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Design of semi-circular patch UWB MIMO antenna with rectangular stub

Graduate School of Chosun University

Department of Information and Communication Engineering

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직사각형 스터브를 갖는 반원형 패치
UWB MIMO 안테나 설계

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Advisor: Prof. Dong-You Choi

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Table of contents

List of figures

List of tables

Abstract

Design of semi-circular patch UWB MIMO antenna with rectangular stub

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The demand for highly efficient wireless systems has motivated many researchers to work on newer antenna designs. Advancement in any sector is inevitable and with the need to improve channel capacity of communication systems, to ensure quality of the link and with the evolvement of IOT (Internet of Things) devices, development of complex, compact and miniaturized antennas have become a high priority. Among the newer compact antenna technologies, multiple-input, multiple-output (MIMO) antennas are quite popular in the current communication market. At present, many wireless communication systems work in the frequency bandwidth, which are usually under ultra-wideband (UWB). Thus, in this thesis, a new and simple design approach for UWB MIMO antenna is described, in which a simple rectangular stub is introduced between two antennas to achieve high isolation.

The thesis paper presents an analysis of microstrip MIMO antenna of semi-circular patch structure with a simple rectangular stub introduced

between two antennas to enhance the isolation of the MIMO antenna. Introduction of simple stub eliminates the use of complex coupling or decoupling structure, complex feeding network or parasitic materials to achieve the desirable isolation. The MIMO antenna is designed and simulated using finite element method based High Frequency Structure Simulator (HFSS). The performance of the antenna is analyzed based on the simulated and measured results of reflection coefficient, radiation patterns, multiplexing efficiency, ECC and DG.

A novel feature of this design is that the UWB MIMO antenna has a high diversity gain of more than 9.99 (i.e. DG > 9.99), and the envelope correlation coefficient is lower than 0.003 (i.e. ECC < 0.003). The MIMO antenna also achieves wide impedance bandwidth from 5.4 to 11.9 GHz, which makes the antenna suitable for UWB applications. The high peak gain over the entire UWB and the upper part of the overall frequency band ensure that the antenna can be used in MIMO applications owing to the close agreement between the simulated and measured results.

요 약

직사각형 슬롯을 갖는 반원형 패치 UWB MIMO 안테나 설계

이 윤 황
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많은 연구자들은 고효율 무선통신 시스템을 위한 새로운 안테나를 지속적으로 개발하고 있으며, 무선통신 시스템의 채널 용량 향상과 링크 품질을 보장하고 IoT (Internet of Things) 기기의 진화에 따른 복잡하고 소형화된 안테나의 개발이 최우선 과제가 되고 있다.

특히, 최신 컴팩트 안테나 기술 중 MIMO (Multiple Input Multiple Output) 안테나에 대한 연구가 활발히 진행되고 있으며, 많은 무선통신 시스템은 UWB (Ultra Wide Band) 주파수 대역에서 활용되고 있다. 따라서, 본 논문에서는 두 안테나 사이에 직사각형 슬롯을 삽입하여 높은 격리도를 갖는 반원형 패치 UWB MIMO 안테나를 설계 및 제작하였다.

제안한 안테나는 HFSS (High Frequency Structure Simulator) 를 사용하여 설계 및 시뮬레이션을 진행하였으며, 반사계수, 방사패턴, ECC 및 DG 등을 기반으로 안테나의 성능을 평가하였다.

제안한 안테나의 주요 특징은 DG 9.99 이상, ECC 0.003 미만을 보임으로서 두 안테나 사이에 높은 격리도를 가지며, 주파수 대역폭은 5.4 ~ 11.9 GHz 로서 UWB 안테나의 주파수 대역에 충족함을 확인하였다. 또한, 시뮬레이션 결과와 측정 결과가 비교적 일치하였으며, 전체 주파수 대역에서 높은 안테나 이득을 가짐으로서 UWB MIMO 안테나로서 활용할 수 있음을 확인하였다.

1. Introduction

1.1 Overview

The current systems working on wireless communication have adopted UWB systems due to the advantages that it possess. The systems built for UWB can be smaller in size, have less complexity, and provide high-speed data transmission, along with high time-domain resolution. UWB also provides wider frequency bandwidth to work on, allowing more devices to work under UWB with lesser interference. Microstrip patch antennas are one of the most popular antenna types in modern communication market, as they are easy to build, fabricate, and have low manufacturing cost. Due to these reasons, multiband UWB microstrip patch antennas have become famous for their simple feeding techniques and simpler designs, which are easy to integrate with active components [1-3]. Furthermore, the demand for specialized antennas capable of various service applications have motivated researchers to work on miniaturized antennas, which are simple in design and compact. As, smaller and simpler antennas can work in low power, those antennas can be integrated with portable systems for applications such as internet of things (IoT), wireless body networks (WBANs), surveillance systems, and imaging and sensing applications that support all data communication system bands [4–7].

With the growth in use of wireless devices around the world, the demand of band spectrum has increased. With that, the requirement of wireless devices to have efficient spectrum management by making use of numerous antennas in single structure plane has been seen in the current wireless market for UWB systems. These demands can be met along with higher data rates with the application of MIMO technology. By using diversity gain technique, MIMO addresses multipath fading problems and further improves wireless range and capacity of the devices, increases data throughput, and improves link reliability that is very difficult to achieve in single antenna system [8]. In terms of channel capacity, MIMO can be considered better technology than single-input, multiple-output (SIMO), or multiple-input, single-output (MISO) systems. However, MIMO also has few limitations regarding correlation between antennas and realizing space efficiency [9]. The isolation factor or correlation in MIMO antennas are improved at expense of the antenna's size and space by using coupling and decoupling structures.

To improve the mutual coupling between antennas of MIMO, various techniques have been employed in microstrip patch UWB antennas. Using defective ground structures (DGSs), and applying decoupling structures like passive resonators and active devices mutual coupling is reduced. Furthermore, mutual coupling has been found reduced by addition of parasitic elements, electromagnetic bandgaps, and loading slots on antenna geometry. In [10], a passive microstrip-based feed network is proposed for UWB microstrip antenna. Similarly, to achieve good radiation efficiency and wideband antenna matching, a UWB amplifier is inserted in [11]. To enable MIMO to operate in higher frequencies [12] has introduced a cylindrical dielectric resonator antenna (CDRA). Likewise, to achieve a reduced mutual coupling in the wide operating band, [13] applied an electromagnetic bandgap structures to a closely placed arrays in ground plane. Without modifying ground plane, effectiveness of antenna in terms of bandwidth and isolation was improved through addition of a neutralization line in [14]. In [15] parasitic monopoles were used to induce reverse coupling that reduced the mutual coupling of the antenna. Likewise, to improve isolation, radiating elements of different shapes (arch, 4, T, F) and slot lines, ground slits, and rectangular rings were designed with DGS in MIMO antenna systems [16-22].

Taking all the above discussions in consideration, a simple UWB MIMO antenna is proposed in this thesis with an improved isolation that has a low mutual coupling

($|S_{21}/S_{12}| < -16$ dB) over the entire operating bandwidth and ($|S_{21}/S_{12}| < -20$ dB) in the center operating frequency band. The presented simple MIMO antenna consists of two semi-circular patch monopole antennas designed on a common radiating surface. The substrate used to design the antenna is Taconic ($\varepsilon_r = 4.5$, tan $\delta = 0.0035$). The MIMO structure has a reduced ground plane on the opposite side of the radiating patch. A small notch is made on the top left corner of the ground plane to increase the impedance bandwidth of the antenna. A thin rectangular stub is placed between the monopole antennas that act as isolator and helps to achieve low mutual coupling for center frequency bands of the antenna. By using a simple rectangular structure, application of complex coupling and decoupling structures are avoided to obtain good isolation. The antenna was simulated on HFSS and the measurements were taken in real environment after fabrication. The obtained results reveal that the presented UWB MIMO antenna performs well in terms of wide impedance bandwidth, high diversity gain, low envelope correlation coefficient, and high radiation efficiency. The proposed UWB MIMO antenna has good pattern diversity, thus, the antenna is suitable for UWB MIMO system.

1.2 Objectives

The need of communication system working under ultra-wide band, capable of coping with big channel capacity and denser device density has spurred growth in designing UWB antennas with larger corporal size. Further, the demand of efficient wireless UWB systems supporting efficient spectrum management by making use of numerous antennas along with providing high data rate has motivated researchers to focus on designing multiple antennas in a single physical substrate (MIMO). Thus, trying to meet the requirement of the current communication market, the main goals of this thesis has been set as:

- To design a semi-circular MIMO microstrip patch antenna suitable for UWB applications
- Implementing the simple rectangular stub element between antennas to avoid the use of complex coupling or decoupling structure or complex feeding network to maintain high isolation in UWB MIMO antenna.
- The general UWB frequency band is 3.1 ~ 10.6 GHz, but the target frequency band is designed to be 5 ~ 10 GHz in order to obtain the appropriate frequency of the DSP chip and radar module we want to use.

1.3 Contributions

In this thesis, a design of simple UWB MIMO antenna has been discussed. A semi-circular patch fed by microstrip is designed, which works under ultra-wide band. A simple rectangular stub patch is placed between MIMO antennas to achieve high-isolation. The application of rectangular stub avoids use of complex coupling or decoupling structure in the design to achieve the desirable result. Further, a small notch of rectangular structure is made in the ground plane to extend impedance bandwidth of the antenna. The presented UWB MIMO antenna exhibits very low envelop correlation coefficient (ECC < 0.003) with high diversity gain (DG > 9.99).

1.4 Thesis layout

Rest of this thesis is organized as follows. In Chapter 2, the background and theory of UWB along with MIMO antenna is explained. In chapter 3, the detailed design of presented UWB MIMO antenna is discussed. In this chapter, complete design procedure is explained and the performance of the antenna is verified through simulated and measurement results. The parameters of the antenna are presented based on reflection coefficient, radiation pattern, multiplexing efficiency, ECC, Diversity gain and Total active reflection coefficient (TARC). Further, an evaluation to validate the novelty of the antenna is done by comparing the results with the existing antennas. Finally, chapter 4 concludes the thesis and presents some assumptions of this study.

2. Theory and background

2.1 Microstrip patch antenna

The origin of microstrip patch antennas date back to more than 50 years ago. Deschamps was the first researchers to introduce microstrip patch in 1953 at the third Unitd States Air Force (USAF) Symposium on Antennas [23], though many authors have been given credit for discovering microstrip antennas. However, the patch antennas have acquired a widespread popularity in many fields of commercial wireless communication market. This is due to the advantages possessed by microstrip antennas. The patch antennas saw its increase in application since the mid of 1970's after the commencement of the development of printed-circuit technology. With the increase in its utilization in various sectors, the microstrip antennas has been researched and applied by engineers and researchers throughout the world. Wireless networks, military applications, mobile satellite, personal systems, and many more sectors have found use of microstrip patch antennas. The reason for its wide applications are as follows: [24-26]

- Microstrip patch antennas are easier to design and fabricate.
- The designing and fabrication cost is very low.
- The size of microstrip antennas are smaller.
- They have a thinner profile configuration and weight is less.
- They can be fit into any type of surface of a product (e.g. vehicle) due to in conformable nature.
- Dual polarization and dual frequency can be easily achieved.
- Microstrip antennas can be converted into arrays.
- Smart antennas can be built by combing phase shifters of PIN-diode switches.
- Microstrip antennas can be integrated with microwave circuits.

- Linear or circular polarization can be produced using microstrip antennas.
- An array of microstrip antennas can be used to form a pattern that is difficult to synthesize using a single element.

Differently, microstrip antennas also have limitation, which are as follows: [24–26]

- Microstrip antenna's efficiency is poor.
- The bandwidth produced are usually narrow (1%), while many mobile communication applications require wider bandwidth (8%).
- They are affected by humidity and temperature, thus, sensitive to environmental factors.
- Microstrip antennas also have lower gain, usually below 6 dB.
- Array antennas of microstrip patch's efficiency is affected by the presence of feed network.

Conventional microstrip patch antennas usually consists of three parts: patch, ground and substrate. The dielectric layer, on which the main antenna is designed, sandwiched between two conducting layers of patch and ground is called the substrate. The patch is the conducting layer, which is the main source of radiation. It is situated on the upper layer of the substrate. It is a thin conductor, which is parallel to lower conducting layer, and is a portion of wavelength in amount ($0.25\lambda_0$ - $1\lambda_0$). When the power is supplied to the microstrip antennas, the electromagnetic energy fringes off the edges of patch and into the substrate. The ground plane reflects the energy back into free space through the substrate. It is the lower conducting layer in the substrate. The patch and the ground plane are designed and etched opposite to each other on the non-magnetic dielectric substrate. The geometry of the conventional circular microstrip patch antenna is shown in Figure. 2-1.

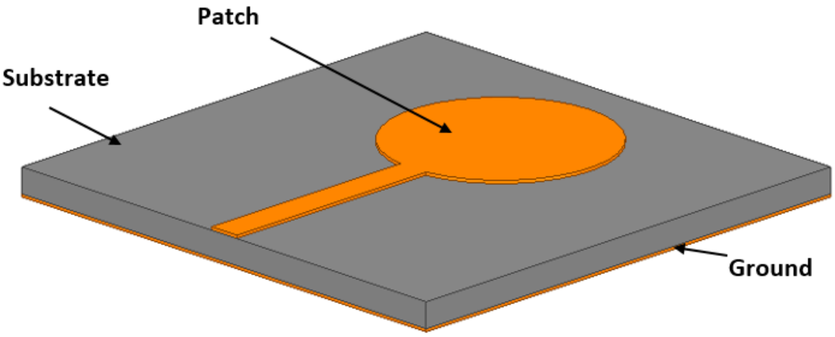


Figure 2-1. Geometry of circular microstrip patch antenna

In the current market, various simple and complex design of patch antennas are found. However, circular, rectangular, square or the modified versions of them are the most practical ones. Though rectangular and square patches are the most common microstrip antennas, circular patch designs are also popular configuration as they are easy to analyze, modify and fabricate. In this thesis, the modified version of circular patch antenna is designed.

Since, the thesis present a MIMO antenna built on microstrip patch which is of semi-circular design, in this section, a method to design the circular microstrip patch will be explained. First, to build a microstrip patch antenna, the substrate material with dielectric permittivity ε_r , thickness h, and the target center frequency f_r (resonant) must be chosen. After that, the radius of the circular patch a can be calculated by the following formulla [27]:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}}, \qquad (1.1)$$

where

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}}. \tag{1.2}$$

Here, *h* must be in cm and *F* must be in Hz. By using the above equation, the radius of the patch can be determined for center frequency. The antenna can then be designed using the calculated parameters, and simulated using any simulation tool like HFSS. Its parameters can be further optimized to get the optimum antenna performance.

2.2 UWB technology

Since UWB was enlisted for commercial use in 2002, its applications in the industrial as well as academic field has gained immense popularity for various radio communication systems. For commercial purpose, the Federal Communications Commission (FCC) has listed the UWB's frequency band range for 3.1 ~ 10.6 GHz. FCC has also made a requirement for transmission power of the system to be not more than -41 dBm/MHz. Due to the highly specific and generic nature of UW's applications, the antenna to be used in system should have good impedance matching, omnidirectional radiation patterns, flatter group delay, and the design of the antenna should be compact. In addition, there should be presence of one or more overlapping channels. A UWB antenna will be able to transmit lower power over a wide spectrum. Due to this nature, UWB system will be useful for devices that consume lower power and have shorter range. This property of UWB makes the application run within limited resources at lower operating costs.

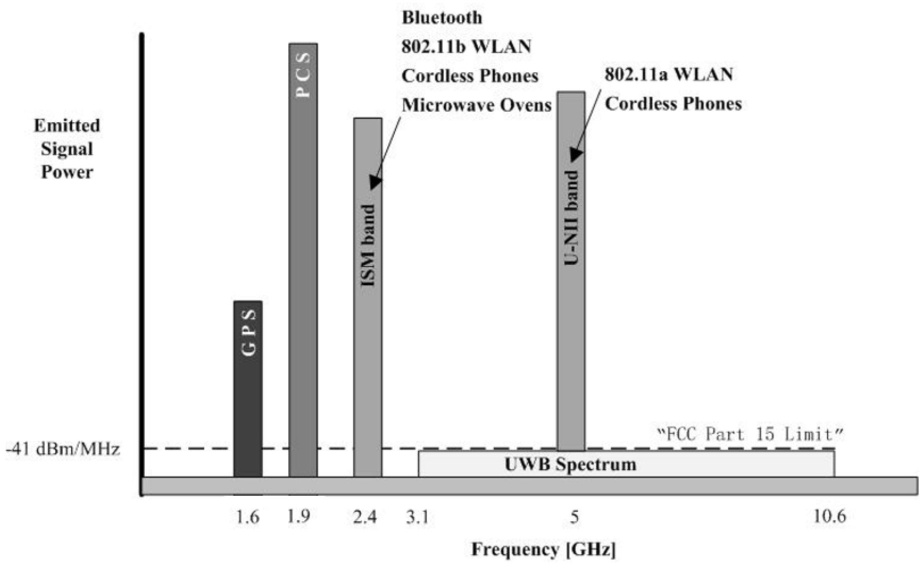


Figure 2-2. UWB versus other narrowband radio communication systems

Figure 2-2 shows the signal spectrum of UWB along with other narrowband communication systems that are present in the current commercial market. As seen from the figure, UWB works with lower power consumption and has wider spectrum compared to other systems [28]. Due to these reasons, UWB have wider scope of technological applications. Few of those are, Internet of Things (IoT), vehicular radar systems, medical applications, wall-imaging radar systems, surveillance systems, communication and measurement systems, and wireless body are network (WBAN).

2.3 Characteristics of UWB

As UWB is a technology applicable for numerous essential applications, in basic essential sectors like communication, sensors, security, localization, automotive, and even imaging, it has a potential to grow. The growing applications of digital devices in wireless personal area networks (WPANs) like digital cameras, gaming consoles, digital camcorders, computers, laptops, high-definition TVs (HDTVs), and even office devices such as printers, fax machines, keyboards, mouse, and cordless connections to peripherals, requires a powerful wireless solution that can provide high bandwidth and easy connection. For these mentioned applications, UWB communication technology can be pointed out as the best solution, because of its numerous advantages such as:

- **High bandwidth**: The FCC has defined that a UWB technology will work in the frequency band of range of 3.1 ~ 10.6 GHz. Further, a UWB system will transmit signals in a bandwidth greater than 500 MHz or 20 % percent bandwidth. Thus, UWB has wider operating frequency bandwidth.
- **Low power consumption**: UWB communication devices can operate at low power levels resourcefully. For transmission of hundreds of Kbps up to 5 meters distance, UWB devices will require less than 1mW. This is due to the absence of a carrier signal.

- **Secure**: Since, UWB technology works at very low power level on wide bandwidth, the probability for any kind of interception becomes very low. Thus, UWB is considered highly secure. Practically, it is extremely tough to filter a pulse signal from a background of electronic noise. Thus, to detect signal by an external observer becomes near impossible
- **Low power spectral density**: Without producing any interference to other communication systems like WLAN, Wi-Fi, GPS, WiMAX, and cellular network system, UWB technology successfully coexists. The reason is that UWB has low power spectral density.
- **High data transfer rates**: UWB can transmit at the rate of 500Mb/s over 5m, 250Mb/s over 10m, 200Kb/s over 50m, 10Kb/s over 100m. The reason for high data transfer rates is due to the availability of huge volume of bandwidth.
- **Low cost**: UWB technology does not require Radio Frequency (RF) converter or modulator. In addition, for transmission purpose it also does not require any carrier signals. Due to this, it is easier and simpler to design transmitters and receivers for UWB systems. Thus, the implementation cost is low.

2.4 UWB MIMO antenna

Due to the increase in the applications of wireless systems as well as the use of wireless devices around the world, need for efficient spectrum management as well as high data rate is growing. One of the solutions for this growing need could be the use of two or more antennas in single physical sustrate or mobile terminal. This technique can enhance wireless capacity, reliability, data rate and wireless range. While doing so, additional spectrum bandwidth or transmitted power, which can cause scattering and fading, is not required. This application of diversity teqhnique is known as MIMO. As compared to conventional SIMO or MISO systems, application of MIMO antennas in UWB systems will be able to increase the range along with the channel capacity. Further, UWB diversity antenna system can also be considered as a solution for the multipath fading problem in indoor wireless communication systems. To implement MIMO antenna in portable wireless devices, while desiging the antenna, following challenges must be considered.

2.4.1 Design challenges in UWB MIMO antenna systems

- **Bandwidth**: For the impedance bandwidth to cover entire UWB range, VSWR of the antenna should be less than 2, and the return loss (S_{11}) must be lower than -10 dB from 3.1 GHz to 10.6 GHz. In case of MIMO, for a system to operate, the isolation factor must be lower than -15 dB in the operating region. Maintaining impedance bandwidth and isolation factor together in a single antenna structure is a great challenge while building MIMO antenna for UWB system.
- **Isolation:** While desiging any type of MIMO antenna, mutual coupling reduction between antennas must be considered. Mutual coupling between the antennas can influence diversity gain, correlation, total active reflection

coefficient, and multiplexing efficiency. It also has major effects on the antenna efficiency. For MIMO antenna to operate successfully, the isolation factor must be lower than -15 dB throughout the operating region of the antenna system.

- **Size:** To increase wireless capacity, achieve high speed data transmission, improve link reliability, and increase wireless range, mobile technology uses various communication techniques like WLAN, WiMAX, WCDMA, and UWB. However, the mentioned improvements cannot be achieved using single antenna system. Since, only limited space is available in wireless devices, compact wide band MIMO antenna systems is needed to fulfilment the requirement of such applicatons.

Thus, for UWB wireless applications, a compact UWB MIMO antenna system with low mutual coupling can be consisdered.

2.4.2 Isolation and bandwidth enhancement

Enchancement of isolation factor in a UWB MIMO antenna along with improvement of the antenna bandwidth can be achevied by applying various isolation structures, and coupling and decoupling methods.

Among various methods of reducing mutual coupling, addition of patches between antennas, or introducing complementary slots on reduced ground plane are few of them. Mutual coupling can be reduced by adding stubs in the design as well. Addition of slots either in the ground plane or the main patch can also increase the impedance bandwidth of the antenna. MIMO antenna systems with two or four radiation elements have also been studied for the improvement of mutual coupling and increse in impedance bandwidth. Various designs with structures of T, F, mushroom, arch–shaped, EBG structures and slot lines have been researched to decrease mutual coupling by suppressing the ground current flowing between the radiating elements. Other techniques to achieve lower mutual coupling are defected ground structures (DGS), decoupling networks, neutralization techniques, and addition of rectangular rings. To improve antenna performances, ground slits have also been used. Application of ground slits during antenna design has decreased the size of antenna, and further improved gain, reduced mutual coupling between antennas, and even increased bandwidth.

3. Modeling of proposed antenna, simulations and measurement

3.1 Semi-circular patch UWB MIMO antenna with rectangular stub to improve isolation factor

3.1.1 Design specification

Figure 3-1 shows the geometry of the proposed UWB MIMO antenna. The total dimension of the antenna is 38 mm × 37 mm × 1.62 mm, and it is built on a Taconic substrate (ε_r = 4.5, tan δ = 0.0035). The design of the antenna is composed of a semi-circular microstrip patch of radius 9 mm connected by a microstrip feedline of width 2 mm. The ground plane is made on the bottom of the antenna, which is not continuous, and consists of a small defect. At first, the lower frequency bandwidth is estimated as 5.4 GHz to meet frequency requirement using the following equation.

$$f_n = \frac{c}{2l_t\sqrt{1+\frac{\varepsilon_r}{2}}}, \tag{3.1}$$

where, f_n is the lower operating frequency, ε_r is the relative permittivity of the substrate, c is the speed of light, and l_t is the combined total effective length of the circular patch radius of both antennas minus the width of the rectangular stub placed between the antennas. The addition of rectangular stub between the antennas along the center of the substrate is done to improve the isolation between antennas. The ground plane has a small notch, which has been made to achieve the characteristic impedance of 50 Ω. The ground plane is also not continuous; rather the total width and length of the ground plane are 13.5 mm and 9.6 mm respectively. A small notch of size 2.3 mm × 2.4 mm is made on the top left corner of the plane.

The structure of the microstrip is made semi-circular; the ground plane has a small defect; and a thin rectangular stub is placed between the antennas. All of this is done to maintain characteristic impedance, increase the operating frequency bandwidth, and improve the isolation factor of the MIMO UWB antenna. The proposed design is similar to a microstrip patch antenna with feeding points placed opposite to each other. The optimized antenna structure is able to achieve isolation enhancement without using complex coupling and decoupling structure. Further, antenna performance is presented in terms of bandwidth, diversity gain, and other significant parameters for any MIMO UWB antenna.

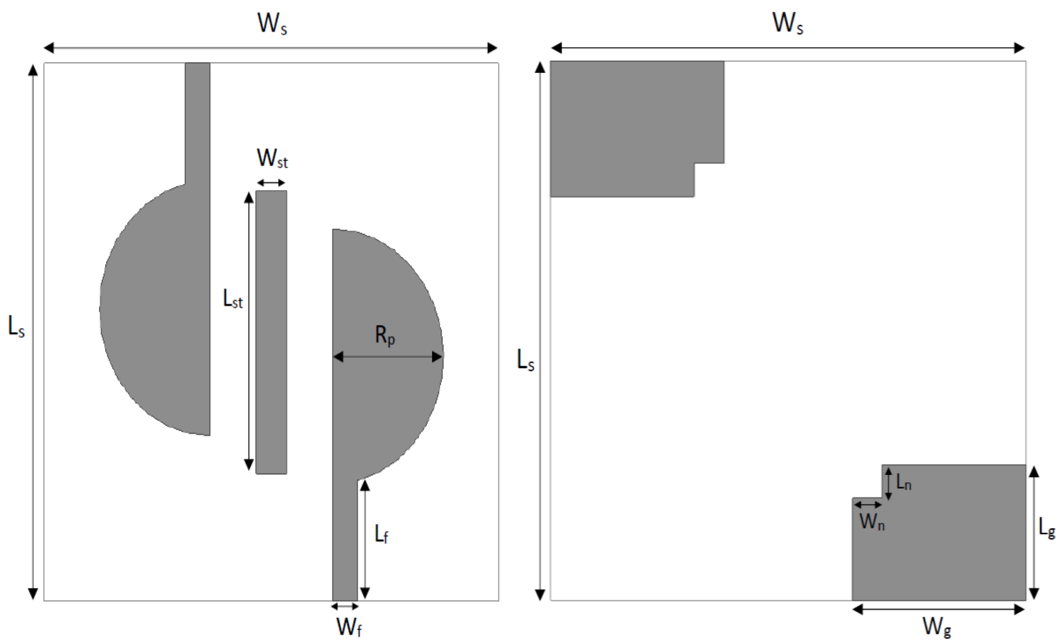


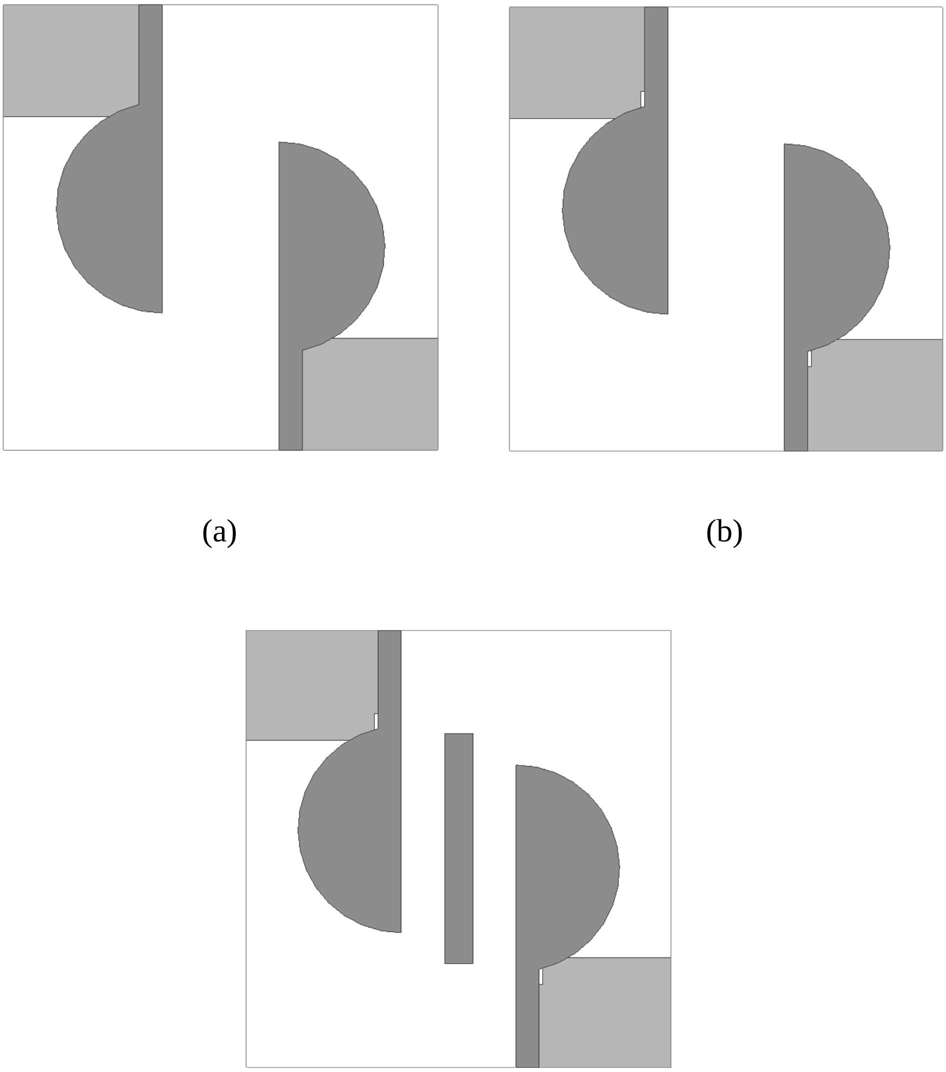
Figure 3-1. Geometry of the proposed UWB MIMO antenna

Table 1. Dimension of UWB MIMO antenna

Parameter	Dimension (mm)
Ls	38
Lf	8.5
Lst	20
Lg	9.6
Ln	2.4
Rp	9
Ws	37
Wf	2
Wst	2.5
Wg	13.5
Wn	2.3

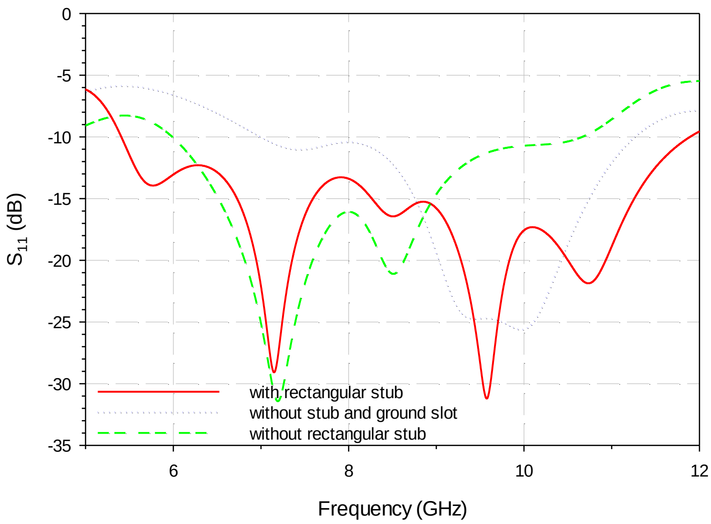
3.1.2 Design strategy

Antenna design steps are presented in Figure 3-2 along with the effect on mutual coupling and antenna bandwidth. In first step, shown in Figure 3-2 (a), the initial design of antenna is prepared with semi-circular microstrip patches fed with microstrip feedline. Both antennas are separated by certain distance and the reduced ground plane is placed in the bottom section of the substrate. The semi-circular design of the MIMO antenna could supply good pattern diversity for the MIMO system.

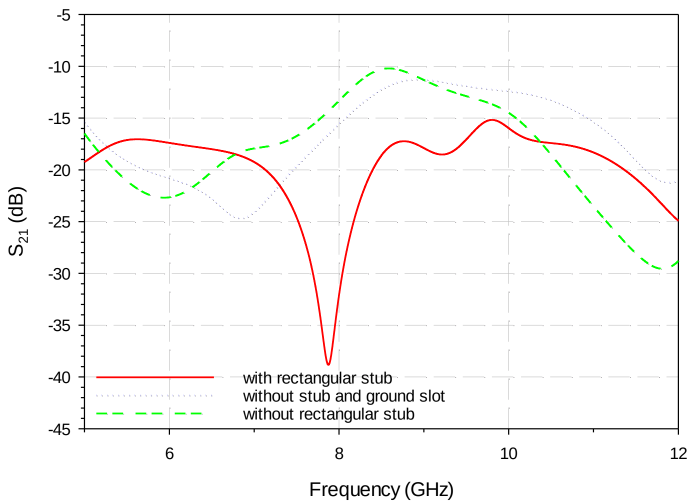


(a) (b) (c)

Figure 3-2. Geometry of UWB MIMO antenna with different evolution steps.
(a) without stub and ground slot, (b) without rectangular stub, (c) with rectangular stub



(a)



(b)

Figure 3-3. Simulated S-parameters illustrating on different stages of antenna variations. (a) S_{11}(dB), (b) S_{21}(dB)

Figure 3-3 (a) and Figure 3-3 (b) presents the simulated reflection coefficient (S_{11} and S_{21}) of the design, and as seen from the graph, antenna works in the UWB band, however has very poor isolation around the center frequency range. Notch made on the ground, as seen in Figure 3-2 (b), has improved the bandwidth in the entire UWB as seen in Figure 3-3 (b). However, mutual coupling between the proposed antennas is still not improved, as seen in Figure 3-3 (b). Thus, to enhance the mutual coupling of the antennas in the presented MIMO UWB antenna, a simple rectangular stub is placed between the antennas as seen in Figure 3-2 (c). With the addition of rectangular stub, isolation is below -16 dB throughout the operating frequency band. As seen in Figure 3-3 (b), the isolation factor is even below -20 dB around the center frequency band. The rectangular stub not only improved the mutual coupling, but also increased the frequency bandwidth. This improvement of bandwidth and mutual coupling is achieved by avoiding complex coupling and decoupling structures.

Figure 3-4 shows the peak gain of the different stages of the antenna variations. As seen from the figure, the gain of the antenna throughout the operating band is lower than 5 dB without addition of rectangular stub. Addition of notch in the top left corner of the ground further reduced the overall gain. As seen in the figure, the gain in the entire operating frequency band is even less than 4 dB with the addition of ground slot. This shows that, though addition of ground slot improved the bandwidth of the antenna, it affected the overall gain. It is a compromise between bandwidth and gain.

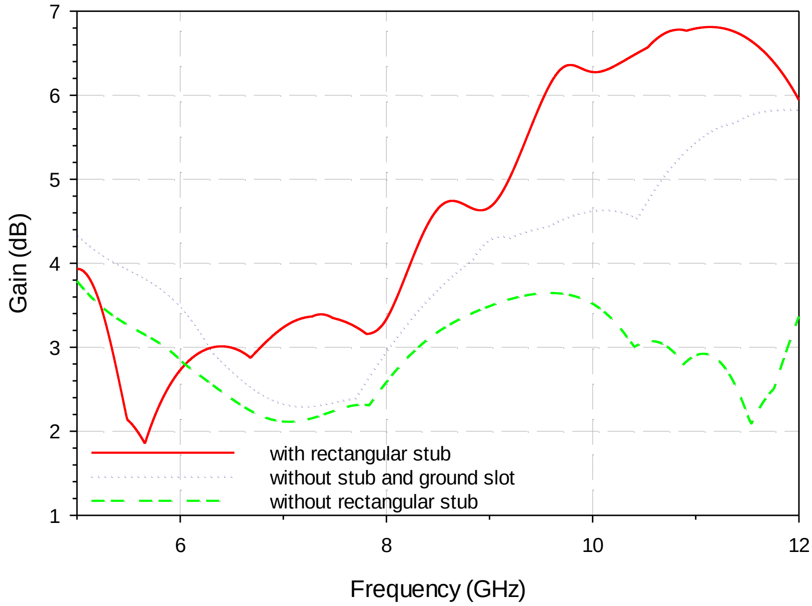
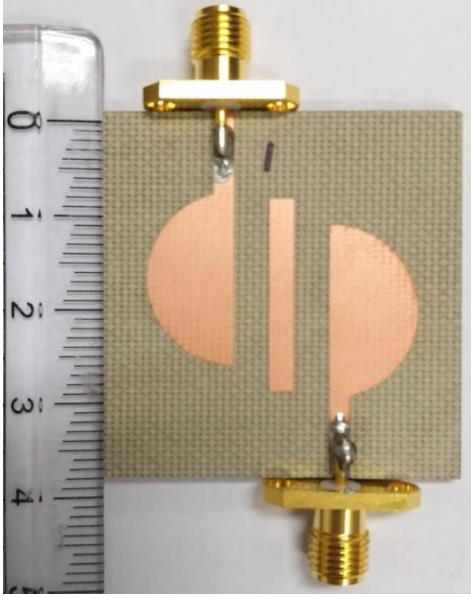
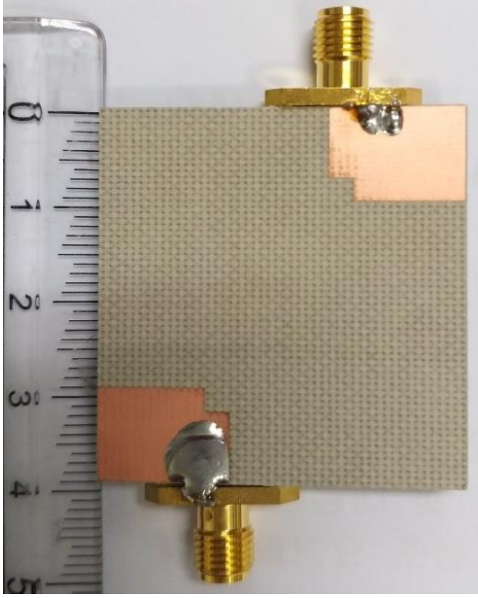


Figure 3-4. Simulated gain illustrating on different stages of antenna variations

However, at the final stage, when rectangular stub was added between the antennas of MIMO, the gain was further improved. As microstrip patch antennas have lower gain, the presented antenna shows gain in the region of 6 dB. The gain of antenna seems to increase in the upper frequency band. Figure 3-5 presents the fabricated antenna design.

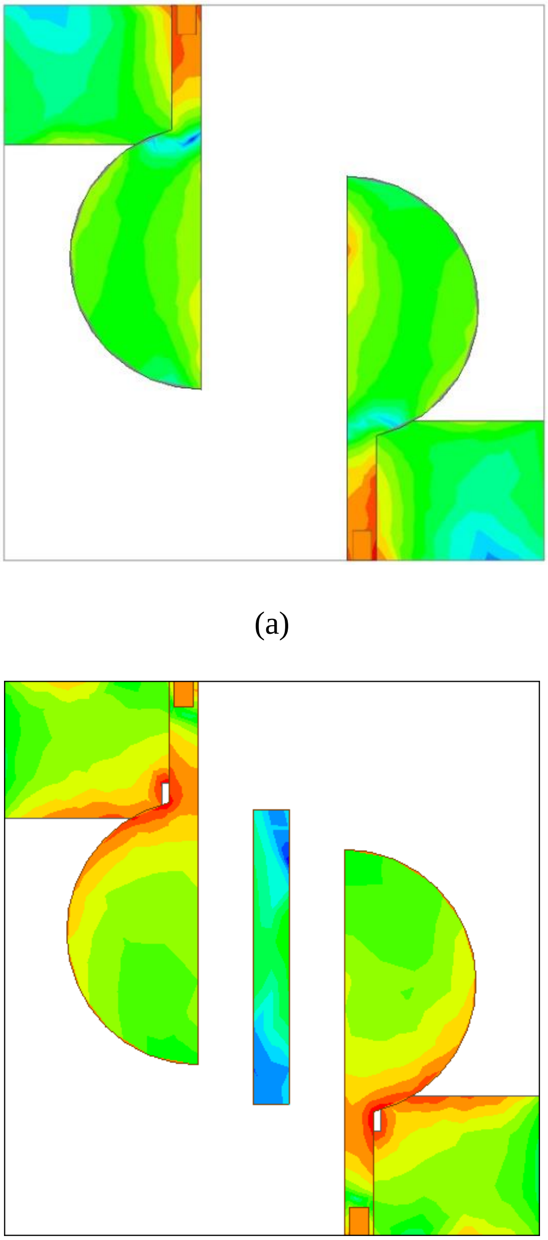


(a)



(b)

Figure 3-5. Fabricated antenna design. (a) top view, (b) bottom view



(a)

(b)

Figure 3-6. Simulated surface current distribution at 9.6 GHz. (a) without rectangular stub, (b) with rectangular stub

The validation of mutual coupling reduction due to application of rectangular stub between the antennas is done through the simulated surface current distribution. Figure 3-6 presents the current distribution around the patch with and without rectangular stub. As seen in Figure 3-6 (a), due to equal spread of current concentration around the patch, high coupling is seen. In Figure 3-6 (b), due to insertion of rectangular stub between the antenna patches, it is observed that current is concentrated at the radiating patches due to repulsive effect from the added stub, thus, the improved isolation is achieved.

3.1.3 Measurement and simulation results

The proposed antenna was designed using a Taconic substrate, which has a relative permittivity (ε_r) 4.5, and loss tangent (tanδ) 0.009. 1.6 mm thick substrate was used to implement the proposed design of UWB MIMO antenna. The antenna was simulated on a commercially available High Frequency Structure Simulator (HFSS), and after optimizing the parameters to achieve the desired results, the design was manufactured and measured in the real environment.

The voltage standing wave ratio (VSWR) is one the elementary parameters to evaluate antenna performance. VSWR is related to the quality of performance of the antenna, and the antenna's efficiency is portrayed by it. It can be defined as the proportion between the maximum to minimum amplitudes of standing waves [27]. VSWR can be calculated by measuring the voltage along the transmission line leading to an antenna. The equation of VSWR is as follows:

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}, \tag{3.2}$$

where

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}. \tag{3.3}$$

Z_{in} is the input impedance of the antenna, and Z_0 is the characteristic impedance of the transmission line. Though return loss is quite popular while analyzing antennas used in the research field of microwave communication, VSWR is more preferred.

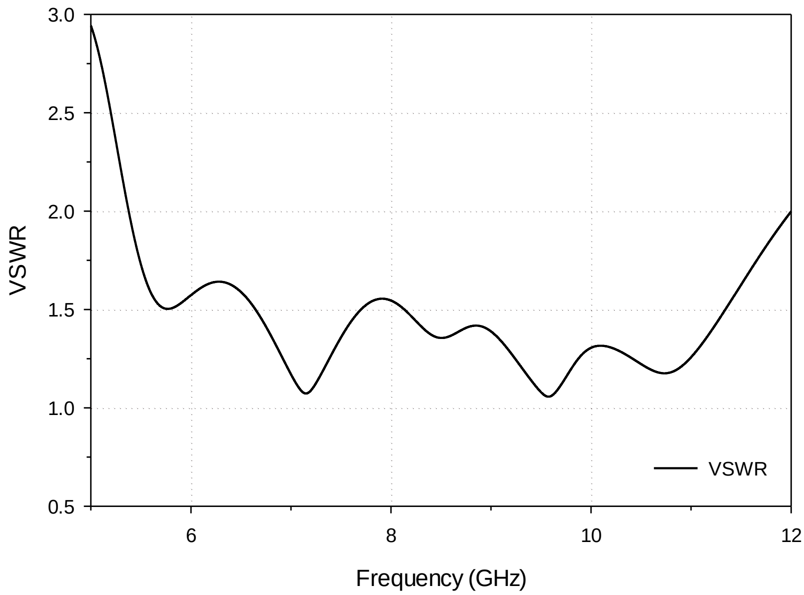
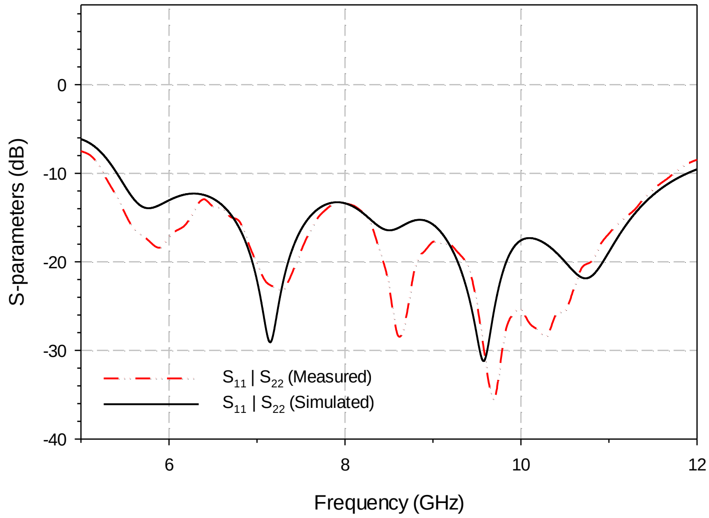
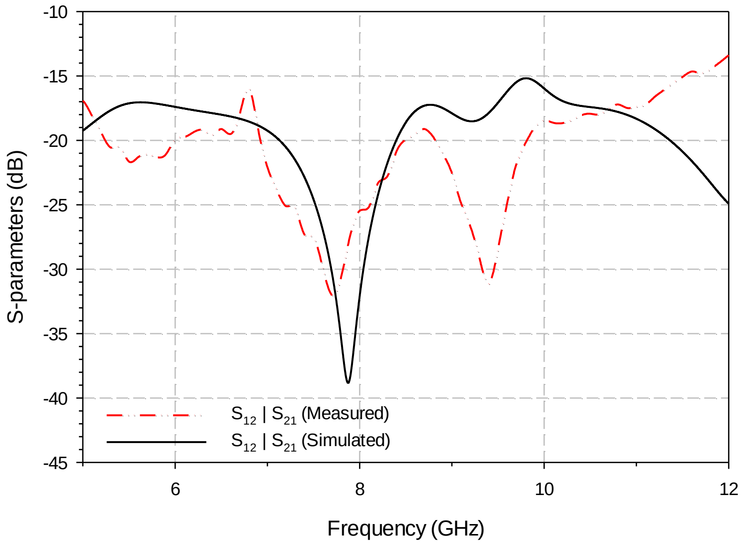


Figure 3-7. VSWR of the proposed UWB MIMO antenna

Figure 3-7 shows the VSWR of the proposed UWB MIMO antenna. As seen from the figure, the semi-circular patch MIMO antenna is operational from 5.4 GHz to 11.9 GHz.



(a)



(b)

Figure 3-8. Simulated and measured results of S-parameter. (a) S_{11}/ S_{22}, (b) S_{12}/S_{21}

Figure 3-8 shows the measured and simulated S-parameters. As seen in Figure 3-8 (a), the measured and simulated return loss (S_{11}) is less than -10 dB from 5.4 ~ 11.9 GHz. Figure 3-8 (b) presents the mutual coupling between the antennas, and as seen from the figure, the result is less than -16 dB throughout the operating frequency bandwidth, and even below -20 dB in the center frequency region. The measured and simulated results have a close agreement. Slight difference between the simulated and measured reflection coefficient can be because of the losses due to connector, fabrication errors, and imperfect soldering.

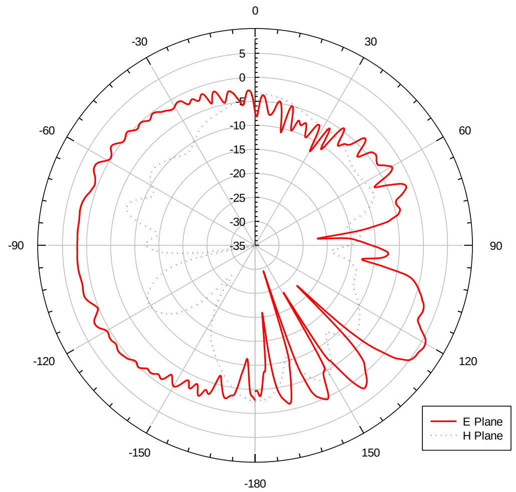
a. Antenna gain and radiation efficiency

Figure 3-9 presents the measured radiation patterns in 2D. The measurement was done by terminating one of the ports by 50-Ω load and vice versa. As seen in the figure, the antenna has achieved almost omnidirectional radiation pattern in both of the planes, i.e. E-plane and H-plane. By achieving close to omnidirectional radiation pattern, the proposed antenna shows the required characteristics for MIMO antenna.

Further, to validate the competence of the proposed antenna, DG and ECC between the antennas are also measured. For higher pattern diversity of MIMO antenna, ECC and DG between the antennas in MIMO must be as low and high as possible. The ECC between antennas in the MIMO can be calculated using following equation [29],

$$ECC = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|^{2}}{\left(1-\left|S_{11}\right|^{2}-\left|S_{21}\right|^{2}\right)\left(1-\left|S_{22}\right|^{2}-\left|S_{12}\right|^{2}\right)}, \tag{3.4}$$

where, S_{11} and S_{22} are the antenna refection coefficient measured in two ports and S_{12} and S_{21} are the insertion losses of the antenna.


0
-30
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60
-90
90
-120
120
-150
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-180
5
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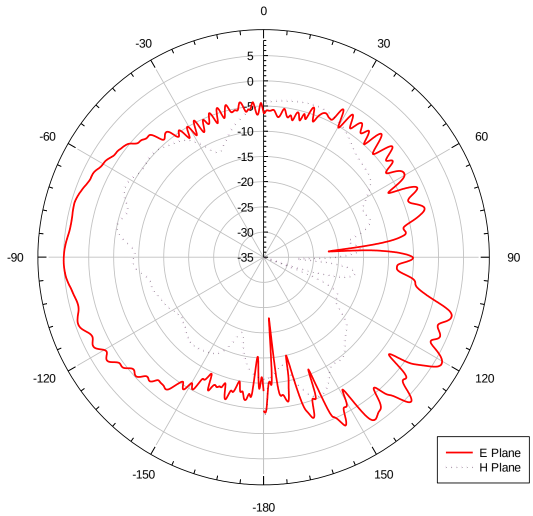
-15
-20
-25
-30
-35
E Plane
H Plane

(a)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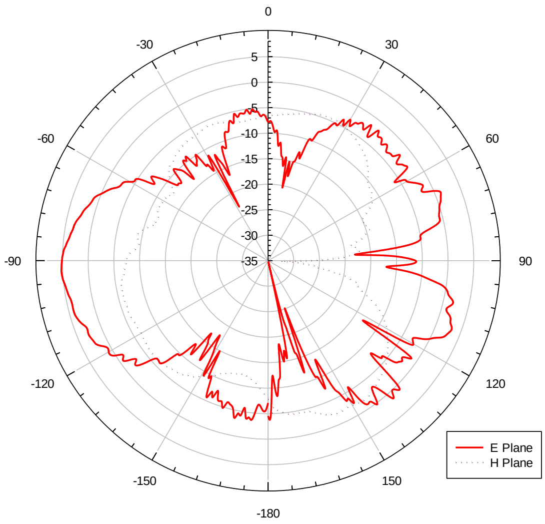
E Plane
H Plane

(b)



(c)

Figure 3-9. Measured radiation pattern. (a) 5.5 GHz, (b) 7.5 GHz, (c) 10.5 GHz

ECC is calculated, and plotted using the parameters of reflection coefficients and insertion loses of the antenna, and Figure 3-10 presents the plotted result of ECC. Although diversity gain and MIMO capacity characterizes the overall effect of MIMO antenna, MIMO capacity is a complex function. Thus, to make the characterization of antenna design simple, intuitive metric like TARC is proposed. Multiplexing efficiency is another simple metric applied to simplify the antenna design. It defines the required degradation or losses of power efficiency while using a MIMO antenna to get to the capacity same as that of the reference antenna system in same propagation channel within uniform 3D angular power spectrum. The signal-to-noise ratio (SNR) degradation due to MIMO antenna –channel losses for a given MIMO capacity, η_{mux} is given by [30]

$$\eta_{mux} = \sqrt{(1 - |\rho_c{}^2|)\eta_1\eta_2}\,, \tag{3.5}$$

where, $\eta_1\eta_2$ are the total efficiency of two radiating antenna elements and ρ_c represents the complex correlation coefficient between them. If the total efficiency of an antenna is very high, its ECC will be almost equal to $|\rho_c{}^2|$. Thus, for the proposed antenna, the DG can be calculated as,

$$DG = 10\sqrt{1 - ECC^2}\,. \tag{3.6}$$

As seen in Figure 3-10, values of ECC of the proposed UWB MIMO antenna over the operating frequency bandwidth are less than 0.003. The DG of the antenna throughout the entire UWB band is also seen to be greater than 9.99. Figure 3-11 shows the multiplexing efficiency of the antenna, and as seen in figure, the values are high on the entire frequency bandwidth.

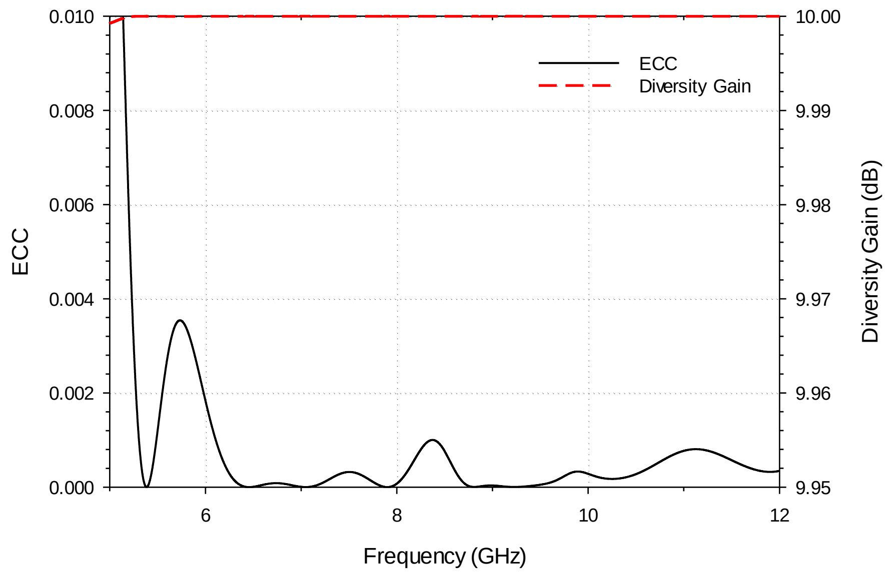


Figure 3-10. ECC and diversity gain of the proposed antenna

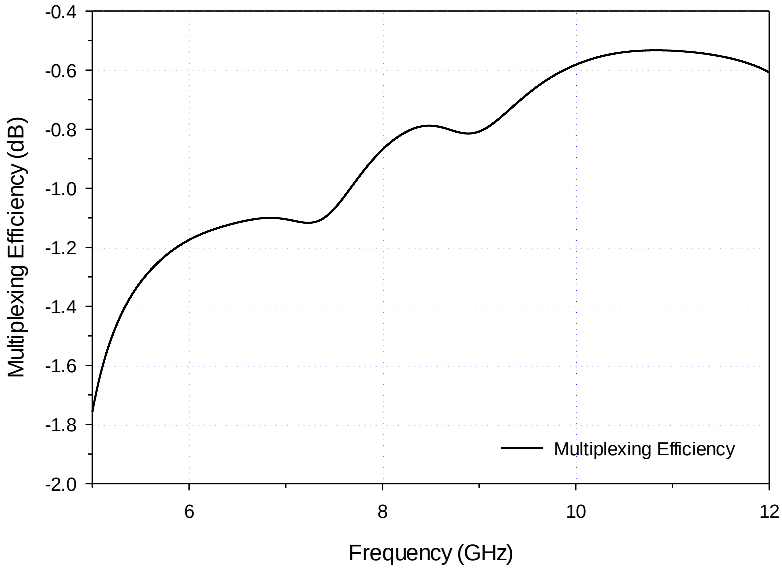


Figure 3-11. Multiplexing efficiency of the antenna

To measure the actual behavior of antenna by predicting return loss of MIMO antenna system TARC is used. It can be calculated using following equation [31],

$$\mathrm{TARC} = \sqrt{\frac{(S_{11} + S_{12})^2 + (S_{21} + S_{22})^2}{2}}\ . \tag{3.7}$$

In Figure 3-12, the calculated TARC is plotted, and as seen from the figure, the values of TARC of the proposed antenna are less -4 dB for the entire frequency band. These results show that the proposed antenna is suitable for UWB and sensor applications.

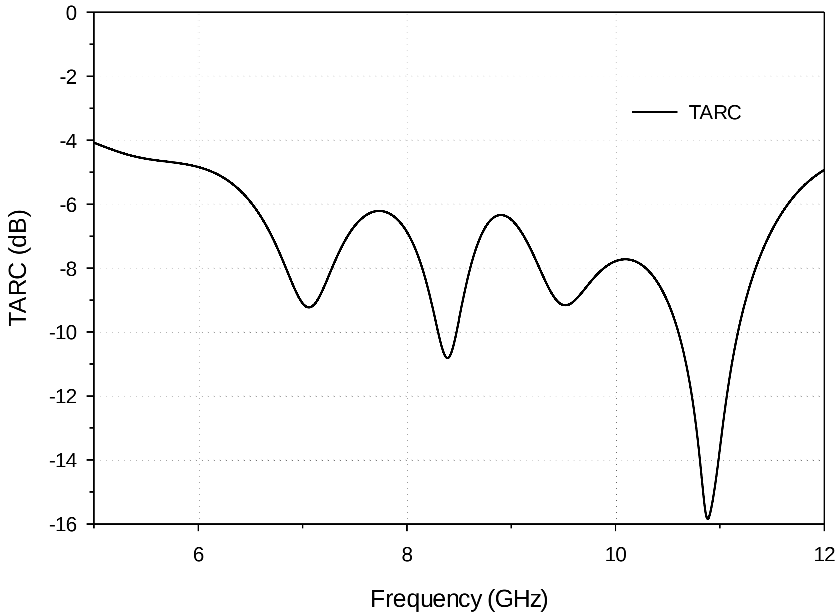


Figure 3-12. TARC for the proposed antenna

b. Comparison with other references

Table 2. Comparison with the recently reported UWB MIMO antenna

Ref.	**Size (mm)**	**Bandwidth (GHz)**	**Isolation (dB)**	**ECC**	**Diversity gain**
[32]	50 × 80	3.1~10.6	< −17	<0.056	NA
[33]	32 × 32	3.1~10.6	< −15	< 0.04	NA
[34]	26 × 40	2.1~10.6	< −15	NA	NA
[35]	45 × 25	3 ~12	<−15	<0.2	> 9.79
Proposed Work	38 × 37	5.4~11.9	< −16	< 0.003	> 9.99

Table 2 presents the comparison of the proposed UWB MIMO antenna with other recently proposed similar MIMO antennas for UWB applications. As seen in the table, the proposed antenna demonstrates the better trade-off against other proposals in terms of isolation, ECC and diversity gain. In terms of bandwidth, though other antennas have wider bandwidth, the proposed antenna is suitable for UWB. The presented antenna is smaller compared to [32]. Though the size of [33], [34] and [35] are smaller, the proposed antenna outperforms in terms of ECC and DG. The proposed antenna has achieved isolation less than -16 throughout the operating bandwidth and even below -20 in the center operating frequency band, thus, performs better than the compared designs. Hence, the proposed simple MIMO antenna with simple technique to improve isolation is capable for ultra-wideband MIMO and sensor applications.

4. Conclusion

A microstrip patch MIMO antenna with high isolation, and compact and simple design is presented in this thesis. A semi-circular patch elements fed by a microstrip line that operates in the UWB region is designed. The ground plane is reduced and a notch is made on the top left corner of the plane to achieve the desired frequency band. The notch made on the ground plane widens the operating bandwidth of the antenna, and improves the impedance matching of the antenna. Further, a thin rectangular stub is placed between the antennas to achieve high isolation factor. The addition of a simple rectangular stub avoids the use of complex coupling or decoupling elements, or application of complicated feeding technique to improve the MIMO antenna performance.

Upon simulation and measurement in the real environment, the proposed antenna was able to achieve return loss below -10 dB from 5.4 to 11.9 GHz. The isolation was also below -16 dB in the entire operating band, and even below -20 dB around the centre frequency band. ECC of the antenna was less than 0.003, and DG was higher than 9.99 throughout the operating frequency bandwidth. This validates that the proposed design strategy was successful in increasing the bandwidth and reducing mutual coupling between antennas. The antenna also has almost omnidirectional radiation pattern and the multiplexing efficiency is high. The acquired simulated as well as measured results shows that the proposed antenna is suitable for UWB and sensor applications.

In future, different techniques can be applied on the antenna to further improve the performance. Smart materials can be used to improve diversity performance, and novel procedures such as neural networks, graph model can be applied to adjust the antenna parameters and design procedure.

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