate with overall size of 26×23mm$^2$. Major achievement of this design is maximum isolation achieved in the lower UWB that is better than 24.5dB. This level of isolation is realized by introducing a slot of T shape in the ground plane. Measured and simulated results for both antennas show good agreement. Radiation patterns are nearly Omni-directional. Stable radiation patterns, better impedance matching, stable gain and lower envelope correlation coefficient (ECC) level make these antennas promising candidates for UWB applications.  There are a lot more improvements in the related research field that can be focused in future. Slot antennas must be studied thoroughly to get deep insight due to its promising features. New isolation techniques must be introduced for compact designs.

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