INVESTIGATIONS ON NOVEL HEXAGONAL PATCH ANTENNAS

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STATEMENT OF ORIGINALITY

I, **Mishor Biswas**, registered on 22/02/2017 do hereby declare that this thesis entitled "**Investigations on Novel Different Hexagonal Patch Antennas**" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

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This is to certify that the thesis entitles "**Investigations on Novel Hexagonal Patch Antennas**" submitted by **Shri Mishor Biswas**, who got his name registered on **22/02/2017** for the award of Ph. D. (Engineering) degree of Jadavpur University is absolutely based upon his own work under the supervision of **Prof. Bhaskar Gupta**, Dept. of ETCE, Jadavpur University, Kolkata-700032, West Bengal, India and **Dr. Kaushik Patra**, Dept. of ENX, Bosch Global Software Technologies, Bengaluru-560095, India and that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

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Abstract

Hexagonal patch antennas are widely used in different RF applications. The hexagonal antennas have current distribution similar to that of circular patch antenna with less area occupation. Along with this, hexagonal antenna has other advantages such as low profile, ease of fabrication, conformability, cost feasibility etc. These advantages enhance interest on hexagonal patch antenna design.

There are basically two types of techniques available for antenna analysis such as analytical methods consisting of Transmission Line Model (TLM), cavity model and Multiport Network Model (MNM), and numerical methods such as integral and differential equations for spectral and spatial domain analysis, full wave techniques etc. Analytical methods are quite easier than numerical method by sacrificing accuracy. However, MNM shows better accuracy (lower than numerical methods) than other analytical techniques. Therefore, in this thesis work, MNM is chosen for the analysis of hexagonal patch antenna. MNM analysis of regular shaped hexagonal patch antenna has been studied previously. That's why, MNM analysis of irregular shaped hexagonal patch is performed here.

Now-a-days, one of the important focuses of the engineers is miniaturization of antenna to place it within small area of any chip or board. Therefore, comparison of antenna performances between full hexagonal patch and half of it has been studied here. From this study, it is observed that half hexagonal patch antenna shows advantages in terms of bandwidth over full hexagonal patch antenna.

Rapid development of wireless communication systems in the last decade has increased thedemand for microstrip antennas with compact size and multiple operating frequencies. Therefore, a circular slotted half hexagonal patch is designed here for multiband operation of the antenna. Radius of the circular slot has been optimized to tune this antenna for multiple applications such as Bluetooth, WLAN and point to point wireless communication bands. A defected grounded microstrip-line feed hexagonal patch antenna tuned at 5.17 GHz has been designed and analyzed here for wireless communication and aeronautical navigation applications. This antenna provides sufficient gain to establish good communication link.

Fifth generation is the latest iteration of wireless technology which was introduced for enhancing responsiveness and speed of the communication. 5G canallow sharp increase in data transmitted over channel due to high bandwidth based on Shannon's Channel Capacity theorem. Fourth generation (4G) cellular technology demands large and high-power cell towers for radiating signals over long distances whereas 5G signals can be transmitted over large numbers of small cell towers which may be located in places like building roofs, light poles etc. A peripheral slot based dual band hexagonal patch antenna has been designed here. This antenna can be utilized for 2.45 GHz ISM band WLAN and sub 6 GHz 5G. This antenna is radiating over 2.46 – 2.48 GHz with realized gain if 2.67 dBi and 3.69 – 3.71 GHz with 4.29 dBi realized gain. MNM technique is used for analyzing hexagonal patch antenna analytically. Bandwidth and gain enhancement has also been studied in hexagonal patch antenna. The outcome of this work is design of some novel hexagonal patches for different applications such as 5G and wireless communication, aeronautical navigation, multiband operation etc.

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Chapter 1: Introduction

1.1 Introduction

Hexagonal patch antennas are widely used in different RF applications. The hexagonal antennas have current distribution similar to that of circular patch antenna with less area occupation. Along with this, hexagonal antenna has other advantages such as low profile, ease of fabrication, conformability, cost feasibility etc. These advantages enhance interest on hexagonal patch antenna design [1-2]. Therefore, hexagonal patch antenna has been chosen for this work.

Transmission line model (TLM) and cavity model were widely used for analysis of microstrip antennas previously. Later, full wave solution methods were developed with the availability of computational resources to develop complex antenna structures. However, full wave methods requirehigh computational resource and computation time. Multiport Network Model (MNM) is a solution which can reduce complexity as well as provide better accuracy than TLM and cavity model. This thesis aims to investigate hexagonal shaped microstrip antennas in planar form using MNM.

Modern communication systems have need of antennas with multiband performance, highrealized gain, wide bandwidth and conventionally smaller dimensions which can easily be integrated within small area of chips or board or any other systems with the packaging structures [3-5]. Some key advantages of multiband antennas are space efficiency, versatility, global roaming capability, improved spectral efficiency, enhanced connectivity and adaptability. Speed of communication link is also a focus of communication engineers. Therefore, 5G technologies are preferred for wireless communication [6-10].

In spite of havingthe number of advantages coexistent with current narrowband radio service, low transmit power, resistance to jamming, low SNRs etc., there are some challenges related to designmultiband antenna, such as impedance matching, type of feed and excitation, compact size, and limitation of short range transmission also. In last few decades, microstrip patch has been one of the most favoredantennas due to some features like ease of fabrication, low cost and light weight. Microstrip antenna has been chosen for communication link establishment in the mobile phone, base stations, radar and surface of high performance aircraft, satellites etc. where small size, light weight and easy installation are important factors. Generally, antennas operatedin single frequency are notsuitable for multiple applications.This may increase number of antennas requirement for multitasking leading to on-board space constraints. This problem can be easily solved by designing single antenna with multiband characteristics. By applying slots, shorting or fractal in to the patch, multiband antenna can be produced [11-12].

World Radio communication Conference (November 2015) has recognized frequency bands in lower part of the C-band (3.4-3.6 GHz) allocated for Mobile Broadband Services (MBS).Several designsof narrow C-bandantennas were reported between 2015 and 2020. As C-band antennas are the very oldtype of 5G antennas, they have laid a base for the forthcoming multi-band and wideband antennas for 5G NR band n77/n78/n79(3.3-5 GHz), not to mention the new extended 5G NR band n46 (5.2-5.9 GHz) and n96(5.9-7.1 GHz)[13-14].

1.2 Motivation

Research on Microstrip Patch Antenna (MPA) is going on after its introduction in 1953 by Deschamp. Antennas for high frequency applications are prime focus of antenna engineers.Microstrip patch antenna has various shapes like rectangular, circular, elliptical, triangular etc. Analysis of microstrip antenna is required to obtain its characteristics such as impedance matching, radiation pattern, realized gain, bandwidth, resonant frequency etc. Several techniques have been utilized previously to analyse different antenna shapes. Hexagonal patch antennas have some advantages over other antenna shapes in terms of size reduction and bandwidth enhancement. Therefore, in this work hexagonal patch based antenna has been designed for different applications such as multiband operation, establishment of 5G communication, aeronautical navigation etc. Multiport network model (MNM) analysis for irregular shaped hexagonal patch antenna has not been studied yet in the literature. In this thesis, this research gap has been studied.

1.3 Organization of the Thesis

Chapter 2 starts with the literature survey on the existing works related to planar hexagonalantenna and its different applications.This is followed by the review of arbitrary shaped microstrip patch antenna analysis techniques.

Chapter 3 discusses the steps involved in MNM analysis of any irregular hexagonal patch antenna structure.

Chapter 4 is about effect of size reduction of hexagonal patch antenna and slot incorporation on patch for analyzing its multiband performance.

Chapter 5 deals with the design and analysis of a defected grounded hexagonal patch antenna for aeronautical navigation application at 5.17 GHz.

Chapter 6 shows slotted hexagonal patch antenna design for dual band performances at 2.45 GHz and 3.65 GHz for WLAN and 5G communication.

Chapter 7 summarizes the concluding remark and future research.

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Chapter 2:
Literature Survey

2.1 Introduction

Microstrip antennas are very useful in high speed aircraft, satellite and modern smart devices where size, weight, cost are constraints to be met. Nowadays microstrip patch antenna have numerous applications especially mobile radio and high speed wireless 5G networks. Microstrip antennas are attractive for their low profile, conformal to planar and non-planar surface, inexpensive manufacture process, easy to fabricatewith modern printed-circuit board (PCB) technology, mechanical robustness while mounted on rigid surfaces and compatibility with design of Monolithic Microwave Integrated Circuit (MMIC).

2.2 Review on Different Hexagonal Patch Antennas

The complexity of hexagonal-shaped microstrip patch antennas in comparison to rectangular-shaped microstrip patch antennas arises from the resonance frequency calculation method. For rectangular patch antennas, the resonant length follows approximately the formula $L = \frac{C}{2 \times f_r \sqrt{\varepsilon_r}}$, where L is the patch length, and other parameters are the same, while hexagonal patch antennas have unique resonant length calculations. Closed-form expressions for accurately determining the resonance frequency of hexagonal and half-hexagonal microstrip antennas have been presented in [1], drawing on their equivalence to rectangular microstrip antennas.

Various antenna characteristicssuch as circular polarization, frequency agility, dual-frequency operation, wide bandwidth, feed-line flexibility,Omni-directional patterning, beam scanning etc. can be altered when transitioning from a regular hexagon to irregular hexagon or modified hexagon-shaped microstrip patch antennas. These changes are due to variations in electric field distribution, current distribution on the patch surface and feed impedance variation.

Performance analysis of a hexagonal microstrip antenna in the S-band was reported in [2] and for the ISM band in [3]. For circular polarization in S, C and X- band applications with hexagonal-shaped microstrip patch antennas, a study was conducted in [4]. This study incorporated a semi-arc-shaped ground defect and a tilted hexagonal ring for orthogonal mode wave generation. Hexagonal shaped stack configuration patch antennas for 3.5/5.2 GHz have been studied in [5].

Monopole hexagonal patch antenna have been reported in [6].The designed antenna operates at 9.124 GHz with return loss -23.43 dB and they incorporate slot to the initial patch antenna for reducing the resonant frequency from 13.39 GHz to 9.124 GHz with a size reduction of 56.55% compared to conventional antenna.A regular hexagonal structure of a wide-slot antenna for broadband circular polarization, based on coplanar waveguide (CPW) feed, was reported in [7]. In this design, a pair of inverted-L grounded stripes served as perturbation structures, enabling the excitation of two orthogonal resonant modes. This approach aimed at achieving improved radiation performance, better impedance matching and compactness.

In the study conducted by Dassari et al. [8], a hexagonal-shaped patch antenna was designed at 2.45 GHz for RF energy harvesting applications.Dual-band antenna design using graphene material was discussed in [9].The design first featured a regular graphene-based hexagonal patch antenna and then incorporated a plus-shaped slot in the center. The resulting operating frequencies were 2.14 THz and 5.14 THz, with gains of 4.71dB and 5.61 dB, respectively.

A hexagonal-shaped narrow slot loaded in the center of a hexagonal patch antenna for WLAN applications was examined in [10].Additionally, a hexagonal pizza-shaped microstrip patch antenna with slots on the top surface to enhance return loss and reduce the resonant frequency was described in [11].This antenna operated in the X-band with a bandwidth of 170 MHz (9.21GHz to 9.38 GHz).For gain improvement in polygonal patch antennas [12], a hexagonal patch was transformed into a hexagonal ring for enhanced results. Half-hexagonal antennas with a peak gain of 6.2 dBi and a wide bandwidth of 2.0GHz to 11.5 GHz were reported in [13, 14].Dual-band and multiband responses can also be achieved in hexagonal-shaped patch antennas through slot loading.

In [15], a dual-band response was achieved in a hexagonal slotted patch with a multi-layer stacked antenna. Furthermore, a hexagonal-shaped patch loaded with an octagonal slot in the center demonstrated a multiband response in [16].The noteworthy aspect of this antenna is its resonance frequencies: 3.13 GHz, 8.89 GHz, 10.69 GHz, 16.79 GHz, 20.37 GHz, 26.06 GHz, 30.13 GHz, and 36.26 GHz, each accompanied by widely used gains of 5.17dBi, 9.12dBi, 15.83dBi, 6.05 dBi, 5dBi, 5.84dBi, 5.34dBi, and 3.79dBi, respectively.

The performance of Hexagonal Patch Antenna influenced by Split Ring Resonator was reported in [17].In this paper they printed four Split Ring Resonator at the rear side of the CPW fed hexagonal patch antenna.Additionally, aDual band hexagonal microstrip antenna loaded with hexagonal and cylindrical EBG was reported in [18]. In this design, a hexagonal patch antenna served as the primary radiating element and was periodically loaded with smaller hexagonal patches along the four corners of the substrate.Space utilization and structural similarity are the two main characteristics of fractal miniaturization techniques.An analysis of a miniaturized Sierpinski Gasket fractal hexagonal microstrip antenna for wireless communications was reported in [19]. The antenna exhibited high gain, high directivity and an omnidirectional radiation pattern across multiple resonant frequencies.

In [20] a hexagonal fractal antenna has been designed for super wideband in Terahertz applications. In [21] the authors optimized inscribed hexagonal fractal slotted microstrip antenna using modified lightning attachment procedure.A hexagonal patch antenna with a Swastik slotted design on radiating patch and integration of metamaterial-based Complementary Split Ring Resonator (CSRR) was reported in [22]. Swastik slot with equal arms yields a better result compared to unequal arms. The Swastik slot with equal arms results in a bandwidth of 8GHz (12 - 20GHz) with a peak gain of 6.1dBi.

In [23], a CSRR loaded hexagonal patch antenna was studied under two different cases - first case involved loading with open-end CSRR and the second case used a closed CSRR.High precision navigation systems require reducing the effect ofmultipath interference. Traditionally, bulky and heavy choke ring structures have been employed to achieve this. In [24], it was reported that an FSS substrate reduces the effects of multipath interference by blocking the propagation of surface waves, thereby reducing multipath interference.In [25], a compact microstrip patch with a half-mode substrate integrated waveguide (HMSIW) hexagonal cavity for WLAN applications was presented. The merging of the hexagonal HMSIW cavity and square patch led to high efficiency.

2.3 Comparison between Hexagonal Patch Antenna and Other Antennas: Review

Comparison of three widely populardesigns of microstrip patch antennas has been studied in [26]. In this article,rectangular, square and hexagonal patch antennas were analysed and characteristic comparison was performed among them using High Frequency Structure Simulator (HFSS).In [27] the authors reported a comparison betweensix different shapes i.e. rectangular, circular, square, elliptical, pentagonal and hexagonal along with their corresponding performance parameters.

Table 2.1: Comparison between different patches with hexagonal patch

Parameters of Comparison	Rectangle	Square	Hexagonal
Frequency	3.5GHz	3.5GHz	3.5GHz
Dielectric substrate	Rogers RT /duroid 5880 tm	Rogers RT /duroid 5880 tm	Rogers RT /duroid 5880 tm
Relative Permittivityε_r	2.2	2.2	2.2
tanδ	0.02	0.02	0.02
Impedance Matching	50Ω	50Ω	50Ω
Feeding Technique	Microstrip Line Feed	Microstrip Line Feed	Microstrip Line Feed
Return Loss	-7.8dB	-11.2dB	-18dB
Peak Gain	2.7736	2.60674	2.9877
Peak Directivity	2.8101	2.62241	3.0631
Radiation Efficiency	0.97042	0.97482	0.9917

Table 2.2: Comparison of various performance parameters of different patches of microstrip antenna with Hexagonal Patch

Shape of patch	Return loss (dB)	Gain (dB)	Lower cut off frequency (GHz)	Higher cut off frequency (GHz)	Bandwidth (GHz)
Circle	-16.50	8.18	6.80	7.43	0.63
Rectangular	-19	6.76	7.33	8.47	1.14
Ellipse	-25	7.23	6.90	7.96	1.06
Pentagon	-23	9.09	7.30	8.54	1.24
Square	-21	8.28	6.53	7.45	0.92
Hexagon	-22	7.44	7.30	8.52	1.22

A Hexagonal Patch Antenna with CPW Feeding was designed and comparativeanalysis with other different patch antenna shapes was reported in [28]. The antenna configuration studied included a simple hexagonal patch with an L-cut in the patch aimed at improving impedance and circular polarization bandwidth. They achieved 3dB axial ratio bandwidth of 1.33% for the simple hexagonal patch and 1.98`% for the L-cut hexagonal patch, respectively.

2.4 Frequency Reconfigurable Hexagonal Microstrip Patch Antenna

A frequency reconfigurable antenna is a type of antenna that can be adjusted or tuned to operate at different frequencies within a certain range. The concept behind a frequency-reconfigurable antenna is to have the ability to change its resonant frequency or operating frequency without physically altering its structure. This is typically achieved through the use of various tuning techniques or components, such as varactors(voltage-controlled capacitors),switches or other electronic elements that can modify the antenna's electrical properties.

A novel miniaturizes hexagonal shaped frequency reconfigurable antenna was reported in [29]. The proposed design had a hexagonal patch antenna with four oblique slits, two longitudinal and two latitudinal. It used four PIN diodes to control frequency and pattern reconfiguration in the longitudinal and latitudinal slits. The operating frequencies of the proposed reconfigurable antenna are 4.25, 5.65, 6.8, and 8.2 GHz and it has pattern slopes of −30°, 0°, +30°, and 180°.The pattern is reconfigurable in four directions without servo systems.

Another research was reported in [30] which presented a compact frequency reconfigurable dual band antenna for switchable frequency bands application. Two PIN diode switches were used to operate the antenna in 4 different modes. Parametric study shown here is concluding that a slight variationin the dimension of slot length in rectangular and hexagonal patchaffects surface current distribution of the patch followed by the operating frequency variation of antenna drastically.

A frequency reconfigurable hexagonal patch antenna with switchable slots was reported in [31].Using Read switches for implementation of reconfigurable patch antennas was reported in [32]. The Read switch connected two patches at their adjacent vertices. A hexagonal patch antenna with T-shaped slot for frequency switching and conical radiation was reported in [33]. Frequency reconfigurable hexagonal shaped patch antenna using PIN diode was reported in [34-35] as well.

Ambient computing, a new paradigm can be defined as a widespread discipline which works in the area of environment, society, security, computing, interacting, intelligence and many more. Mechanically reconfigurable hexagonal fractal patch antenna for ambient computing was reported in [36]. Frequency reconfigurable operation was achieved by varying the ground plane length mechanically and fractal concept was used to achieve miniaturization of triangle inscribed hexagonal patch. The proposed antenna resonated at varying frequency in the range of 2GHz to 10 GHz with good reflection coefficient of less than -10dB.

2.5 Biomedical Application of Hexagonal Microstrip Patch Antenna

Hexagonal microstrip patch antennas have been explored for various biomedical applications due to their unique properties and advantages. Here are a few example of how hexagonal microstrip patch antennas have been used in the biomedical field:

2.5.1. Implantable Biomedical Devices:

Hexagonal microstrip patch antennas can be integrated into implantable medical devices such as pacemakers, neuro-stimulators and drug delivery systems. These antennas can enable wireless communication between the implanted device and an external monitoring or control system. The hexagonal shape can help optimize the antenna size and radiation pattern to fit within the limited space available in the body. [37,38] present a hexagon-shaped bow –tie antenna design that offers reduced size, increased accuracy and good performance characteristics, making it a viable option for implantable biomedical applications within the specified frequency range.

2.5.2. Wireless Biomedical Sensing:

Hexagonal microstrip patch antennas can be used for wireless sensing applications in biomedical devices. For example, they can be integrated into wearable sensors to monitor vital signs such as heart rate, respiration rate and body temperature. The compact size and tunable characteristics of hexagonal antennas make them suitable for such applications. In [39], the development and significance of a novel SRR (Split Ring Resonator) loaded circular ring surrounding a hexagonal patch antennawas discussed, specifically designed for wearable devices intended for Electro Encephalo Gram (EEG) and healthcare monitoring applications.

2.5.3. Medical Imaging:

Hexagonal microstrip patch antennas can be employed in microwave imaging systems, such as microwave breast imaging, which is a non-invasive technique used for early detection of breast cancer. These antennas can help transmit and receive microwave signals for imaging purposes and their shape can be optimized to provide better resolution and sensitivity. In [40, 41], the focus is on the design and simulation of a hexagonal microstrip antenna, including its application in breast phantom simulation.

2.5.4. Capsule Endoscopy:

In medical procedures like capsule endoscopy, where a small wireless capsule is swallowed to capture images of the gastrointestinal tract, hexagonal microstrip patch antennas can be used to facilitate communication between the capsule and an external receiver. Their compact size and efficient radiation properties are well-suited for this purpose.

2.6 Multiband Application of Hexagonal Microstrip Patch Antenna

Hexagonal microstrip patch antennas are versatile and can be designed to operate across multiple frequency bands, making them suitable for various multiband applications. Here are a few examples of how hexagonal microstrip patch antennas can be used in multiband applications:

2.6.1. Wireless Communication Systems:

Hexagonal microstrip patch antennas can be designed to cover multiple frequency bands used in wireless communication systems. For instance, a single antenna could be tuned to operate in both Wi-Fi and Bluetooth frequency bands, providing compatibility with different wireless devices and standards. In [42], the work focused on compact dimensions of 35X30mm, using FR4 substrate material for 2.40 GHz, 5.03 GHz and 8.67 GHz for multiband operation. The patch consisted of four rectangular slots and a circular slot, contributes to its multiband performance. The antenna has many practical applications like in GSM, wireless LAN, WIMAX. A multiband antenna was reported in [43] where hexagonal patch connected its peripheral rectangle through a small switch operated according to application.

2.6.2. Satellite Communication:

Hexagonal microstrip patch antennas can be used in satellite communication systems to cover multiple frequency bands, such as C-band, Ku-band and Ka-band. This allows for efficient data transmission and reception from satellites in different orbital position. In [44], the study focuses on the design of a planar antenna using metamaterial. The antenna's key components are an L-shaped slit etched within a rectangular patch,along with a grounded inductive spiral. The slit acts as a series left-handed capacitance, while the spiral functions as a shunt left-handed inductance. Designed antenna was made to work in L, S and C-bands(400MHz, 3.25MHz and 6.55 GHz).

2.6.3 Radar Systems:

Radar systems often require antennas that can operate at various frequencies to perform function like target detection, tracking, and imaging .Hexagonal microstrip patch antennas can be designed to cover multiple radar bands, enabling a radar system to be versatile and adaptable to different operational scenarios. In [45], the study introduces a novel concept of a multi-band antenna based on a hexagonal fractal shape. This fractal design offers the ability to create multiple frequency bands within a single antenna structure. By employing three iterations of the hexagonal fractal, the antennas multi-band capabilities are enhanced. The ability to operate with the 0.5 GHz to 10 GHz frequency range can make it adaptable to S band and C band applications. In [46],the study presents a new design for a microstrip patch antenna that utilizes metamaterial. The aim of the design is to achieve multiband functionality, which is essential for applications requiring communication over multiple frequency bands. The proposed antennas are suggested to be useful for designing lightweight receivers for airborne synthetic aperture radar (SAR) systems. This highlights a specific application area where the antennas could offer benefits due to their high gain and multiband capabilities.

2.6.4. Multiband Wireless Sensor Networks:

In wireless sensor networks, where sensors communicate with each other and a central hub, hexagonal microstrip patch antennas can be utilized to enable communication across multiple frequency bands. This can enhance network flexibility and robustness. In [47], tri-band MHCSR (Modified Hexagonal Complementary Spiral Resonator) loaded patch antenna with an octagonal slot is designed to work on 900 MHz, 2.4GHz, and 5GHz. In [48], the study introduces a novel design of an ultra-wideband (UWB) antenna using a hexagonal shape as its basis. The design incorporates principles of fractal geometry and grooves on the ground plane to improve reflection characteristics across the UWB frequency range (3.1GHz to 10GHz).The antenna's ultra-wideband characteristics make it well suited for wireless sensor networks deployed in industrial environments for monitoring and control.

2.6.5. Radio Frequency Identification(RFID):

In RFID systems, which are used for tracking and identification, hexagonal microstrip patch antennas can cover multiple RFID frequency bands, allowing compatibility with different RFID tags and applications. The center frequency of 2.42GHz, return loss 32dB, axial ratio bandwidth of 7.5%, minimum axial ratio of 1.82 dB, gain of 4.9 dBi with a broadside radiation characteristics of RHCP antenna design for RFID reader have been discussed in [49].Half E-shaped patch antenna for RFID reader with wideband circular polarization was reported in [50]. The measured results show that the antenna has an impedance bandwidth of 14.2% (833-960MHz), a 3-dB AR bandwidth of 9.0% (846-926MHz), and an average gain of 7.3 dBi cover a 3dB AR bandwidth.

2.7 Wide band Application of Hexagonal Microstrip Patch Antenna

Hexagonal microstrip patch antennas can be designed for wideband applications, where they are intended to operate across a broad frequency range. Wideband antennas are particularly useful in scenarios where communication or sensing is required over a wide range of frequencies. Here are some examples of wideband applications of hexagonal microstrip patch antennas.

2.7.1.Ultra-Wideband(UWB) Communication:

UWB technology enables high-data-rate communication over a wide frequency spectrum. Hexagonal microstrip patch antennas can be designed to cover the

UWB frequency range, which spans from several hundred megahertz to several gigahertz. UWB is used in applications like short-range wireless communication, radar systems and precision location tracking. In [51], the study focused on designing process of Ultra-wideband antenna. Hexagonal patch antenna with triangular shaped tapered microstrip feed line and partial ground plane was proposed. Hexagonal radiating patch had six circular cuts at its vertices and partial ground had five half circular sleeves. The results of the antenna showed good impedance matching over (3-27.57) GHz for a return loss (RL)>10dB. In [52], designed two UWB slot antennas with CPW-fed were designed. Rectangular radiating element had octagonal slot with impedance bandwidth of 2.5GHz at the center frequency of 4.35 GHz and L-shaped stub located in the ground plane of hexagonal radiating patch with impedance bandwidth of 2.2GHz at the center frequency of 4.24GHz.In [53], authors reported a CPW- fed hexagonal antenna for UWB applications. For miniaturized size of the antenna and improved impedance bandwidth they added fractal elements at the edges. The antenna showed large bandwidth of 1.7 GHz -11GHz with average gain of 2.35dBi.

In [54], authors reported a co-planar waveguide (CPW) fed hexagonal shaped microstrip fractal antenna. The stepping feed configuration was used for better impedance matching. The reported antenna operated from 3.1 GHz-10.6GHz with reflection co-efficient less than -10dB.In [55], authors reported a hexagonal microstrip patch antenna whose operating frequency varied between 3.68GHz - 18.297GHz. Reported antenna had partial ground plane with unsymmetrical slots. A compact ultra wide band antenna based on hexagonal split-ring resonator for pH sensor application was reported in [56].The fractional bandwidth and bandwidth-dimension ratio were achieved with the metamaterial-inspired antenna as 146.91% and 3183.05, respectively. The operating frequency of this sensor covers the bandwidth of 17 GHz from 3 to 20 GHz with a realized gain of 3.88 dB and total efficiency of the antenna is 70%.In [57], authors reported CPW-fed hexagonal patch antenna impedance bandwidth was 2.9GHz -12GHz.In [58],a novel CPW-fed hexagonal shaped monopole-like UWB antenna was proposed, whose operating frequency was 2.71GHz-12.61GHz.

2.7.2. Ground-Penetrating Radar(GPR):

GPR systems are used for subsurface imaging in various applications, including geophysics, archaeology and civil engineering. Wideband antennas are crucial for GPR to achieve better depth of penetration and resolution, Hexagonal microstrip patch antennas can be designed for specific GPR frequency bands. In [59] the study focused on design of hexagonal patch with two-folded Capacitive Loaded Line Resonators(CLLR) on the left edge of the patch antenna. Operating frequency of the antenna was 3.1GHz to 10.6GHz for two CLLRs on bottom of the antenna to provide extra dual resonant frequency at 2.4 GHz and 9.1GHz for Bluetooth and radar applications. Inset fed hexagonal patch antenna was reported in [60].Here both ground plane and radiating patch were modified to obtain the desired performance. This antenna used hexagonal shape with fractal at its edges and defected ground structure arrangement for the antenna provided improved gain and axial ratio. Good performance of GPR antenna needs enhanced bandwidth as reported in [61- 65] and high gain [66-69] respectively.

2.7.3. Software-Defined Radio (SDR):

SDR systems require antennas that can cover a wide frequency range to accommodate different communication standards and bands. Hexagonal microstrip patch antennas can be designed as versatile wideband elements suitable for SDR platforms. In [65] the study addresses the critical issue of bandwidth, particularly in the context of handheld radio antennas. In [66] we are introduced to a unique antenna design that can be tuned to operate within specific narrow frequency bands. This allows the antenna to adapt and perform optimally across a wide frequency range. The introduction of cognitive radio presents a challenge for antenna design. The changing frequency bands and the dynamic nature of cognitive radio systems require antennas that can effectively adapt to these variations while maintaining their performance [67].

2.7.4. Wideband Radio Astronomy

In radio astronomy, antennas are required to cover a wide range of frequencies to observe different celestial phenomena. Hexagonal microstrip patch antennas can be designed for use in radio telescope or other wideband radio astronomy equipment. In [68], an Antipodal Vivaldi Antenna Surrounded by Dielectric (AVA-SD) was proposed for multiple applications such as microwave and millimeter-wave imaging, see-through wall and radio astronomy. The main characteristics of the designed AVA-SD are wide bandwidth, high front-to-back ratio, high gain, E-plane tilt of beam, narrow half power beam width and low side lobe and cross-polarization levels. In [69],different trade-offs and difficulties in the design of ultra-wideband array antenna elements were analyzed for these radio telescopes at frequencies below 500 MHz. Bandwidths of 7:1 are desired while using low-profile elements to keep the overall cost within the budget.

2.8 5G Application of Hexagonal Microstrip Patch Antenna

Hexagonal microstrip patch antennas can be used in various applications related to 5G (fifth-generation)wireless communication systems.5G technology aims to provide higher data rates, lower latency, increased network capacity and improved connectivity. Hexagonal microstrip patch antennas can contribute to the implementation and optimization of 5G networks in several ways. Now we are reviewing application of microstrip patch antenna in 5G along with hexagonal shaped microstrip patch.

2.8.1.Beam forming and Massive MIMO:

Beam forming and massive Multiple-Input, Multiple-Output (MIMO) technologies are integral to 5G systems. Hexagonal microstrip patch antennas can be configured to support beam forming and MIMO techniques, improving spatial multiplexing and interference management. A linearly polarized series-fed 8×16 rectangular antenna array with through element technology at 28 GHz was designed in [70] and the paper also pointed out beam steering MIMO applications.

A metamaterial-based thin planar lens antenna has been reported in [71] for spatial beam forming and multi-beam massive Multiple Input Multiple Output (MIMO) systems. Antenna elements were a planar lens linear array for receive/transmit elements. The operating bandwidth of the antenna was 26.6 GHz-29 GHz with maximum gain of 24.2 dBi.Digital beam forming-based massive MIMO has been reported in [72-74] for transceiver of 5G millimeter-wave communications.

2.8.2. Small Cell Network:

5G networks rely on a dense deployment of small cells to improve coverage and capacity in urban and high-density areas. Hexagonal microstrip patch antennas can be designed for small cell base stations, enabling efficient and compact antennas for localized coverage. In [75] unique design challenges associated with size, cost, and performance in 5G SBSs are presented. Next-generation micro- and Pico-cellular wireless Networks antenna design process was point out in [76-79].

2.8.3. Millimeter-Wave(mm-Wave)Communication:

5G networks utilize mm-waves frequencies to achieve high data rates. Hexagonal microstrip patch antennas can be designed to operate in the mm-Wave frequency bands, providing directional and efficient communication links for outdoor and indoor environments. Millimeter-wave (30-300 GHz) is proposed for 5G as it is relatively unused and can provide large absolute bandwidth.

In [80], the author presents a novel mm-Wave multiband patch antenna design for 5G communication. The 5G mm-Wave antenna resonates at band of 37 GHz and 54 GHz with maximum bandwidth of 5.5 GHz and 8.67 GHz respectively. Circularly polarized antennas are highly anticipated in millimeter (mm)-wave mobile communication to reduce the delay spread in a multipath environment [81].

In [82], a 5Gmm-Wave wireless antenna was designed to realize broadband performance to maintain a low profile nature. The longitudinal slot on patch element changes the E-field distribution of the TM_{20} mode for realizing a broadside radiation pattern. The microstrip patch antenna is a key candidate that has a numerous applications in wide spread wireless communication system for 5G applications [83-84].

2.8.4. Vehicle-to-Everything (V2X) Communication:

5G enables V2X communication, allowing vehicles to communicate with each other and within infra-structure .Hexagonal microstrip patch antennas can be integrated into vehicles to facilitate reliable and low-latency V2X communication. It is expected that the new technologies (5G) will investigate the issues within V2V, V2X,V2I,wireless healthcare services, utility applications and industrial automation, consumer, virtual and augmented reality services and primary broadband access services areas.It will also address the performance criteria for low latency, high, speed, enhanced reliability, peak throughput per connection, systems spectral efficiency, connection, capacity density and low power consumption[85-86.]. Some vehicle-to-everything (V2X) services need secure transmissions and should be prevented from eavesdropping. Physical layer security, an information-theoretical framework, utilizes the randomness of underlying channels to ensure secrecy in the physical layer. Different from ground communications, unmanned aerial vehicles (UAVs) create line-of-sight connections to vehicles and mobile users making them an ideal platform to conduct physical layer security strategies [87-88].

2.8.5. Internet of Things (IoT) Connectivity:

5G supports massive IoT connectivity for various applications, including smart cities, industrial automation and health care. Hexagonal microstrip patch antennas can be designed to support IoT devices providing efficient communication for a large number of connected devices. The antennas for IoT applications are required to exhibit three important characteristics namely; (i) small size [89-91] (ii) energy efficiency [92]and (iii) ability to operate in multi antenna environment [93].

2.9 Arbitrary Shaped Microstrip Patch Antenna Analysis Techniques

Full-wave methods are mathematical and numerical techniques used for accurately analyzing electromagnetic problems. MoM (Method of Moments) is used to solve integral equations that describe electromagnetic field behavior for rectangular [94] and circular [95] patch antenna analyzed using MoM. FDTD (Finite Difference Time Domain) is a numerical technique that discretizes space and time to simulate electromagnetic behavior. Rectangular patch antennas in [96] and circular patch antennas in [97] were analyzed using FDTD technique. FEM (Finite Elements Method) is a numerical technique used for solving differential equations, including Maxwell's equations. FEM was used in [98] for triangular & circular and in [99] for rectangular shaped patch antenna. Conformal antennas are designed to match the shape of their host structure. MoM, FDTD, FEM can also be used to analyze conformal patch antennas.

In [100] finite element method (FEM) analysis of antennas conformed to cylindrical shapes was documented. Finite difference time domain (FDTD) method was used to analyze rectangular antennas that are conformed to cylindrical shapes in [101].Method of Moment(MoM) technique was also employed to analyze rectangular patch antennas that are conformed to cylindrical shapes in [102].Finite difference time domain (FDTD) method was used to analyze annular microstrip patch antennas conformed to conical shapes in [103].Method of Moments (MoM) technique was used to calculate the input impedance of a conical annular patch antenna in [104].

Full wave analysis methods are powerful tools for studying the electromagnetic behavior of antennas or structures with complex and arbitrary shapes, whether they are regular shaped or curved. But full wave analysis is computationally expensive and time-consuming. To analyze microstrip antennas with regular shapes approximately cavity model technique is suitable. It is more efficient in terms of computational resources and time. However the cavity model technique may not provide the same level of accuracy as full wave analysis methods. Working principle of cavity model is that patch antenna is imagined to be a closed cavity and the fields are represented in terms of the natural modes of the cavity. Historical origin of the cavity model [105] and in this technique the internal electromagnetic field within the imaginary cavity is expressed in relation to Eigen functions. Eigen functions are mathematical functions that have special properties in the context of solving certain mathematical and physical problems. Essentially Eigen functions were used to predict how different kind of regular structures of antennas behave.

In [106] advancement of cavity model was introduced. This improvement involved considering the losses (such as dielectric losses) of the antenna. The losses were combined to create a parameter called the “effective loss tangent” which is important for antenna performance. Cavity model analysis was used to study the circular shaped patch antenna in [107-108]. Cavity model technique was applied to analyze different types of microstrip antennas like annular antennas, annular sector antennas in [109]. Application of cavity model analysis technique to study an antenna with an equilateral triangle shape was done in [110].Cavity model analysis technique was used to study rectangular patch antenna that conforms to a cylindrical surface in [111-112].Cavity model analysis was applied to study yet another type of antenna: an annular sector patch antenna conforming to a conical surface in [113, 114].

Small section of big transmission line looks like rectangle or square patch.These antennas can be modeled as section of transmission lines. Similarly small sections from cylindrical transmission line look like a circular or annular ring patch .Therefore this antenna can be modeled as a section of transmission line [115-117]. The transmission line model [118-120] was the first technique employed to analyze a rectangular microstrip antenna by Munson in 1974 [118]. In this model, the interior region of the patch antenna is modeled as a section of transmission line. The characteristic impedance, Z_0, and propagation constant (β) for the line are determined by the patch size and substrate parameters.

In [121] compact probe-fed microstrip patch antennas with folded-patch feed techniques for UWB application have been reported. The reported basic antenna has been analyzed using equivalent transmission line model to achieve an impedance bandwidth of 92% in the frequency range 3.94-10.65GHz.

Rectangular, Circular and Equilateral triangular microstrip antennas have been analyzed using the improved transmission line model reported in [122].In [123] quasi-TEM lossy transmission-line model is used to express the radiation admittance of an arbitrary-shape symmetrical patch which is linearly polarized. A transmission-line coupled patch antenna analyzed by transmission line model have been reported in [124].Cavity model analysis as previously discussed is a technique suitable for regular shaped geometries. It works well when one can easily determine the Eigen function (natural modes) by applying boundary conditions. In other words, it is effective when one can describe the electromagnetic behavior of the antenna within a closed cavity. When dealing with microstrip antennas that have irregular shapes, cavity model analysis may not be directly applicable due to the complexity of determining Eigen functions.

In response to this limitation a new technique called Multiport Network Modeling (MNM) was developed. The name "Multiport Networking Modeling" itself provides a hint about how this technique works. MNM is built on the concept of treating the microstrip antenna as a multiport network. In other words it represents the antenna as a system of interconnected ports or terminals. The following section of the discussion or text will provide an overview of the types of problems and scenarios that have been addressed using the MNM technique as also likely examples of irregularly shaped microstrip antennas that have been analyzed and modeled using MNM.

2.10 Multiport Network Modeling Technique

The basic idea of MNM was initially introduced in [125].The key point is that irregular structures can be understood and analyzed if they are composed of or can be related to regular structures in some way. The technique for analyzing irregular structures is called the segmentation method. It involves using the S-parameters of regular segmented structures to deduce or determine the properties or characteristics of the overall irregular structure. MNM was used to analyze a strip line 3dB hybrid circuit. It was observed in [126] that using Z matrices instead of S-matrices can make the segmentation method more computationally efficient.

Additionally, it should be mentioned that this improved technique was first applied to analyze a planar circuit. It was later realized that certain irregular structures could be better represented or understood as the difference between two or more regular shapes or structures. In other words, irregularities can be seen as variations from regular patterns. In desegmentation technique irregular structures too are broken down into regular shapes. This technique was introduced in [127].It mentioned that the desegmentation technique was applied to two different circuits and the interesting finding was that both the segmentation and desegmentation techniques produced the same results, implying the reliability and consistency of these methods in analyzing irregular structures.

Characteristics of a simple rectangular patch antenna using simple transmission line model was shown in [128]. MNM method is not limited to just basic rectangular patch antennas but is also effective in analyzing rectangular patch antennas operating in higher order modes [129]. An application of the MNM method to analyze an almost square patch antenna that was fed at two different locations with a 90^0 phase difference to study the antenna's response in terms of circular polarization was presented in [130]. MNM technique was utilized to determine the transmission characteristics of a circular patch antenna in [131]. MNM method has been employed to analyze circular sectors with varying angles in [132-133]. Segmentation and desegmentation technique were combined for the analysis of pentagon-shaped patch antenna in [134]. Various microstrip circuits can also be analyzed using MNM techniques effectively.

An application of the MNM technique is to calculate radiation losses in microstrip circuits with specific discontinues. The right-angled bend, a step-junction, T-junction and chamfered bends [135] are some examples. Calculation of radiation from similar kind of discontinues from coupled microstrip lines was reported in [136]. MNM analysis of multiport microstrip disk circuits was reported in [137]. [138] involved the analysis of power dividers that are constructed based on circular sectors. MNM was used as the method of analysis to understand the properties and performance of these power dividers.

The concept of using parasitic patches near a driven patch is to broaden the frequency response of a microstrip antenna.In certain situations, coaxial feeding can be applied to parasitic patches located very close to the primary patch antenna. This feeding method can influence the antenna's behavior.MNM technique is relevant and applicable in such scenarios involving parasitic patches and coaxial feeding. In these cases, MNM uses a model for the gap region between different patches to analyze the antenna's performance.

In [139] two parasitic patches were positioned near the radiating edges of a microstrip patch antenna, which was operating in its dominant mode. In [140], four parasitic patches were added to a rectangular microstrip antenna, one on each side. MNM was used to analyze this antenna configuration and its performance. [141] describes the use of MNM to analyze different arrangements of square patches positioned near a dual-fed square patch antenna that exhibits Circular Polarization (CP) response. In literature [142], authors involved the analysis of a gap-coupled microstrip patch using MNM.This configuration includes a rectangular microstrip patch and a microstrip line positioned in close proximity to each other.

MNM was used to investigate this setup. [143] appears as an extension of the previous work [142]. In this case, a series of microstrip patches were placed next to each other and were excited .MNM was used to study coupled microstrip lines in [144].MNM technique was used to incorporate and study the mutual coupling effects that occur between different edges of a rectangular microstrip antenna in [145]. MNM was also able to calculate coupling between edges of different microstrip antennas in an array [146].

MNM analysis can compute the effects of mutual coupling between different microstrip circuits as shown in [147]. Concept of proximity coupling can be used to excite microstrip patch antenna. In [148], MNM was utilized to analyze a rectangular patch antenna that was excited using proximity coupling. In aperture coupling method slots are created in the ground plane of the antenna to allow energy to couple into the antenna structure. MNM was also used to study performance of aperture coupled antenna in [149].

In [150], the desegmentation technique was employed to study the behavior of the notch-loaded rectangular patch antenna. [151] discusses the analysis of a collinear patch antenna configuration which includes a rectangular slot in the center of a rectangular patch antenna.This setup resulted in high directivity due to the excitation of the TM_{03} mode and MNM was used to analyze this configuration. In [152] a rectangular patch antenna was loaded with two rectangular slots to achieve even higher directivity. The excitation of the TM_{05} mode was used to achieve this and MNM was used to study this antenna configuration. [153] analyzes of microstrip square ring antennas that were loaded with single and double stubs, along with a shorting post. The purpose was to achieve triple and quad band operation. MNM was used for the analysis of these antennas. In [154] MNM was applied to study a proximity-coupled microstrip square ring antenna that was loaded with a single stub. This configurations resulted in the excitation of two broadside radiating modes.

In [155] two configuration involving fractal shapes were studied. Specifically, an arm of a proximity-coupled microstrip ring antenna was modified using a Minkowski curve, and both first and second iterations of this modification were applied. MNM was used to analyze the performance of these antenna structures, which exhibited dual-band operation.In [156] MNM was used to study a square spiral antenna using the segmentation method. The antenna exhibited a wideband circularly polarized response. In [157] two different square patch antennas were analyzed using the MNM technique. The first antenna had corners truncated along one of the diagonals and the second antenna had a diagonal slot. Both these antennas exhibited circular polarization (CP). MNM analysis was used to investigate these two antenna configurations. [158] involves the MNM analysis of two different antennas. The first antenna is a circularly polarized (CP) microstrip ring antenna and the second antenna is a cross-strip microstrip antenna. MNM was applied to study and analyze the characteristics of these antennas.

2.11 Conclusion

The simple transmission line model is conceptually very simple and approximate so that model is well applicable on rectangular patch only. However improved transmission line model is applicable to rectangular and square patches. This model has limitations too as it cannot account for field variations along the width of the patch. Again improved transmission line model is also not able to calculate higher order modes of the antenna and does not properly work at high frequency for patch design. Transmission line model is also not able to design irregular and arbitrary shaped patch antennas.

Full-wave analysis methods often require significant computational resources, especially for complex structures or high-frequency designs. The meshing requirements and computational time can increase substantially with the size and complexity of the antenna structure.While cavity models might work well for specific types of patch antennas with simple geometries or certain modes of operation, it is not able to analyze more complex and irregular structures. Therefore, for the analysis of irregular arbitrary shape microstrip patch antenna. MNM is suitable compared to transmission line, cavity model analysis and full wave analysis techniques. It offers less complexity compare to full wave techniques with better accuracy than the transmission line model, and applicability to all shapes.

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Chapter 3:
Circular Slotted Half Hexagonal Patch Multiband Antenna Design for 5G Applications using Multiport Network Model (MNM)

3.1 Introduction

Advantages of microstrip patch antennas such as light weight, compactness, conformability, low volume, low fabrication cost, easy fabrication process etc. causes microstrip patch antenna to be used widely in several applications [1-3]. Microstrip antennas were initially used in military applications only (rockets, satellites, missiles, aircraft etc.). In last few decades, it is found to be used for several other purposes such as radio altimeters, radars, mobile phones, biomedical devices, satellite receivers and different telemetry systems etc. [2-4].

The analysis of irregular microstrip patch antenna is challenging due to several factors such as substrate configuration, dielectric inhomogeneity, variety of feed, shape of patch etc [5]. To analyze microstrip antennas, many approximate analytical techniques were proposed which include Transmission Line Model (TLM) [6-7], cavity model [8-9], Multiport Network Model [10-11].

High accuracy of analysis has been achieved by rigorous full wave techniques [12-15] which are basically based on Sommerfield integral equations and Maxwell's equations. Method of Moment (MoM) has also been utilized for analyses of rectangular [16], circular [17], conformed rectangular [18] and conical annular [19] patches. Full wave analysis techniques require huge computation resource and time to converge. Cavity model analysis is not applicable for irregular antenna architecture which is solved by using MNM instead of cavity analysis. MNM can reduce complexity compared to full wave analysis while it has higher accuracy than TLM.

Multiport Network Model (MNM) is an extension of cavity model in which multiple numbers of ports are defined along periphery of the patch element of microstrip antenna [11]. MNM of any irregular shaped antenna has been obtained by two ways – segmentation and de-segmentation techniques. In [20], MNM analysis of irregular patch was first proposed and S matrices were used for analysis of strip line hybrid circuit. MNM analysis using Z matrices instead of S matrices in segmentation technique of simple patch was performed in [21]. Desegmentation technique was described in [22].

MNM for rectangular patch antennas with circular polarization (CP) were analyzed in [23-24]. Pentagonal patch has also been studied using MNM by Gupta *et al*. [25]. Nile *et al*. [26] performed MNM analysis of a circular sector. MNM technique has also been used for analysis of microstrip circuits in [27-28]. 2-D regular hexagonal and rhombic patches were analyzed in [29] using MNM. For MNM analysis of regular hexagonal patch in [29], the whole structure has been segmented into six equilateral triangles and segmentation technique has been applied. However, MNM analysis of irregular hexagonal patch has not been studied yet.

In this chapter, analysis of an irregular shaped hexagonal patch antenna using MNM technique is studied. For analysis of irregular patch, the patch should be decomposed into several regular shaped segments for which calculation of Green's function is easy. Here irregular hexagonal patch is decomposed into a rectangular structure and four right-angled triangular segments. Ports are placed around the periphery of each segment and based on Green's functions, Z matrices are calculated using MNM technique. Finally all segments are merged based on these Z matrices to obtain responses of the whole antenna structure. The obtained antenna responses of the antenna from MNM analysis are compared with its simulated and measured responses.

3.2 Irregular Hexagonal Patch Antenna

The geometry of irregular hexagonal patch antenna is shown in Fig. 3.1 (a). Point O is considered here as origin. Coordinates of the feed point are taken as (F, 0). L_1 and L_3 are the sides of irregular hexagonal patch as shown in Fig. 3.1 and L_2 is considered as the height of hexagon. Arlon AD 250 is taken here as substrate. The MNM analysis of this patch structure is discussed in next section.

3.3 Multiport Network Model (MNM) Analysis

To analyze the antenna using cavity model, determination of extension of physical dimensions due to fringe field is the first step. The expressions for edge extensions of rectangular and triangular elements are available in [5, 30]. The antenna structure is decomposed into five sections as shown in Fig. 3.1(b) and ports are assigned along edges (Fig. 3.1(b)) of segments $\frac{\lambda_g}{20}$ distance apart from each other (λ_g is guided wavelength). Feed location has also been considered as first port. Some of the peripheral ports are shown in Fig. 3.1 (b). The height of substrate is h.

3.3.1. Rectangular Section

Impedance Green's function for a rectangular patch with dimension $L_1 \times L_2$ is given by [31],

$$G(x, y\,;\, x_o, y_o) = \frac{j\omega\mu}{L_1 L_2} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\sigma_m \sigma_n}{\left[k^2 - {\lambda_m}^2 - {\lambda_n}^2\right]} \cos(\lambda_m\, x) \cos(\lambda_n\, y) \cos(\lambda_m x_o) \cos(\lambda_n y_o) \qquad (1)$$

Green's function mentioned in (1) relates electric field at a point (x, y) to the source current density at (x_o, y_o) where $\lambda_m = \frac{m\pi}{L_1}$, m = 1, 2, …..,$\lambda_n = \frac{n\pi}{L_2}$, n = 1, 2, ….., $k^2 = k_o{}^2\epsilon_r\left(1 - j\delta_{eff}\right)$, $k_o{}^2 = \omega^2\mu_o\epsilon_o$ and δ_{eff} is the effective loss tangent [31]. Further,

$$\sigma_m = \begin{cases} 1 & for\ m = 0 \\ 2 & for\ m \neq 0 \end{cases}$$

and

$$\sigma_n = \begin{cases} 1 & for\ n = 0 \\ 2 & for\ n \neq 0 \end{cases}$$

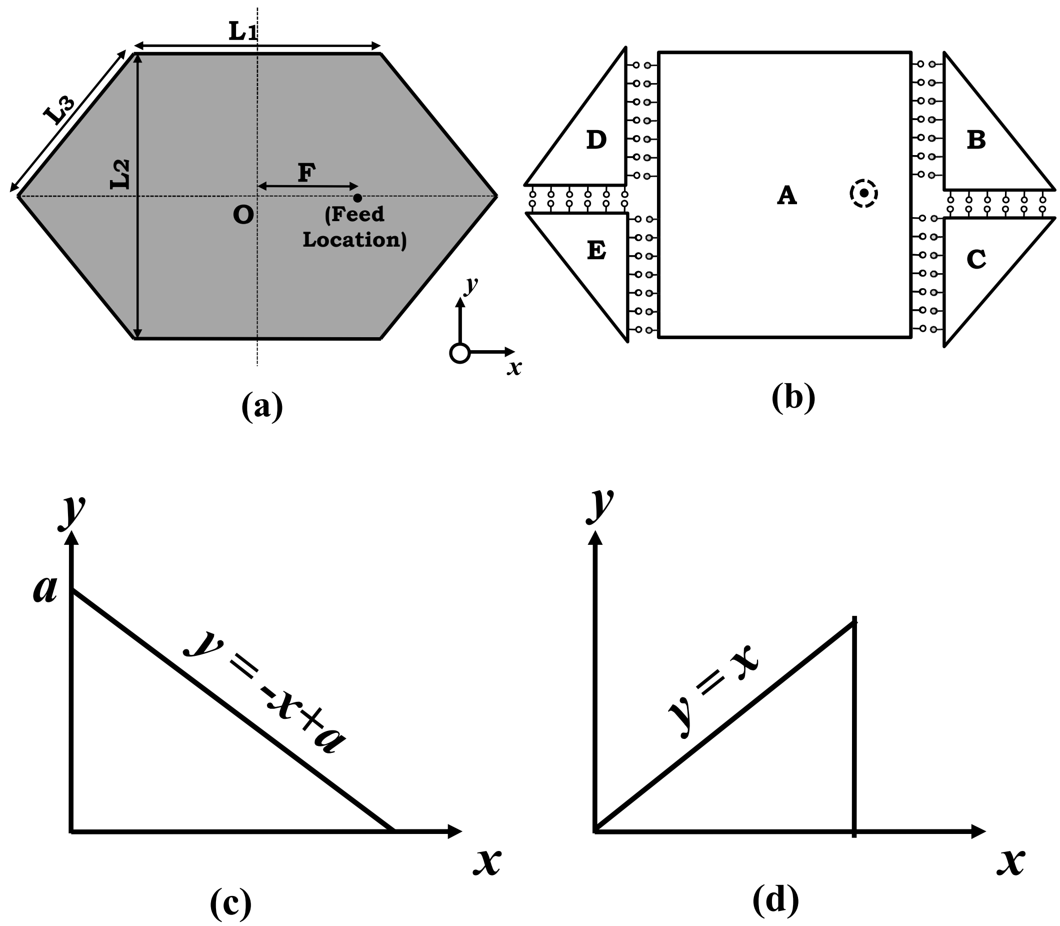


Fig. 3.1: (a) Antenna geometry, (b) Decomposition of antenna structure and port assignment; Right-angle triangle with diagonal (c) y = -x+a and (d) y = x

The impedance matrix of rectangular segment is calculated using above Green's function. Impedance matrix relates currents and voltages of ports. The mutual impedance between two ports i and j of widths W_i and W_j respectively can be expressed as

$$Z_{ij} = \frac{1}{W_i W_j} \iint_{W_i W_j} G(x, y\,;\, x_o, y_o) dW_i dW_j \quad (2)$$

For modeling of peripheral ports, port assignment can be performed in either x-direction or y-direction. For self-impedance at feed port of port-width $\Delta x_i \times \Delta y_i$, the impedance is evaluated as

$$Z_{ii} = \frac{1}{(\Delta x_i \Delta y_j)^2} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{j\omega\mu\sigma_m\sigma_n}{[k^2 - \lambda_m^2 - \lambda_n^2]L_1 L_2} \times$$
$$\left[\int_{x_i - \frac{\Delta x_i}{2}}^{x_i + \frac{\Delta x_i}{2}} \int_{y_i - \frac{\Delta y_i}{2}}^{y_i + \frac{\Delta y_i}{2}} \cos\{\lambda_x (x - x_o)\} \cos\{\lambda_y (y - y_o)\}\, dxdy \right]^2 \quad (3)$$

By integrating we get

$$Z_{ii} = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{j\omega\mu\sigma_m\sigma_n}{[k^2 - \lambda_m^2 - \lambda_n^2]L_1 L_2} cos^2\{\lambda_x (x_i - x_o)\}$$
$$cos^2\{\lambda_y (y_i - y_o)\} sinc^2 \left\{\lambda_x \frac{\Delta x_i}{2}\right\} sinc^2 \left\{\lambda_y \frac{\Delta y_i}{2}\right\} \quad (4)$$

The impedance relation for considering feed port as port$i$ and x-directed peripheral port as port jthus becomes

$$Z_{ij} = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{j\omega\mu\sigma_m\sigma_n}{[k^2 - \lambda_m^2 - \lambda_n^2]ab} \cos\{\lambda_x (x_i - x_o)\}$$
$$\cos\{\lambda_y (y_i - y_o)\} \cos\{\lambda_x (x_j - x_o)\} \cos\{\lambda_y (y_j - y_o)\}$$
$$sinc \left\{\lambda_x \frac{\Delta x_i}{2}\right\} sinc \left\{\lambda_y \frac{\Delta y_i}{2}\right\} sinc \left\{\lambda_x \frac{\Delta x_j}{2}\right\} \quad (5)$$

Similarly, the impedance relation for considering feed port as port i and y-directed peripheral port as port j is obtained as

$$Z_{ij} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{j\omega\mu\sigma_m\sigma_n}{[k^2 - \lambda_m^2 - \lambda_n^2]L_1L_2} \cos\{\lambda_x(x_i - x_o)\}$$
$$\cos\{\lambda_y(y_i - y_o)\}\cos\{\lambda_x(x_j - x_o)\}\cos\{\lambda_y(y_j - y_o)\}$$
$$sinc\left\{\lambda_x\frac{\Delta x_i}{2}\right\} sinc\left\{\lambda_y\frac{\Delta y_i}{2}\right\} sinc\left\{\lambda_y\frac{\Delta y_j}{2}\right\} \quad (6)$$

The impedance matrix for segment-A (rectangular section) is calculated using above equations.

3.3.2. Right-angled Triangular Sections

The Eigen function for Fig 1(c) is given by [32] as

$$\psi_{mn}(x,y) = \cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{a}y\right) + (-1)^{m+n}\cos\left(\frac{n\pi}{a}x\right)\cos\left(\frac{m\pi}{a}y\right) \quad (7)$$

The Eigen function for Fig 1(d) is [32]

$$\psi_{mn}(x,y) = \cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{a}y\right) + \cos\left(\frac{n\pi}{a}x\right)\cos\left(\frac{m\pi}{a}y\right) \quad (8)$$

The expression of electric field beneath the triangle can be written as,

$$E_z = \sum_{m=0}^{\infty}\sum_{n=m}^{\infty} A_{mn}\psi_{mn}(x,y)$$

whereA_{mn} values are the modal coefficients which can be found by solving wave equation and expression of $A_{mn}$is obtained as [32]

$$A_{mn} = \frac{j\omega\mu \iint J_z\,\psi^*{}_{mn}\,ds}{[k^2 - k_m^2 - k_n^2]\iint \psi_{mn}\psi^*{}_{mn}ds}$$

Using orthogonal properties of the Eigen functions, we can write

$$\iint \psi_{mn}\psi^*{}_{mn}ds = \iint |\psi_{mn}|^2 ds$$

$$\int_{x_o}^{x_o+a}\int_{y_o}^{y_o+x-x_o} |\psi_{mn}(x,y)|^2 dx\,dy = B_{mn}$$

where generalized origin is considered at (x_o, y_o). $B_{mn}$is expressed as

$$B_{mn} = \begin{cases} 2a^2, when\ m = n = 0 \\ \frac{a^2}{2}, when\ m \neq 0, n = 0\ and\ m = 0, n \neq 0 \\ \frac{a^2}{4}, when\ m \neq 0, n \neq 0\ and\ m \neq n \\ \frac{a^2}{2}, when\ m \neq 0, n \neq 0\ and\ m = n \end{cases}$$

For MNM analysis of right-angled triangular sections (B, C, D, E) shown in Fig. 3.1 (b), we need to consider three types of ports – x-directed, y-directed and hypotenuse directed. If port *i* is x-directed and port *j* is y-directed, then the corresponding impedance relation becomes,

$$Z_{ij} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{-j\omega\mu h}{[k^2 - \lambda_m^2 - \lambda_n^2]B_{mn}} [\cos\{\lambda_x(x_i - x_o)\}$$
$$\cos\{\lambda_y(y_i - y_o)\}\, sinc\left(\lambda_x \frac{W_i}{2}\right) + \cos\{\lambda_y(x_i - x_o)\}$$
$$\cos\{\lambda_x(y_i - y_o)\}\, sinc\left(\lambda_y \frac{W_i}{2}\right)] \times [\cos\{\lambda_x(x_j - x_o)\}$$
$$\cos\{\lambda_y(y_j - y_o)\}\, sinc\left(\lambda_y \frac{W_j}{2}\right) + \cos\{\lambda_y(x_j - x_o)\}$$
$$\cos\{\lambda_x(y_j - y_o)\}\, sinc\left(\lambda_x \frac{W_j}{2}\right)] \quad (9)$$

If port *i* is x-directed and port *j* is along hypotenuse of triangle, then the impedance relation becomes,

$$Z_{ij} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{-j\omega\mu h}{[k^2 - \lambda_m^2 - \lambda_n^2]B_{mn}} [\cos\{\lambda_x(x_i - x_o)\}$$
$$\cos\{\lambda_y(y_i - y_o)\}\, sinc\left(\lambda_x \frac{W_i}{2}\right) + \cos\{\lambda_y(x_i - x_o)\}$$
$$\cos\{\lambda_x(y_i - y_o)\}\, sinc\left(\lambda_y \frac{W_i}{2}\right)] \times [\cos\{(\lambda_x + \lambda_y)(x_j - x_o)\}$$
$$sinc\left((\lambda_x + \lambda_y)\frac{W_j}{2\sqrt{2}}\right) + \cos\{(\lambda_x - \lambda_y)(x_j - x_o)\}$$
$$sinc\left((\lambda_x - \lambda_y)\frac{W_j}{2\sqrt{2}}\right)] \quad (10)$$

This equation is similar for the case when port *i* is y-directed port and port *j* is along the hypotenuse.

3.4 MNM Analysis and Simulation of Irregular Hexagonal Patch Antenna

In this work, values of L_1, L_2, L_3 and F are considered as 30.01, 38.37, 27.13 and 7 mm respectively. The simulation of antenna structure is then carried out using CST Studio Suite 2021. A 50 Ω coaxial connector is connected as feed and waveguide port is added at the end of connector for EM excitation. The surface current distribution obtained from MNM analysis is compared with simulated surface current distribution in Fig. 3.2 (a and b). From these plots, it is observed that the surface current distribution of irregular hexagonal patch antenna obtained by MNM analysis is similar to the simulated response.

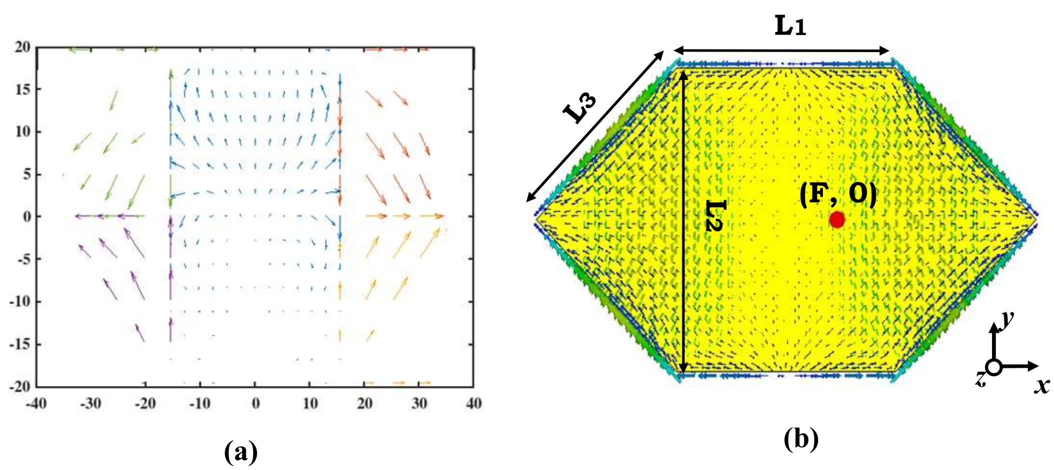


Fig. 3.2: Surface current distributions of patch obtained from (a) MNM analysis and (b) simulation

3.5 Results of Hexagonal Patch Antenna

The irregular hexagonal patch antenna shown in Fig. 3.1 (a) is fabricated on 1.5 mm thick Arlon AD 250 substrate with relative permittivity 2.5 and loss tangent

0.0013. Fabricated prototype is shown in Fig. 3.3. The return loss responses of the antenna obtained from MNM analysis, simulation and measurement are shown in Fig. 3.4.From Table 3.1, it is observed that return loss value obtained from MNM is quite similar to the return loss from measurement. Fractional bandwidth values obtained from MNM and simulation are very close as well.

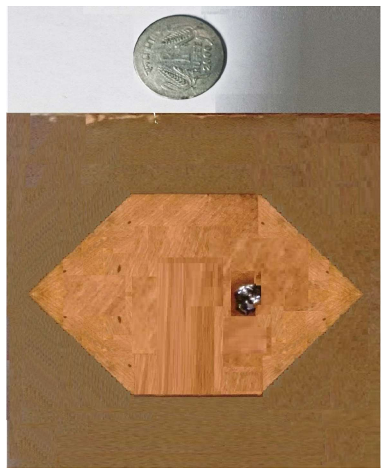


Fig. 3.3: Fabricated Prototype of antenna

Table 3.1: Comparison of Antenna Responses

Antenna Responses	MNM Analysis	Simulation	Measurement
Operating Frequency (GHz)	2.65	2.46	2.38
Return Loss (dB)	16.48	22.98	13.13
10 dB Return Loss Fractional Bandwidth (%)	1.05	1.97	3.25

Table 3.2: Realized gain and cross polar discrimination

Configuration	MNM Analysis	Simulation	Measurement
Realized Gain (dBi)	-2.41	0.89	1.16
Cross polar Discrimination (dB)	8.22	7.5	6.7

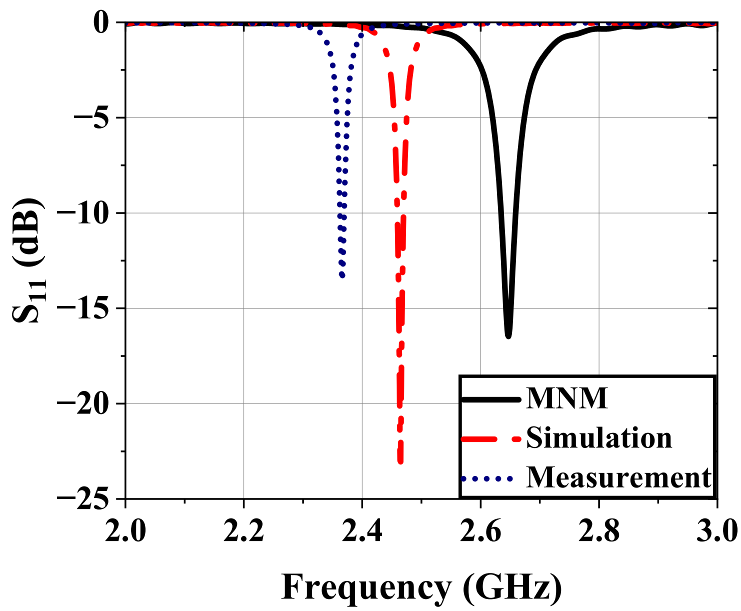
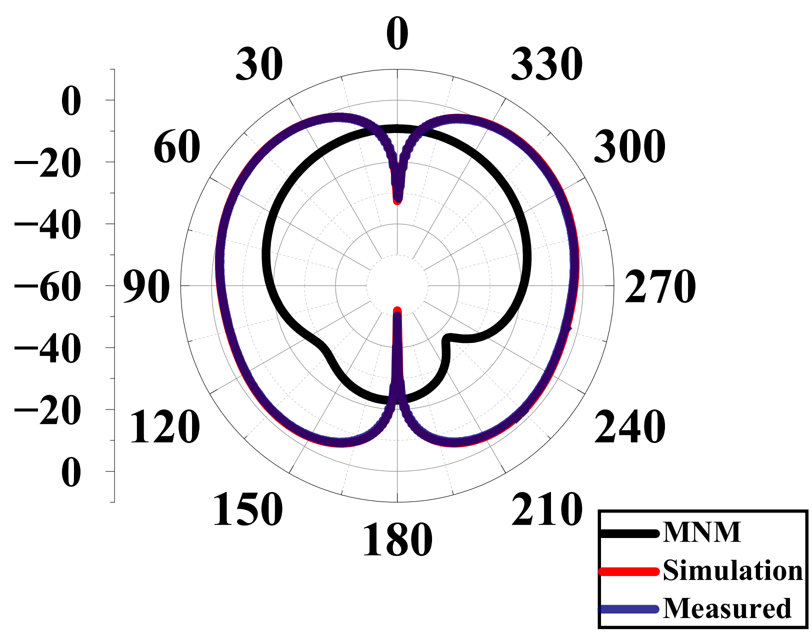
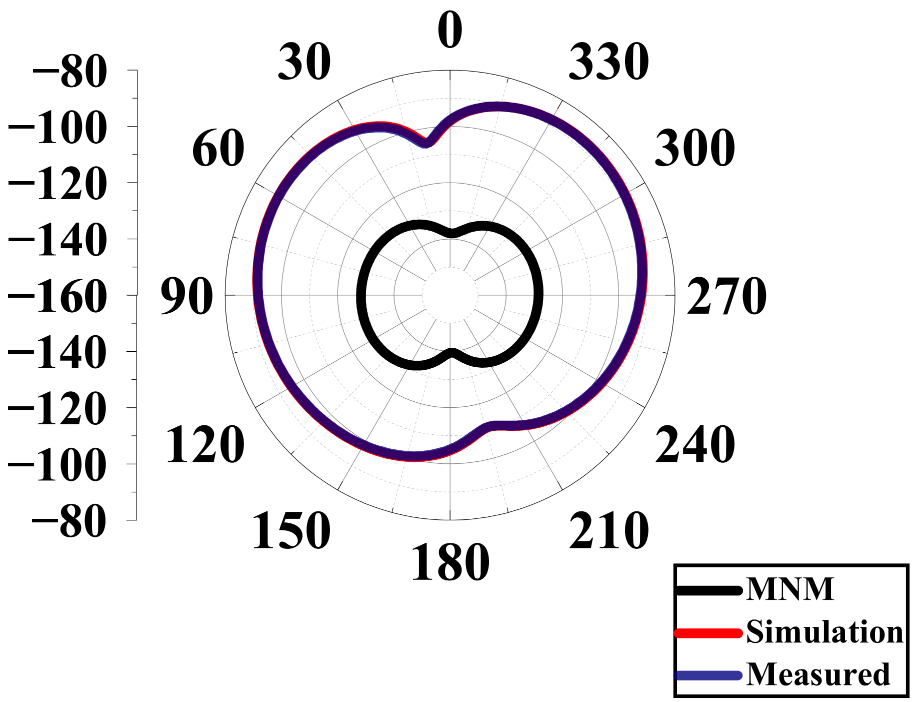


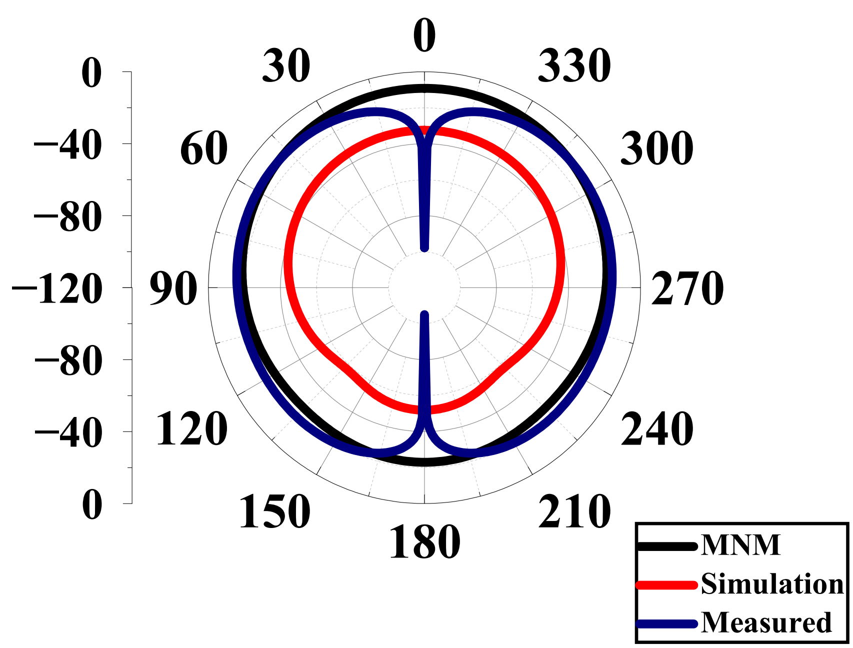
Fig. 3.4: Return loss plots of antenna from MNM, simulation and measurement



(a)


0
30
330
60
300
90
270
120
240
150
210
180
−80
−100
−120
−140
−160
−140
−120
−100
−80
MNM
Simulation
Measured

(b)


0
30
330
60
300
90
270
120
240
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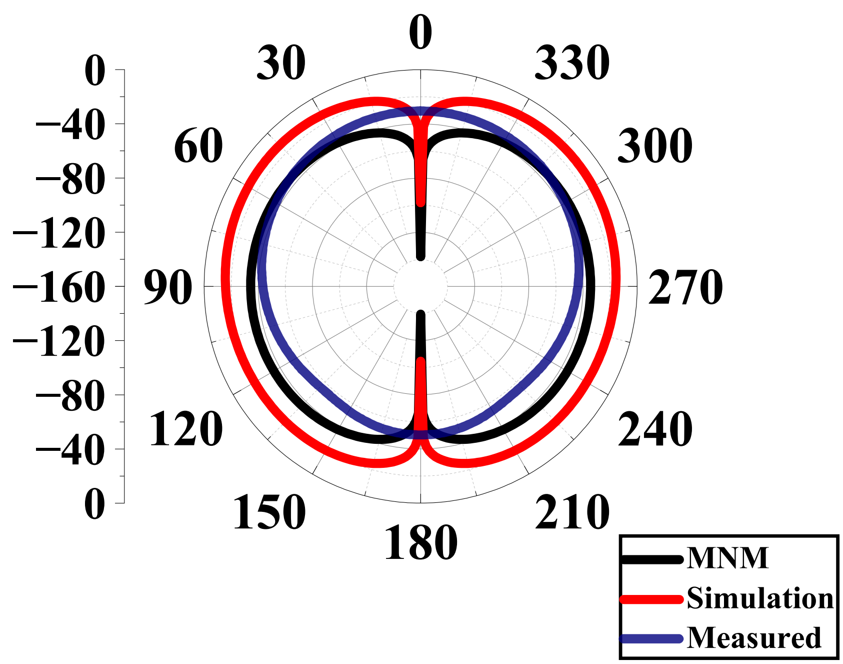
210
180
0
−40
−80
−120
−80
−40
0
MNM
Simulation
Measured

(c)



(d)

Fig. 3.5: Radiation patterns of the antenna - (a) E-theta (phi=0) co polar, (b) E – theta (phi=0) cross polar, (c) H-theta (phi=90) co polar and (d) H-theta (phi=90) cross polar configurations of the antenna

Initially, values L_1, L_2 and L_3 are taken arbitrarily. Then using simulation, we have tuned these values in such a way that this antenna can operate at 2.45 GHz ISM band. After setting their values, we have performed MNM on this antenna structure. Table 3.1 shows comparison between MNM, simulation and measurement results in terms of return loss, operating frequency and 10 dB return loss bandwidth of this antenna. The far field radiation patterns of the irregular hexagonal patch antenna are shown in Fig. 3.5. The obtained realized gains (in dBi) and cross polar discrimination (dB) from MNM, simulation and measurement are mentioned in Table 3.2. From Table 3.1 and 3.2, MNM technique is estimating antenna responses with low error because it is an approximate technique. However, this technique is simple and it is providing workable estimation of antenna responses.

The MNM analysis of regular shaped hexagonal antenna was performed by K. C. Gupta [29]. However, MNM analysis of irregular shaped hexagonal patch has not been studied yet as per our literature survey. However, this study is very important because irregular hexagonal patch antenna has several advantages. Now-a-days, miniaturization is one of the prime focus to embed antenna within small area of chip. Hexagonal patch has almost similar surface current configuration compared to circular patch. As corners present in hexagonal patch are more in number than rectangular and circular patches, it can increase bandwidth due to accumulation of charges at the corners. It is impossible to use regular hexagonal patch in all cases, especially due to lack of space to embed it. In such cases, irregular hexagonal patch is envisaged. This technique can be applied for any other irregular shapes such as irregular pentagon, irregular heptagon etc.

MNM analysis is an approximate analytical technique and it is an extended approach of the cavity model. The simulations are carried out in Finite Element Method (FEM) based CST Microwave Studio 2021 software. The FEM technique can estimate antenna performance more accurately than MNM technique. Therefore, a difference of gain between MNM and simulated responses is observed. However, MNM technique is simple and it is optimizing the realized gain of the antenna by considering ~4% error with respect to simulated gain which is within allowable tolerance range.

3.6 Conclusion

In this work, Multiport Network Model (MNM) approach is studied for irregular shaped hexagonal patch antenna. The antenna is first decomposed into one rectangular and four right-angled triangular sections. Multiple numbers of ports are connected to each segment. The input impedances are calculated for each port of each section using Green’s functions of the corresponding section. Finally ports of two different sections are connected using calculated impedances. The obtained surface current distribution from MNM analysis is verified with simulated surface current response of the antenna. The antenna is fabricated and its measurement is also performed. The obtained return loss and input impedance responses are quite similar for MNM analysis, simulation and measurement. This chapter can provide an idea to perform MNM analysis for any other irregular shaped patch antennas.

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Chapter 4: Circular Slotted Half Hexagonal Patch Multiband Antenna Design for 5G Applications

4.1 Introduction

Rapid development of wireless communication systems in the last decade has increased the demand for microstrip antennas with compact size and multiple operating frequencies. Many multi-band microstrip antennas and wideband antennas utilizing hexagonal patch shapes have been reported in recent years [1-3].In [2], authors have reported a dual band slotted Hexagonal Microstrip Antenna (HMSA) operating at two different frequencies of 1.3 GHz and 1.4 GHz with bandwidth greater than 15 MHz in each case. Ray *et. al*. have designed in [3] a perturbed hexagonal patch antenna for circular polarization where a new configuration of circularly polarized HMSA with single feed have been investigated for GSM frequency of 915MHz.

Recently, scientists are focusing on designing devices for 5G applications. Therefore, antennas should be designed accordingly to support 5G specifications. Different 5G sub-6 GHz lower band antennas have been proposed in literature [4-7]. The above-mentioned designs are mainly designed for dual band and single band operation; whereas now-a-days it is desired that a single device would support many applications like the Wireless Area Network (WLAN) and Worldwide Interoperability for Microwave Access (WiMAX) etc. This necessitates the use of multiband antennas exhibiting more than two bands of operation with a fair amount of radiation [8, 9]. Moreover, multiple resonances help in increasing the number of users for the same or different services [10].

Considering the necessity of obtaining as many operating frequencies as possible within a frequency range, a half hexagonal circular slot loaded patch antenna is designed in this chapter which is resonating at nine different frequencies within the frequency range of 1 GHz to 8 GHz. The operating frequencies are obtained as 1.81 GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz, 7.71 GHz with peak realized gain of 3.42 dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66 dBi, 6.20 dBi, 5.78 dBi, 9.68 dBi respectively. Circular slot is incorporated therein for frequency control and the probe position is optimized to achieve good impedance matching and acceptable radiation patterns, mostly broadside. The proposed designs are simulated using FEM based software using material FR-4 with dielectric constant 4.4 and loss tangent of 0.03 with the thickness of 1.6 mm.

4.2 Design and Analysis of Circular Slot Loaded Hexagonal Patch Antenna

In this section, circular slot loaded half reduced irregular shaped hexagonal patch antenna is designed. At first, simple regular hexagonal patch has been designed and half reduction has been performed. The same procedure has been followed for irregular shaped hexagonal patch also. Finally, a circular slot is loaded on half reduced hexagonal patches. The radius of the slot is varied to observe its effect on antenna performances.

4.2.1. Simple Regular Hexagonal Patch

A regular hexagon of side arm W = 35.4 mm and length L = 29.87mm is considered as the basic patch shape. The patch is fed at point of (-8.0, 0.0) with coaxial probe having inner radius of 0.63 mm and outer radius of 2.11 mm. The feed position is optimized through parametric studies. At first, the feed location is taken arbitrarily. Then this location is tuned in CST Microwave Studio 2021 software so that good return loss value is obtained.

The reflection coefficient (S_{11}) of this structure has magnitude less than -10 dB for the operating frequencies of 2.69GHz, 4.7GHz, 5.91GHz, 6.45GHz, and 7.42GHz. Simulated S_{11} for this configuration is shown in Fig. 1, which indicates that there are multiple resonant modes for the antenna but good impedance matching is not obtained for many of them.

An empirical formula for operating frequency of hexagonal patch antenna given by Ray *et*. *al*. [11] is used in this work as the initial step for the design procedure. The operating frequency for this configuration is given as

$$f = \frac{c}{2(S_{eff} + 2\Delta l)\sqrt{\varepsilon_{eff}}} \quad (1)$$

where the effective resonant length is S_{eff}, the effective dielectric constant ε_{eff} and the line extension factor Δl can be calculated using the expressions

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + 12\frac{h}{W})^{-\frac{1}{2}} \quad (2)$$

$$S_{eff} = 1.60352W + 0.00175 \quad (3)$$

$$\Delta l = \frac{0.412h(\varepsilon_{eff} + 0.3)(\frac{W}{h} + 0.258)}{(\varepsilon_{eff} - 0.258)(\frac{W}{h} + 0.8)} \quad (4)$$

with the symbols having their usual meanings.

4.2.2. Regular Half Hexagonal Patch

Distinct symmetry planes of a regular hexagonal shape are utilized for antenna miniaturization. A regular half hexagon is obtained from the regular full hexagon shape by equally dividing it into two halves as shown in Fig.4.1.

Probe position is kept same as in the case of the regular full hexagonal antenna discussed earlier. A comparison of simulated S_{11} between the full and half hexagonal patches is shown in Fig.4.1. It can be observed that the operating frequencies are not substantially altered in the process while the patch area is effectively reduced by 50%.

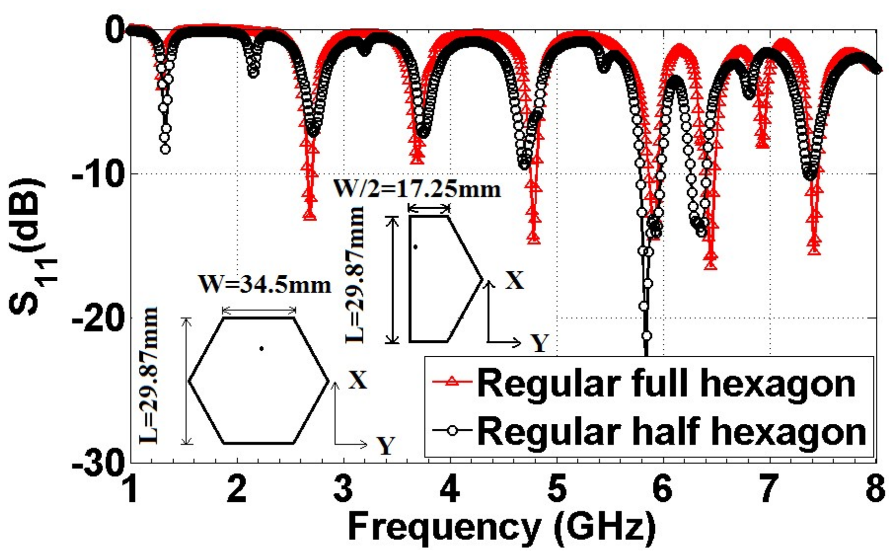


Fig.4.1. S_{11} vs frequency plots for regular full and half hexagonal patch antenna

4.2.3. Irregular Full Hexagonal Patch

An irregular hexagon is designed here with length (L) of 21.75 mm keeping arm length (W) same as that of the regular one i.e. W = 35.4mm. Feed position is also kept same as that for regular hexagon to compare between regular and irregular hexagonal patch performances efficiently. Resonant modes are obtained at frequencies 1.81 GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz and 7.71 GHz. This information is revealed by the simulated S_{11} vs frequency plot for this irregular hexagonal patch antenna (Fig.4.2) indicating better impedance matching at operating frequencies compared to the regular patch. Along with that, this antenna can also be operated in 5G applications as it is resonated at 3.65 GHz with is within the lower band for 5G applications. Therefore, irregular shaped hexagonal patch is chosen for this work.

4.2.4. Irregular Half Hexagonal Patch

An irregular half hexagon is obtained from the irregular full hexagon by equally dividing it into two halves exploiting its symmetry as shown in Fig.4.2. A comparison of S_{11} between the irregular full and half hexagons indicates (refer to Fig.4.2) that the later yields better impedance matching as well as increased bandwidth although the operating frequencies remain unchanged. The irregular half hexagonal antenna thus exhibits the best impedance characteristics among all antennas investigated.

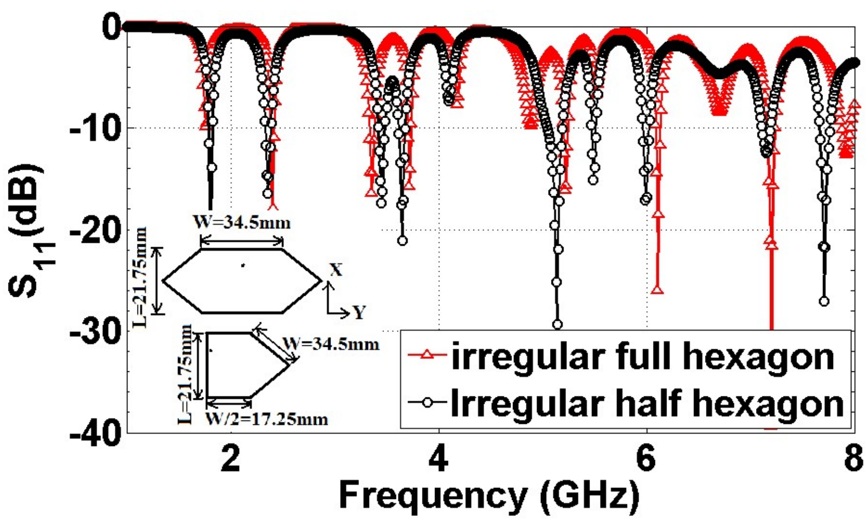


Fig. 4.2: S_{11} vs frequency plots for irregular full and half hexagonal patch antenna

4.2.5. Effect of circular slot on half hexagonal patch

In this sub-section, the regular and irregular half hexagonal patch antennas perturbed with a circular slot and corresponding changes in operating frequencies are reported to ensure additional control over the operating frequencies.

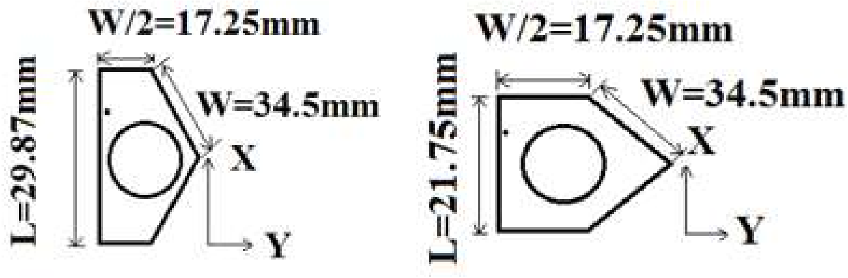


Fig. 4.3. Circular slot loaded on regular and irregular half hexagonal patch

4.2.6. Slot on regular half hexagonal patch

A slotted regular half hexagonal antenna is conceived by introducing a circular slot (Fig. 4.3(a)) to tune the operating frequencies. The coordinate of the center of the slot is taken as (10.875, 11.5) while middle of the base side of patch is considered as origin. Probe position is kept same as before here. Resonant modes of the unperturbed antenna are shifted towards lower frequencies as the slot radius is increased. It is however observed that S_{11} below -10 dB is obtained for only five resonant modes for the slotted regular half hexagonal patch as shown in Fig.4.4. Dimensions of the hexagon are kept same as in the case of the regular half hexagon discussed earlier.

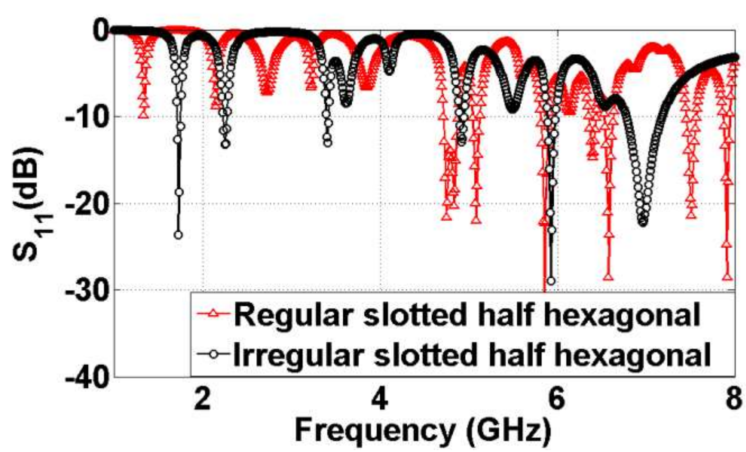


Fig. 4.4: Return loss curves of circular slot loaded regular and irregular half hexagonal patch antennas

4.2.7. Slot on irregular half hexagonal patch

A circular slot is incorporated on the surface of the designed irregular half hexagonal patch as shown in Fig. 4.3(b) to tune its operating frequencies. The coordinate of the center of the slot is taken as (10.875, 14.94) while middle of the base side of patch is considered as origin. Probe position and patch dimensions are kept same as in the case of the irregular half hexagonal patch discussed earlier. It is observed that S_{11} below -10 dB is obtained for six resonant modes for the slotted irregular half hexagonal patch as shown in Fig.4.4.

4.2.8. Radius variation of the slot

Simulated S_{11} for different slot radius values are shown in Fig.4.5. Observations presented in the previous subsections are summarized in Tables 4.1 and 4.2. Table 4.1 shows the comparison of operating frequencies and fractional bandwidths for full and half hexagonal patches with regular and irregular shapes. Clearly, the irregular half hexagon yields best performance in terms of impedance matching and bandwidth. Table 4.2 on the other hand indicates the comparison of regular and irregular hexagonal patches for different slot radii.

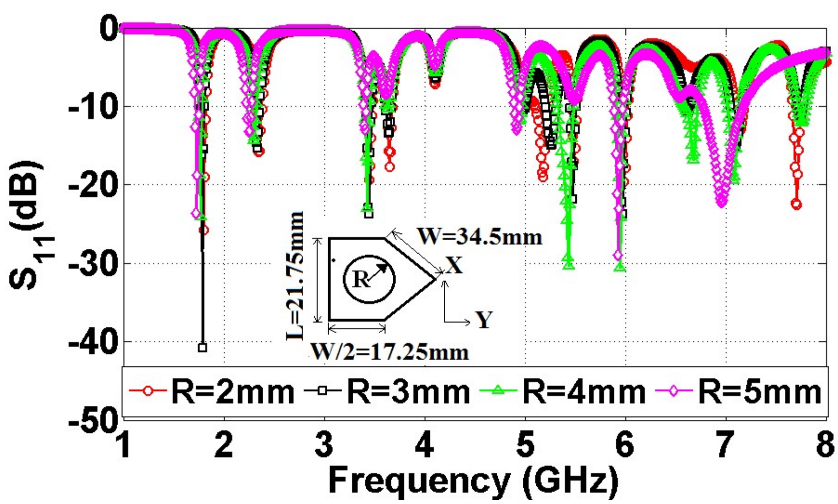


Fig.4.5: Return loss curves on varying radius of circular slot loaded on irregular half hexagonal patch

Table 4.1. Comparison of operating frequency and fractional bandwidth for regular and irregular hexagonal patch antenna

Patch shape	**Results of antenna structures**	
	Operating frequency (GHz)	**Fractional Bandwidth (%)**
Regular full	2.69	1.85
	4.79	1.02
	5.91	1.35
	6.45	1.38
	7.42	1.07
Irregular full	2.4	1.66
	3.36	1.48
	3.72	0.8
	5.23	0.95
	6.11	0.81
Regular half	5.84	3.25
	6.36	2.20
Irregular half	1.81	2.20
	2.36	2.54
	3.45	1.73
	3.65	1.64
	5.14	2.52
	5.49	0.72
	5.99	1.16
	7.15	1.11
	7.71	1.42

The slot radius may be varied to control the operating frequencies as per requirement and the circular slot loaded irregular hexagonal patch structure is finalized for this work. Finally, Table 4.3 summarizes the realized antenna gains for each operating frequency of final antenna. Increasing the slot radius shifts the resonant modes to lower frequencies. The slot radius for the final structure is chosen as 2 mm.

Table 4.2. Operating frequency and fractional bandwidth of circular slotted regular and irregular hexagonal patch antenna for different radii of slot

Patch	Radius (mm)	Results of antenna	
		Operating frequency (GHz)	**Fractional Bandwidth (%)**
Regular	**2 mm**	5.9	1.35
		6.14	1.14
		6.39	1.4
		6.57	1.36
		7.55	2.11
	3 mm	5.9	1.35
		6.15	1.3
		6.38	1.56
		7.54	1.85
	4 mm	4.7	2.55
		5.03	0.79
		5.87	1.53
		6.36	1.41
		7.49	1.46
	5 mm	4.75	3.36
		5.09	1.57
		5.86	1.53
		6.58	1.36
Irregular	**2 mm**	1.8	2.22
		2.36	2.11
		3.45	2.02
		3.65	1.64
		5.18	2.31
		5.49	1.82
		5.99	1.16
		7.13	1.26
		7.71	1.29
	3 mm	1.79	2.23
		2.34	2.13
		3.45	2.02
		3.64	1.64
		5.25	1.90
		5.48	1.09
		5.98	8.69
		7.10	1.54

	4 mm	1.77	2.25
		2.30	2.17
		3.43	1.45
		5.44	2.94
		5.95	1.34
		7.08	1.84
	5 mm	1.73	2.31
		2.25	2.22
		3.41	0.87
		4.92	2.23
		5.93	1.52
		6.97	5.59

Table 4.3: Results of the final antenna structure

Operating frequency (GHz)	**Fractional Bandwidth (%)**	**Realized Gain (dBi)**
1.81	2.22	3.42
2.36	2.11	2.69
3.45	2.02	3.51
3.65	1.64	1.15
5.18	2.31	3.05
5.49	1.82	4.66
5.99	1.16	6.20
7.13	1.26	5.78
7.71	1.29	7.68

4.3 Fabrication and Measurement

The optimally designed circular slot incorporated irregular half hexagonal patch, whose simulated behavior is presented earlier, is fabricated on FR-4 substrate with relative permittivity of 4.4 and loss tangent of 0.03 with the thickness of 1.6 mm. The photograph of the fabricated half hexagonal patch is shown in Fig.4.6. The simulated and measured return loss characteristics of the antenna up to frequency 8 GHz is shown in Fig.4.7. Normalized radiated far field patterns for H plane and E plane are plotted in Fig. 4.8 and 4.9 respectively based on simulation and measurement for different operating frequencies.

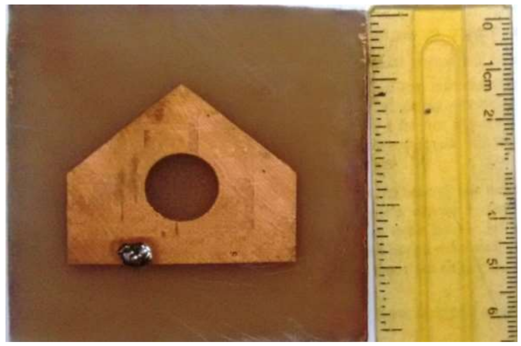


Fig.4.6. Photograph of the fabricated antenna

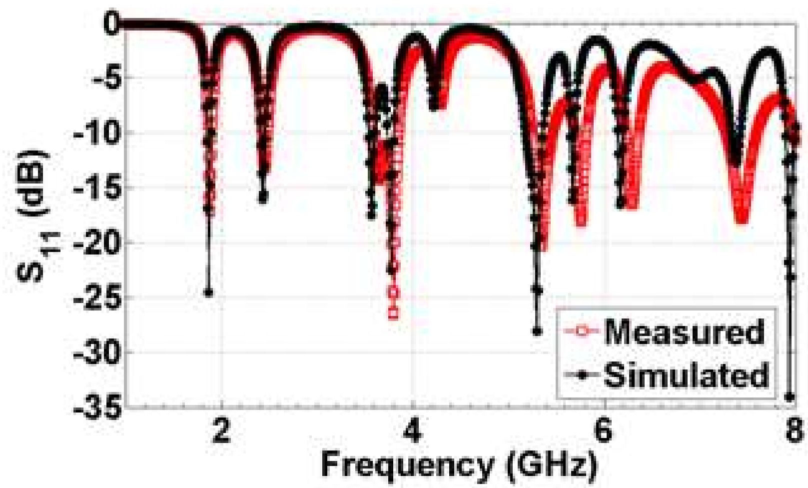
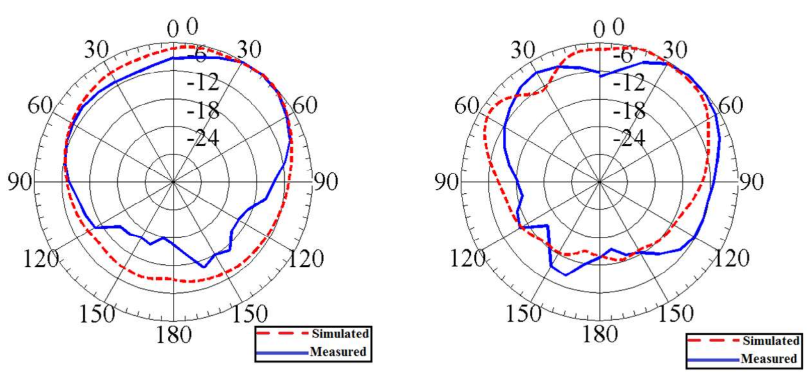
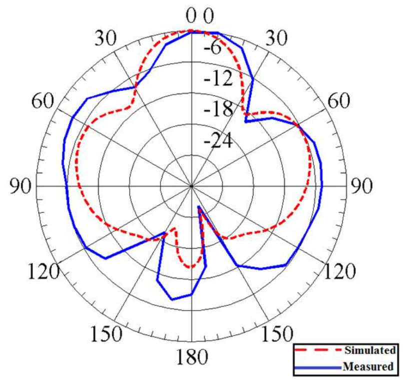


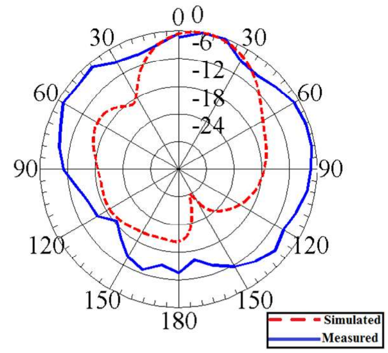
Fig. 4.7. Simulated and measured return loss plots for the proposed antenna structure



(a) **(b)**



(c)



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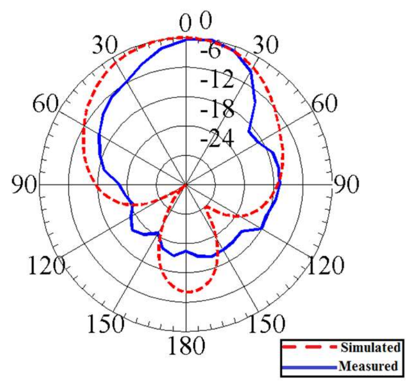

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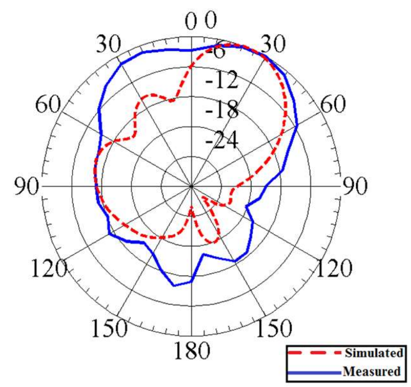

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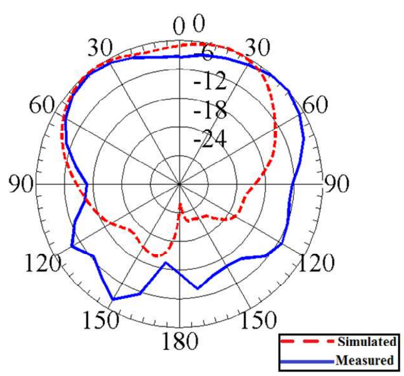

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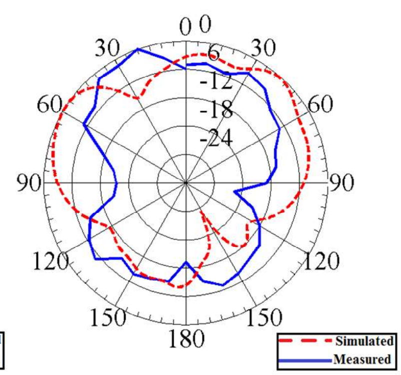
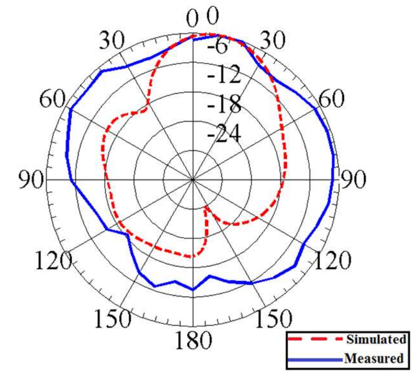


(h)

Fig. 4.8: Simulated and measured far field patterns for H plane at the operating frequencies: (a) 2.36 GHz, (b) 3.45 GHz, (c) 3.65 GHz, (d) 5.18 GHz, (e) 5.49 GHz, (f) 5.99 GHz, (g) 7.13 GHz and (h) 7.71 GHz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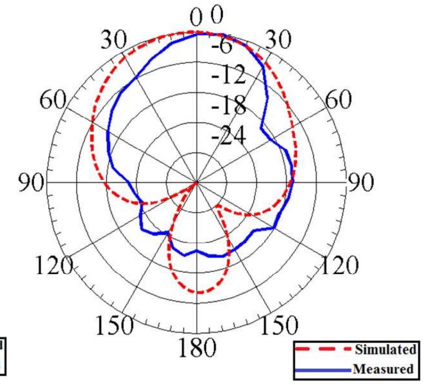
(a)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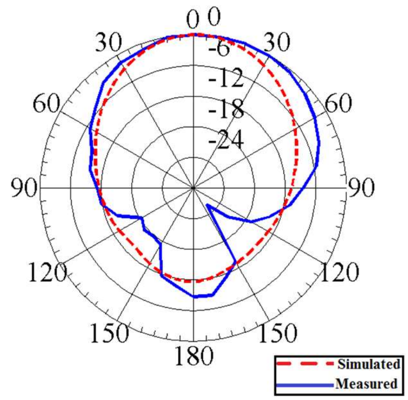
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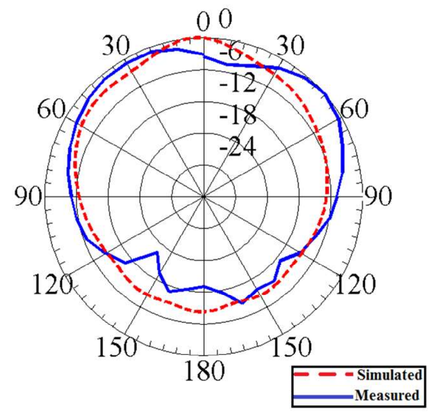
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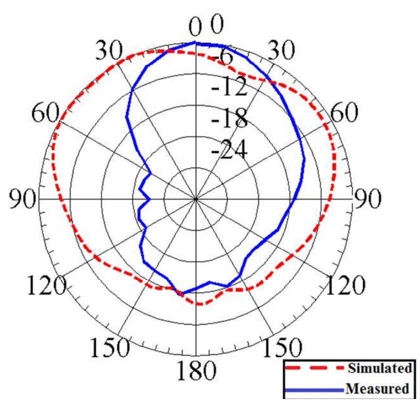
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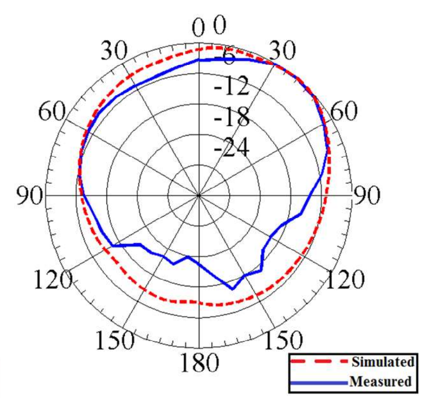
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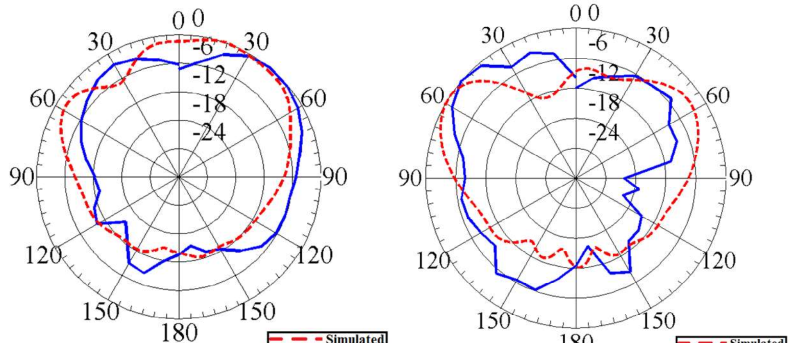
(f)



(g) **(h)**

Fig. 4.9: Simulated and measured far field patterns for E plane at the operating frequencies: (a) 2.36 GHz, (b) 3.45 GHz, (c) 3.65 GHz, (d) 5.18 GHz, (e) 5.49 GHz, (f) 5.99 GHz, (g) 7.13 GHz and (h) 7.71 GHz

Table 4.4. Comparison with Previously Reported Hexagonal shaped 5G Antennas

References	Operating Frequency (GHz)	Realized Gain (dBi)
[12]	3.5	4.42
[13]	2 2.45 3.1 3.4	1.3 1.76 1.98 1.74
[14]	3.5	3.20
[15]	3.7	1.98
[16]	3.7	2.70
This Work	**1.81** **2.36** **3.45** **3.65** **5.14** **5.49** **5.99** **7.15** **7.71**	**3.42** **2.69** **3.51** **1.15** **3.05** **4.66** **6.20** **5.78** **7.68**

4.4 Comparison with Previously Reported Works

The proposed antenna has novelty compared to previously reported antennas which are mentioned in Table 4. From this table, it is observed that the proposed antenna achieves better realized gain than other reported hexagonal based 5G antennas. It provides 9 operating bands to be utilized in applications such as aviation, satellite communications and wireless communications whereas antennas in [12, 14-16] are operating at single frequency and antenna designed in [13] has 4 operating frequencies. Therefore, it can be concluded that this antenna has novelty in terms of its multiband performance as well as higher gain compared to other reported antennas.

4.5 Conclusion

A circular slotted irregular half hexagonal patch antenna is designed for multiband operation purposes. This antenna has nine operating frequencies viz. 1.81GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz and 7.71 GHz with acceptable measured peak realized gain of 3.42 dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66dBi, 6.20 dBi, 5.78 dBi and 9.68 dBi respectively. The antenna is covering Bluetooth, WLAN and point to point high speed wireless communication bands. This antenna also covers 5G sub-6 GHz lower band to support recent trends of communication facilities. On slot loading, it is found that the operating frequencies of the unperturbed antenna are shifted downwards as the slot radius is increased. This antenna is fabricated on FR-4 substrate with thickness of 1.6 mm. The measured results show good agreement with simulation results.

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Chapter 5:
Design and Performance of Novel Hexagonal Patch Antenna for Improved Gain and Bandwidth

5.1 Introduction

In the last decades, scientists are focusing on wideband system because of high transmission rate and low power consumption. Fifth generation 5G wireless networks and the internet of things (IoT) need high channel capacity for smart city, smart wearable devices and safety applications.

A broadband CPW-fed equilateral hexagonal slot antenna with bandwidth 55.39% of the center frequency [1.657 to 2.956 GHz] was reported in [1] for GSM 1800, 1900, IMT-2000 and WLAN. Xin et al. [2] designed a wideband miniaturized G-shaped dual band antenna for WLAN applications at 2.4GHz and 5.60 GHz with fractional bandwidths of 22.9% and 50.9%, respectively. H. Deng et al. [3] designed a square-ring monopole compact ultra wideband antenna with bandwidth of 7.91GHz. In [4], authors presented a Broadband half hexagonal gap-coupled microstrip antenna at 1.87GHz with bandwidth of 54 MHz. In 2010, Zeng et al. [5] reported a UWB band-notched monopole antenna fed by tapered CPW (Co-Planar Waveguide) which radiated over 3.1GHz-11.1GHz with bandwidth of 8 GHz.

A broadband circularly polarized CPW fed regular-hexagonal Slot Antenna with an L-shaped monopole was presented in [6]. Pimpol et. al. [7] designed a hexagonal slot array loaded wideband patch antenna. Ghatak et al. [8] reported a hexagonal Sierpinski carpet shaped fractal compact UWB antenna with band rejection functionality. To obtain broadband performance, different impedance matching techniques such as variations of slot dimensions [9-12], use of hexagonal slot, novel coupling mechanisms [13-15] have been reported.

In this work, a hexagonal shaped patch antenna has been designed for performing wireless communication around 5.2 GHz. Defected ground concept is used to tune this antenna within the desired band. Reduction of the ground plane size of this antenna leads to enhancement of back lobe radiation which may hamper the communication performance in broadside direction. Therefore, a metal reflector is placed at the back side of this antenna at a certain distance of the ground plane to increase realized gain at the broad side of this antenna structure.

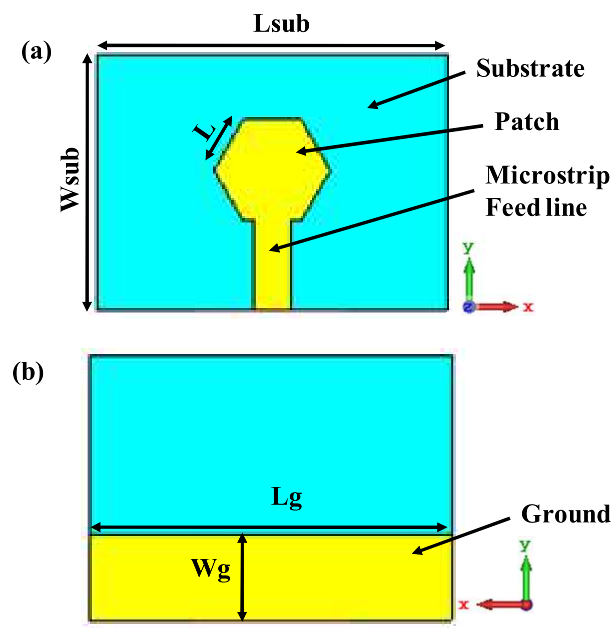


Fig. 5.1. (a) Top and (b) bottom views of antenna where dimensions are in mm: Lsub = Lg = 30, Wsub = 22, Wg = 7 and L = 1.

5.2 Design of Defected grounded Hexagonal Antenna

5.2.1. Design Parameters of the Antenna

Figs. 5.1(a) and (b) show the top and bottom views of the hexagonal shaped defected grounded respectively. Copper is used as patch and ground plane. Arlon

AD 430 with relative permittivity (ε_r) of 4.3 and loss tangent ($\tan\delta$) of 0.003, thickness of 0.762 mm is utilized here as material of substrate layer for designing prototype of the antenna. The substrate size is taken here as 30 mm X 22 mm. The length of the ground plane is same as substrate. However, the width of the ground plane is reduced to tune this antenna within our goal. Each side of the hexagonal patch antenna is 1 mm. The design evolution to the final antenna structure shown in Fig. 5.1 is mentioned below.

5.2.2. Developmental Steps to the Final Antenna

The final design of the proposed antenna has been achieved by optimizing several steps. At the preliminary stage, a hexagonal patch antenna with full ground plane (refer to Fig. 5.2(a)) is taken. This antenna is not tuned at our desired frequency as shown in Fig. 5.3 (a). Then the ground plane is reduced by half amount keeping the patch geometry fixed as shown in Fig. 5.2(b).

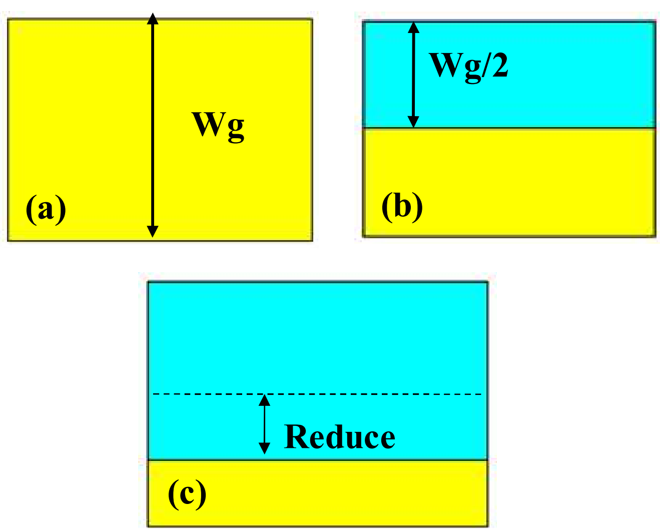


Fig. 5.2: Evolution of ground plane geometry

This antenna structure improves the return loss characteristics as depicted in Fig. 5.3(b). Next, further reductions of the ground plane have been studied here. A variable 'Reduce' shown in Fig. 5.2(c) is taken here and their return loss values and operating frequencies are mentioned in Table 5.1.

From this below table, it is observed that this antenna provides low return loss performance at 5.17 GHz for the reduction value of 4 mm after half reduction of the ground plane. Therefore, the final antenna has ground plane of 7 mm keeping its patch geometry same as preliminary stage. The final antenna has return loss value of 39.41dB at its operating frequency 5.17 GHz.

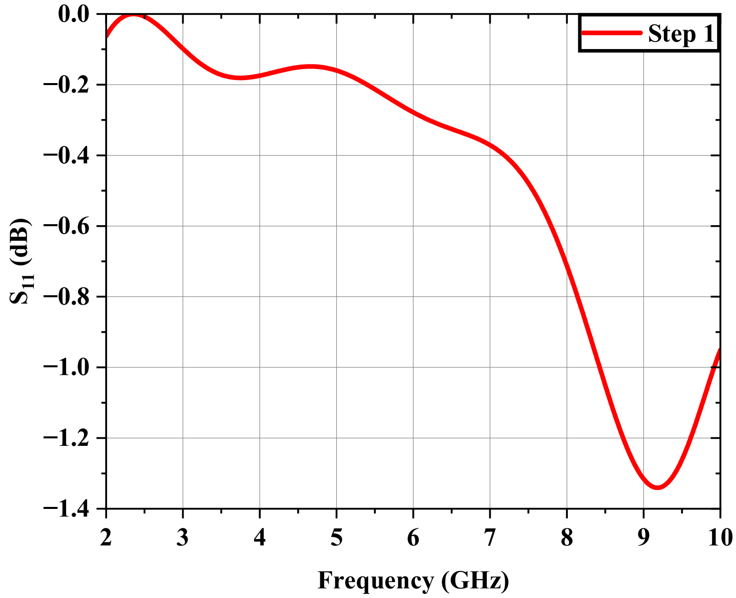
Table 5.1: Return loss values for Different 'Reduce'

Reduce (mm)	Operating frequency (GHz)	Return Loss (dB)
1	6.60	5.83
2	6.27	10.95
3	5.78	21.10
4	**5.17**	**39.41**
5	4.73	25.60

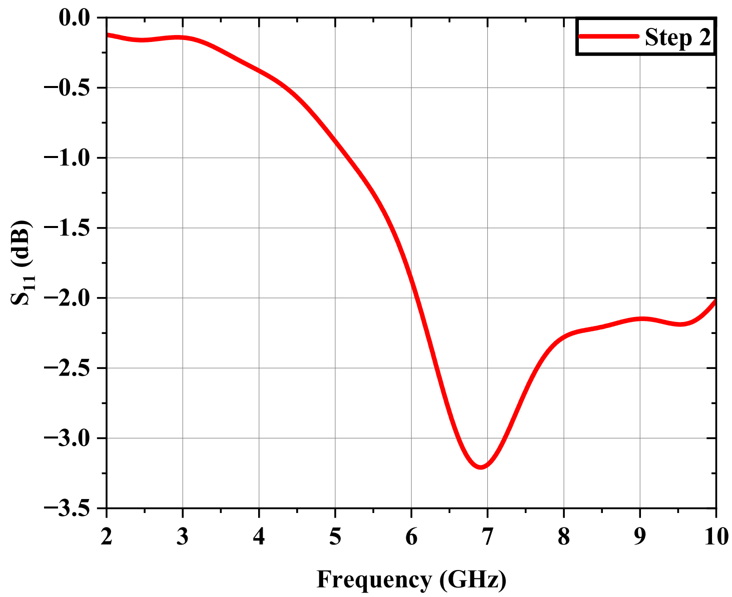
5.2.3. Results of the Final Antenna

All the antenna structures shown in Fig. 5.2 have been simulated using the transient solver available in Computer Simulation Technology Microwave Studio (CST MWS) 2019. Return loss value of the proposed antenna is 39.41 dB at 5.17 GHz. The reflection coefficient curve of the final antenna is shown in Fig. 5.3 (c).

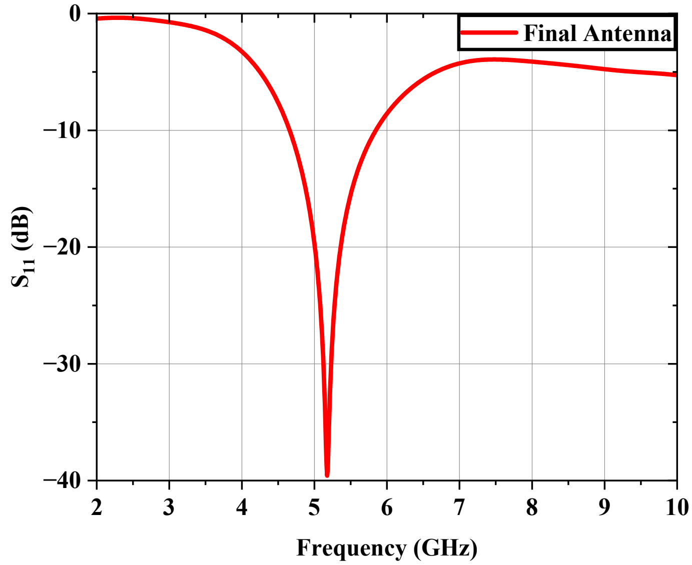
This antenna possesses fractional bandwidth of 22.97 % in the band over 4.66 GHz to 5.85 GHz centered around 5.17 GHz. The proposed antenna provides a realized gain of 16.3 dBi at the operating frequency of this antenna i.e., 5.17 GHz. E-plane and H-plane of the designed antenna is represented by $\varphi = 0^\circ$ and $\varphi = 90^\circ$ respectively. The E-plane and-H plane radiation patterns (co-polarization and cross-polarization) of the proposed antenna inside phantom model are illustrated in Figs. 5.4 (a) and 5.4 (b) respectively.


Step 1
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
S11 (dB)
2
3
4
5
6
7
8
9
10
Frequency (GHz)

(a)

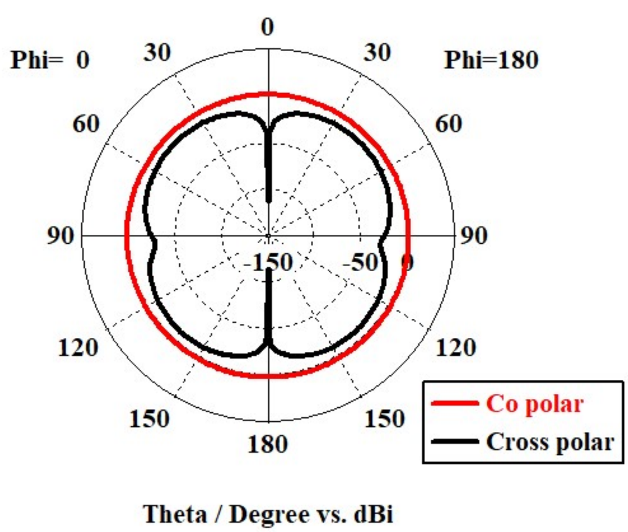

Step 2
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
S11 (dB)
2
3
4
5
6
7
8
9
10
Frequency (GHz)

(b)

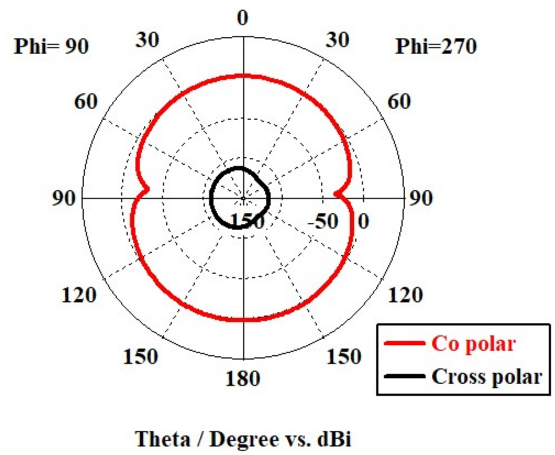


(c)

Fig. 5.3: Return loss performances of different steps shown in Fig. 5.2



(a)

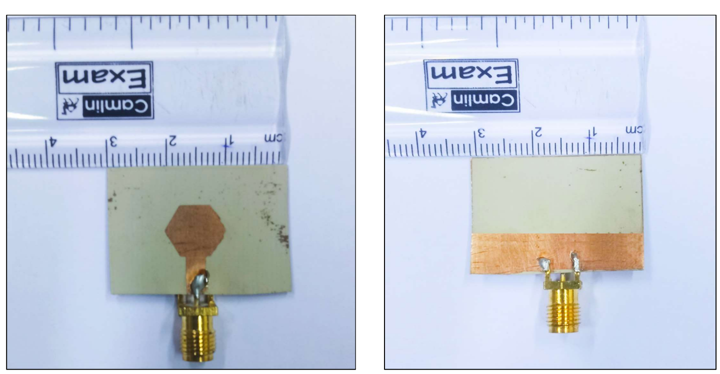


(b)

Fig. 5.4: Simulated co-polarized and cross-polarized radiation patterns of the antenna at 5.17 GHz in the (a) E-plane and (b) H-plane

5.3 Fabrication and Measurement

The designed antenna is fabricated and the fabricated prototype of this antenna is shown in Fig. 5.5 and its return loss curve is shown in Fig. 5.6. The fabricated antenna has return loss value of 13.20 dB at the measured operating frequency of 5.10 GHz. The measured gain of antenna is 3.97 dBi. This variation with simulated results is observed due to fabrication error such as dispute in etching process, improper soldering for connecting SMA connector to the patch etc.



(a) **(b)**

Fig. 5.5: Photographs of fabricated antenna (a) top view and (b) bottom view

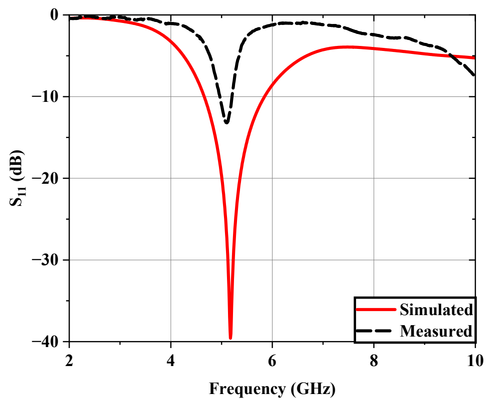


Fig. 5.6: Simulated and measured return loss plots of the designed antenna

5.4 Placement of Reflector

Due to presence of huge back-lobe level in radiation patterns shown in Fig. 5.4, a copper plate is placed at the back side of the antenna as reflector which is shown in Fig. 5.7. This plate is placed at a distance of 25 mm which satisfies the far field condition. After placing it, the radiation patterns are plotted in Fig. 5.8 (Simulated and measured results). This figure shows how the radiation pattern of this antenna improved due to placement of reflector. The realized gain after placing reflector is obtained as 5.98 dBi at 5.17 GHz at the broad side direction which can improve the communication performance of this antenna. This antenna has novelty compared to some previously reported antennas which are mentioned in Table 5.2.This antenna has better gain with respect to [17-18] and fractional bandwidth with respect to [16-18].

Table 5.2. Comparison with Previously Reported Hexagonal Antennas

Ref.	**Operating Frequency (GHz)**	**Fractional Bandwidth (%)**	**Realized Gain (dBi)**
[16]	5.2	11.5	7.07
[17]	5.6	50.9	4.8
[18]	5.2	3.67	4.39
This Work	**5.7**	**22.97**	**5.98**

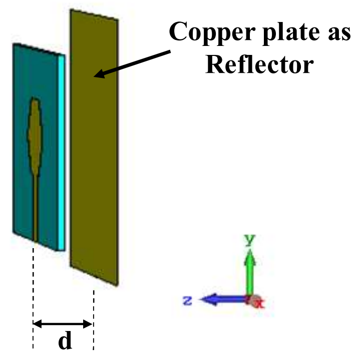
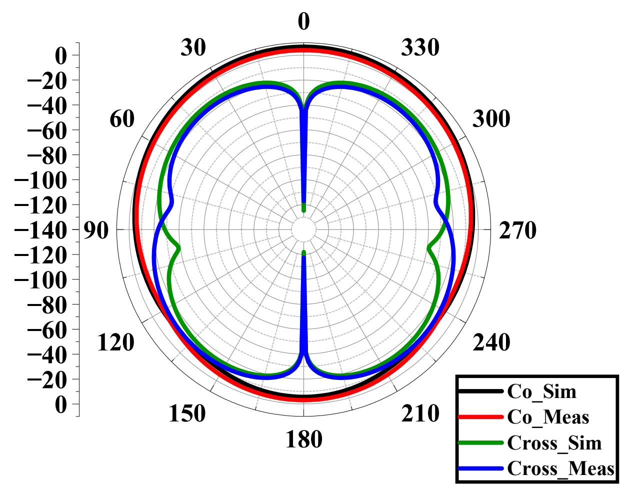
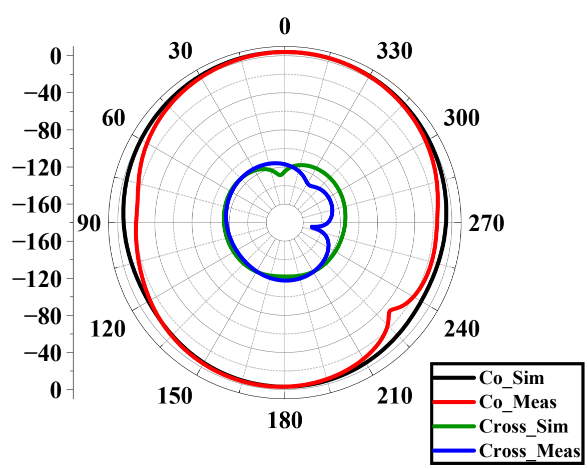


Fig. 5.7: Placement of copper plate as reflector at a distance d = 25 mm



(a)



(b)

Fig. 5.8: Simulated and measured co-polarized and cross-polarized radiation patterns of the antenna with reflector at 5.17 GHz in the (a) E-plane and (b) H-plane

5.5 Conclusion

In this work, a defected ground hexagonal antenna is proposed for wireless communication and aeronautical navigation applications. This antenna has operating frequency of 5.17 GHz. This antenna radiated over 4.66 GHz to 5.85 GHz with realized gain of 1.63 dBi at its operating frequency. However, back lobe is present due to reduced ground. Therefore, a metal reflector is placed at the back side of the antenna which leads to enhance broad side realized gain of 5.98 dBi and fractional bandwidth of this whole structure is 22.97% around 5.17 GHz. The measured gain of the antenna is 3.97 dBi at operating frequency of fabricated antenna.

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Chapter 6: Dual Band Slotted Hexagonal Patch Antenna for 5G Application

6.1 Introduction

Fifth generation is the latest iteration of wireless technology which was introduced for enhancing responsiveness and speed of communication. 5G can allow sharp increase in data transmitted over channel due to high bandwidth based on Shannon's Channel Capacity theorem. Fourth generation (4G) cellular technology demands large and high-power cell towers for radiating signals over long distances whereas 5G signals can be transmitted over large numbers of small cell towers which may be located in places like building roofs, light poles etc. [1]

Several 5G antennas at sub 6 GHz have been designed by peers [2-5]. It is desired to operate a single device for many applications such as WiMAX, Wireless Area Network (WLAN) etc. Multiband antennas can radiate in more than one frequency band with less gain [6, 7]. Moreover, multiple resonances are helpful for increasing the number of users for the same or different services [8]. In 5G cellular technology, different multiple input multiple output (MIMO) antenna arrays have been proposed as this type of antennas has ability to increase channel capacity, data rate and spectral efficiency. Although MIMO antennas can increase channel capacity, incorporating large number of antenna in a small space available in situ. This may lead to degradation of MIMO antenna performance [9-10].

Sin *et. al.* have designed a single patch antenna to develop 1 × 4 antenna array for good scanning and steering performance at 25 GHz for 5G applications [11]. Four sets of 2×3 parasitic square array patches have been loaded for better impedance matching and isolation into their 1×4 antenna array. In literature [12], authors have proposed a 5G MIMO antenna with low specific absorption rate (SAR) operating at 3300-4500 MHz. 2×2 MIMO antennas at 698–960 MHz and 4 ×4 MIMO antennas tuned to1710–2690 MHz and 3400–3600 MHz have been designed in [13]. A dual band 8 × 8 MIMO antenna operating at 3100-3850 MHz and 4800-6000 MHz was designed in [14]. A wideband decoupled 8-element MIMO antenna operating at WLAN 5 GHz band (radiating over 5170 – 5835 MHz) was proposed by Hei *et al.* [15]. Article [16] proposed multiband antenna for 5G technology.

In the present chapter, a dual-band miscellaneous slot loaded hexagonal antenna is designed for 5G application. This antenna is tuned to 2.46 GHz (Industrial, Scientific and Medical (ISM) band) and 3.68 GHz (Sub-6 GHz lower 5G band). Therefore, this antenna can be used for 5G and WLAN.

6.2 Design Parameters of the Antenna Structure

Fig. 6.1 illustrates the geometry of the proposed antenna. In this work, copper is used as the material for ground and patch – whereas, Arlon AD 430 is used to develop the substrate layer of the proposed antenna. Yellow-coloured regions in Fig. 6.1 represent copper layer and sky-blue coloured part represent Arlon AD 430. The relative permittivity and loss tangent of Arlon AD 430 are 4.3 and 0.003 respectively.

The thickness of the substrate is 0.762 mm whereas the thickness of ground and patch of this antenna is taken as 0.035 mm. The detailed antenna design parameters are enlisted in Table 6.1. The side view of the entire antenna structure is shown in Fig. 6.2. Coaxial Feed has been added to excite the antenna. The inner and outer radii of this probe are 0.63 mm and 2.11 mm respectively to provide 50 ohm input impedance.

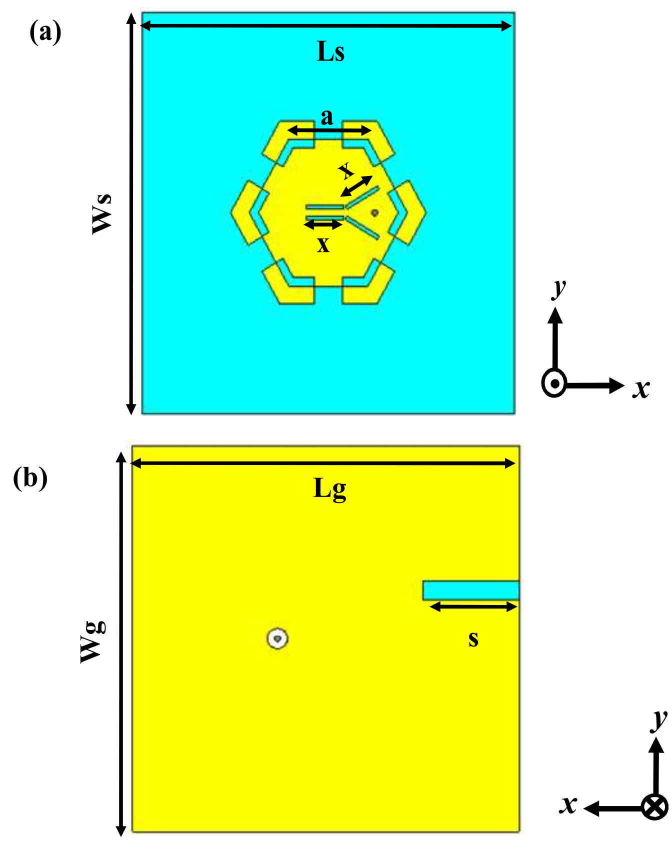


Fig. 6.1:(a) Top and (b) Bottom view of the antenna

Table 6.1. Design Parameters of the Antenna

Antenna Dimensions	Value(mm)	Antenna Dimensions	Value(mm)
Length of Ground (L_g)	80	Width of Ground (W_g)	80
Length of Substrate (L_s)	80	Width of Substrate (W_s)	80
Side of Hexagon (a)	15	Length of slot (x)	8
Length of open slot (s)	20	Width of open slot	4

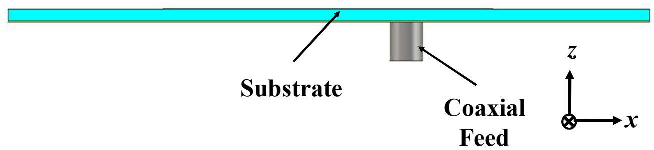


Fig. 6.2: Side view of the complete antenna

6.3 Developmental Steps of the Final Antenna

The final design of the proposed antenna has been achieved by optimizing several steps.

6.3.1. Step 1

At the preliminary stage, a simple hexagonal patch antenna with each side of 15 mm is taken. The choice of hexagonal patch over rectangular patch is preferred because hexagonal patch has more number of corners than rectangular patch which may lead to more charge accumulation in hexagonal patch. The hexagonal patch antenna designed in primary step is depicted in Fig. 6.3 (a). The current distribution for this patch is illustrated in Fig. 6.3 (b).

From the current distribution on the patch element, it is observed that maximum charges are accumulated at the edges and corners of the hexagonal patch. It may lead to increase in bandwidth which is required for 5G operation. This antenna does not provide good impedance matching as $S_{11} > -10\, dB$ which is observed from Fig. 6.3 (c).

6.3.2. Step 2

In the next step, all corners have been cut and set apart as shown in Fig. 6.4 (a) which leads to slots in each corner. Therefore, charge accumulation is increased in corners as illustrated in Fig. 6.4 (b). It leads to increase capacitive effect as manifested in its equivalent circuit. It also improves the reflection coefficient profile (refer to Fig. 6.4 (c)).

From Fig. 6.4(c) it is observed that the antenna is tuned to 2.97 GHz and 3.67 GHz and it has return loss values are 28.08 dB and 23.20 dB at 2.97 GHz and 3.67 GHz respectively. The second operating frequency is lying within sub-6 GHz lower 5G band. As the charge accumulation ismore in corners than the center part, the radiation patterns do not have main lobe in its broad side direction. It is tilted towards its corners for both these frequencies as shown in Fig. 6.4 (d) and (e).

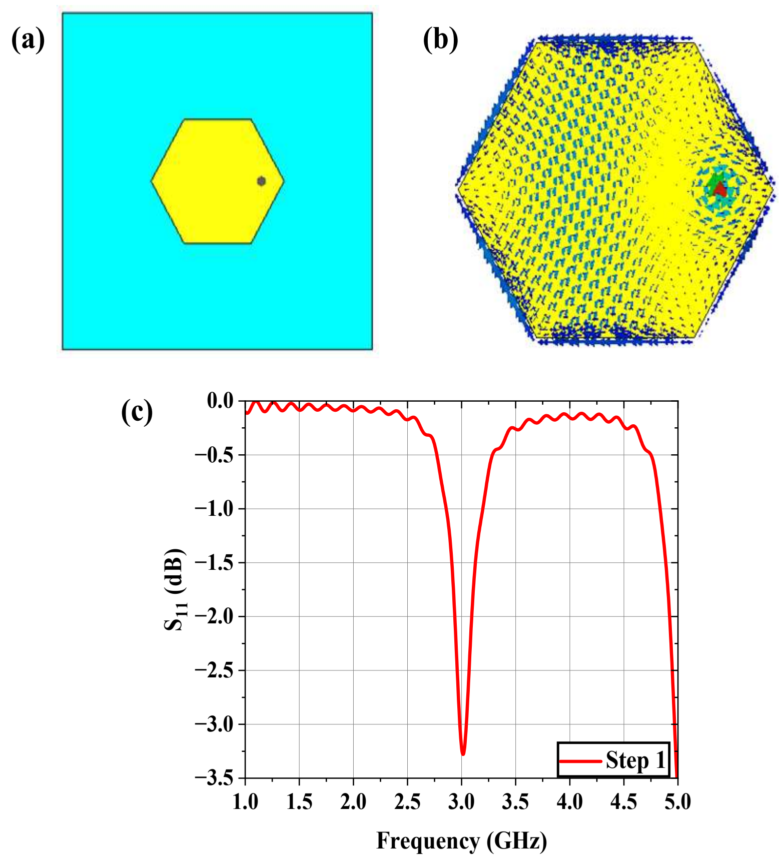


Fig. 6.3: Step 1: (a) Top view of the antenna (b) surface current distribution (c) S_{11} vs Frequency plot of the antenna

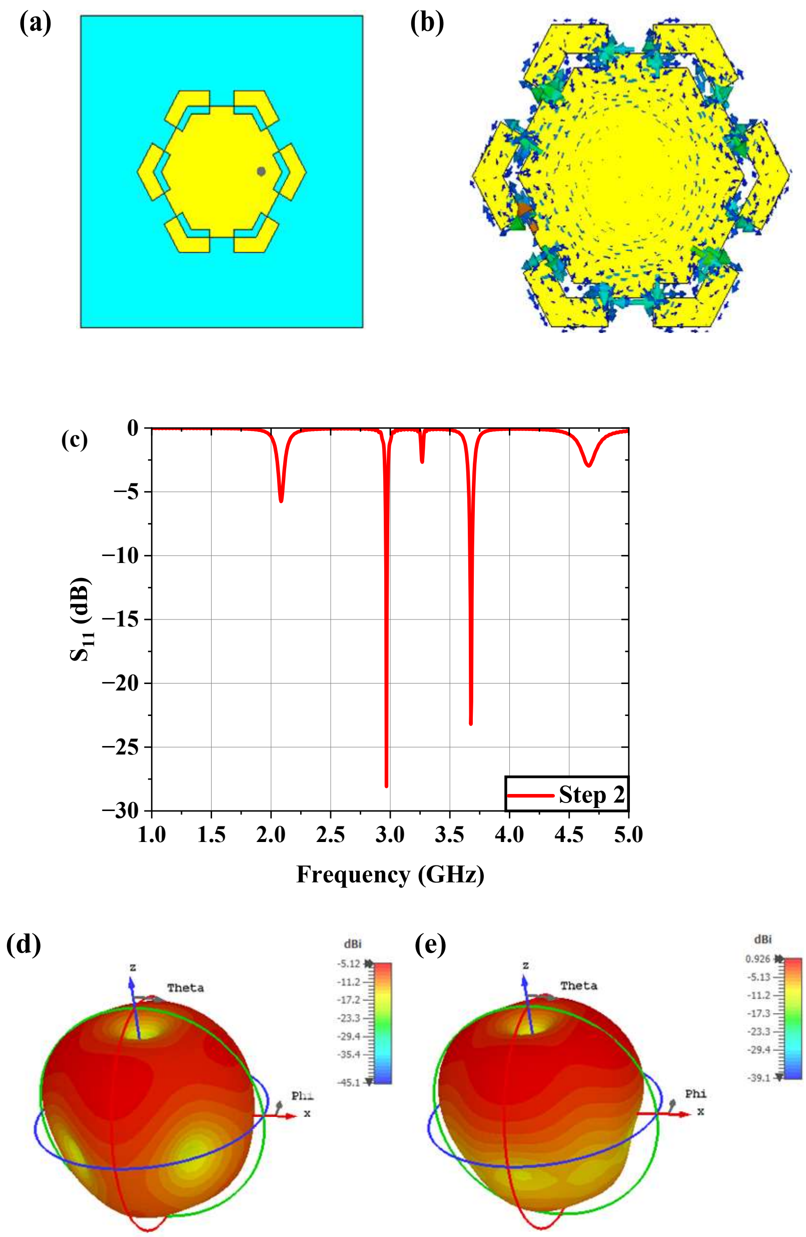


Fig. 6.4: Step 2: (a) Top view of the antenna (b) surface current distribution (c) S_{11} vs Frequency plot of the antenna (d) radiation pattern at 2.98 GHz and (e) radiation pattern at 3.67 GHz

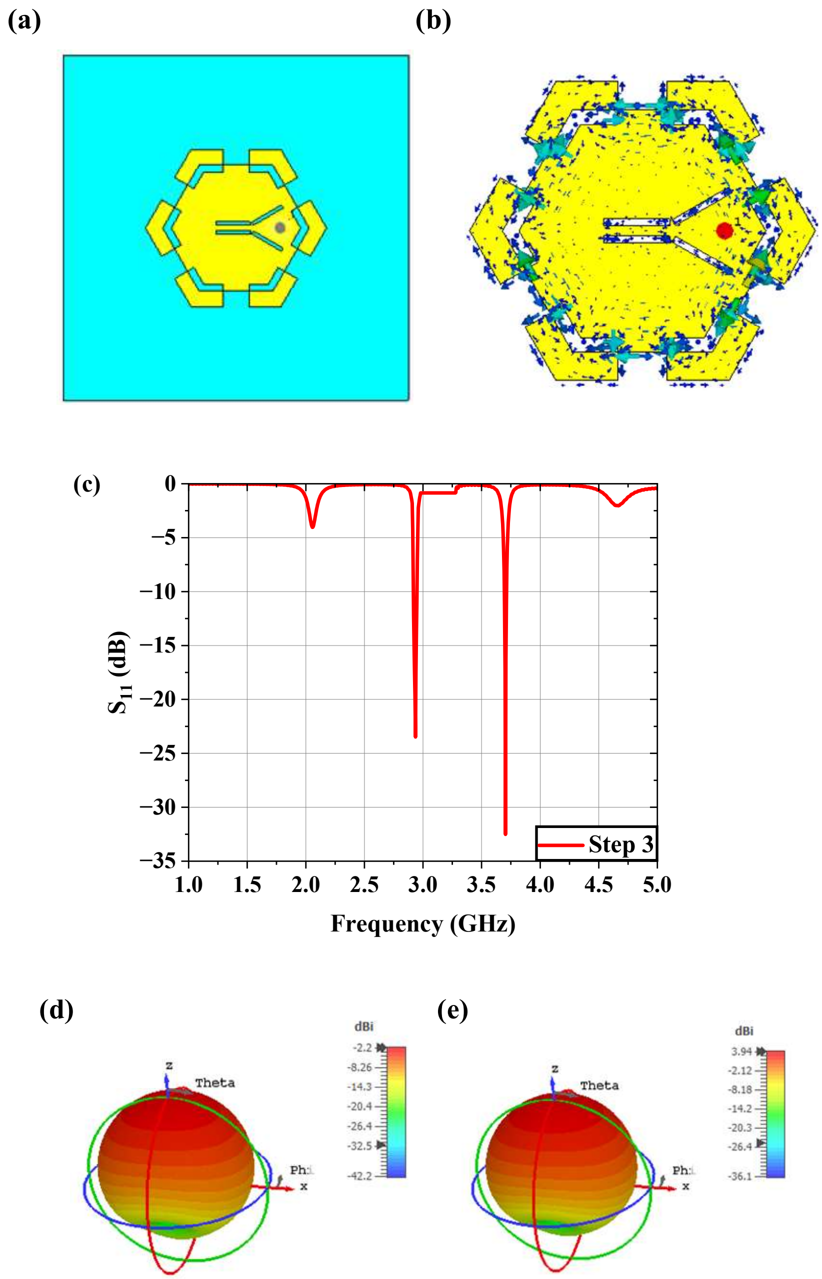


Fig. 6.5: Step 3: (a) Top view of the antenna (b) surface current distribution (c) S_{11} vs Frequency plot of the antenna (d) radiation pattern at 2.94 GHz and (e) radiation pattern at 3.70 GHz

6.3.3. Step 3

Surface charges are accumulated at the corners of the hexagonal patches. In step 3, four rectangular thin slots are incorporated on the patch as illustrated in Fig. 6.5 (a) to allow the currents to flow towards its centre. The current distribution of this structure is shown in Fig. 6.5 (b).

From Fig. 6.5(c) it is observed that this antenna is tuned to 2.94 GHz and 3.70 GHz. This antenna has return loss values of 23.48 dB and 32.51dB at 2.94 GHz and 3.70 GHz respectively. Very small amount of frequency shift is observed due to addition of slots on patch. Due to incorporation of these slots on patch, the charges are accumulated in the centre part of the patch. Therefore, main beam is now tilted towards broad side direction of the antenna which is observed from Fig. 6.5 (d) and (e). This antenna provides -2.2 dBi and 3.94 dBi realized gain for 2.94 GHz and 3.70 GHz respectively.

6.3.4. Step 4

Next an open ended slot is incorporated in ground plane. As reported in literature [16-17], electrical length of open slot (L/λ) on a small ground plane of antenna can control impedance matching at desired frequency; where, L is the physical length of the open slot and λ is the free space wavelength.

In this design, we are designing this antenna for 5G applications. Therefore, it is required to improve impedance matching at 3.7 GHz. In this step, 20 mm ($\approx \frac{\lambda}{4}$) open slot is placed at the ground plane as illustrated in Fig. 6.6 (a). From return loss curve of this antenna shown in Fig. 6.6 (a), this antenna is tuned to two frequencies – 2.47 GHz and 3.68 GHz with return loss values 11.78 dB and 29.95 dB respectively. The realized gain is reduced at 3.68 GHz to 1.68 dBi. The realized gain of this antenna is -0.03 dB at 2.47 GHz.

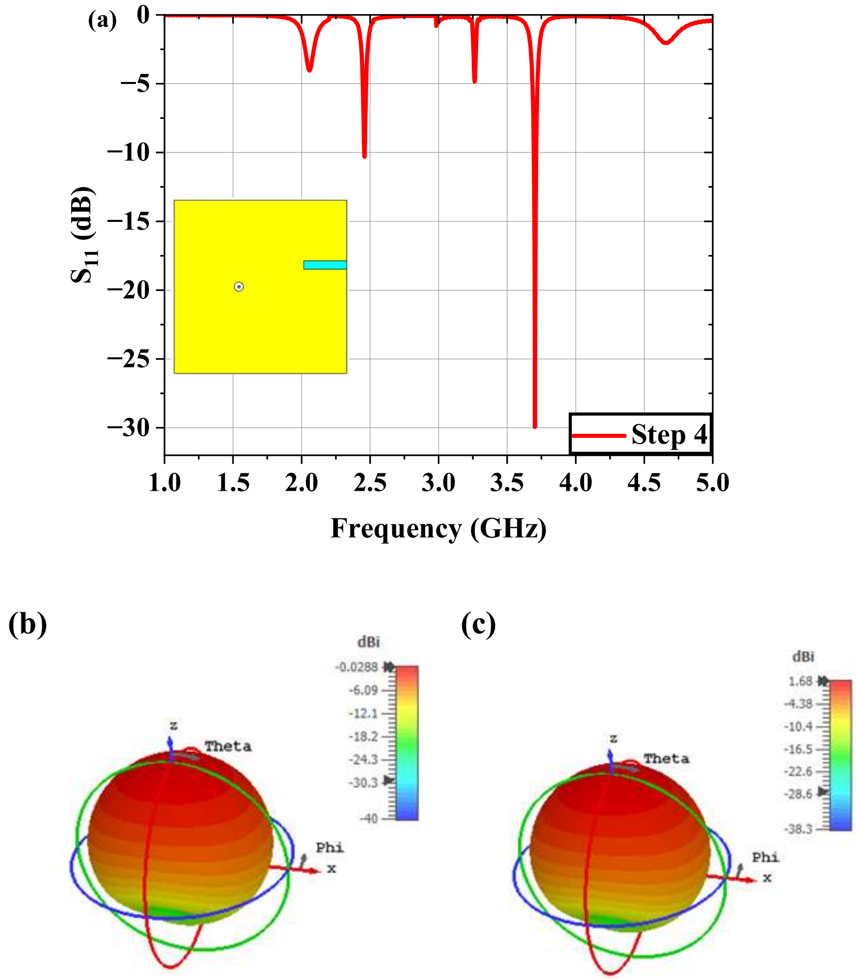


Fig. 6.6: Step 4: (a) Top view of the antenna and S_{11} vs Frequency plot of the antenna (b) radiation pattern at 2.47 GHz and (c) radiation pattern at 3.68 GHz

6.3.5. Step 5

To enhance the gain of the antenna, a copper plate is placed at 20 mm ($\approx \frac{\lambda}{4}$) distance from the ground plane (depicted in Fig. 6.7 (a) and (b)). It does not affect the return loss plot. However, it reduces backlobe and enhances realized gain of this antenna. This antenna provides gain of 2.67 dBi and 4.29 dBi at operating frequencies of 2.47 GHz and 3.68 GHz respectively as shown in Fig. 6.7 (c) and (d).

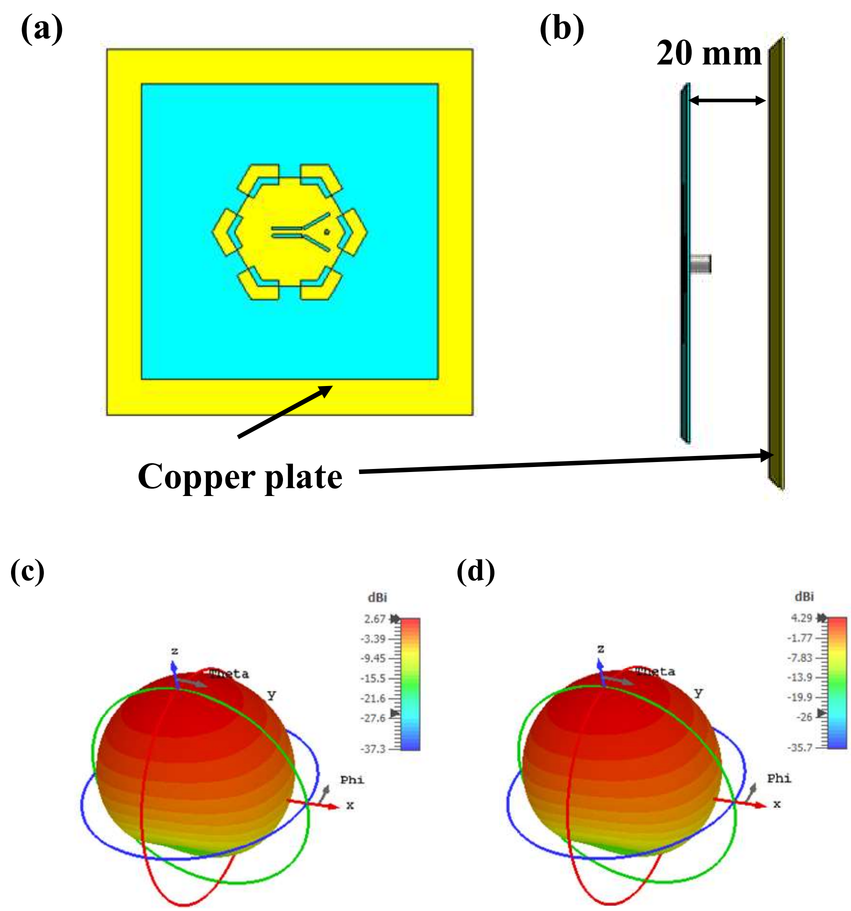
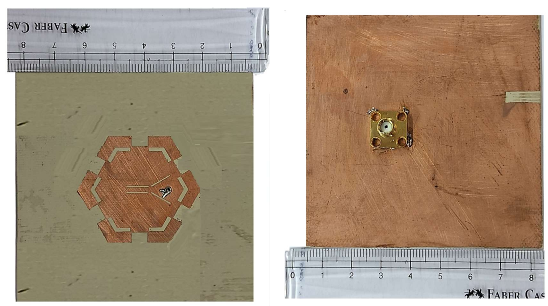


Fig. 6.7: Step 5: (a) Top view and (b) side view of the antenna (b) radiation pattern at 2.47 GHz and (c) radiation pattern at 3.68 GHz

6.4 Fabrication and Measurement

All the antenna structures shown in Figs. 6.4-6.7 have been simulated using the CST MWS 2019. The finally proposed antenna has been fabricated using photolithography technique and photograph of the fabricated antenna is shown in Fig. 6.8. The comparison between simulated and measured return loss values are illustrated in Fig. 6.9. From this plot, it is observed that the simulated operating frequencies are 2.47 GHz and 3.68 GHz whereas measured operating frequencies are 2.53 GHz and 3.65 GHz. The measured return loss values of the fabricated antenna are 10.86 dB and 28.46 dB at 2.53 GHz and 3.65 GHz respectively. Fig. 6.10 shows the radiation patterns for 2.47 GHz and 3.65 GHz for E and H planes.



(a) **(b)**

Fig. 6.8:(a) Top view and (b) bottom view of the fabricated antenna

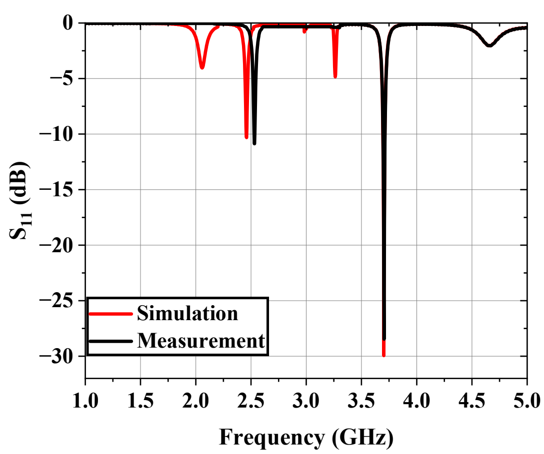
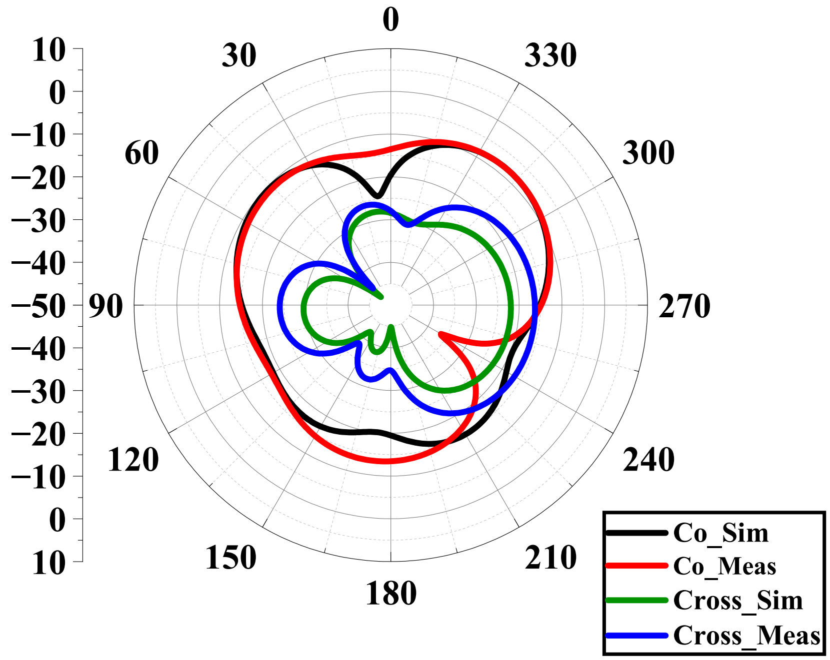
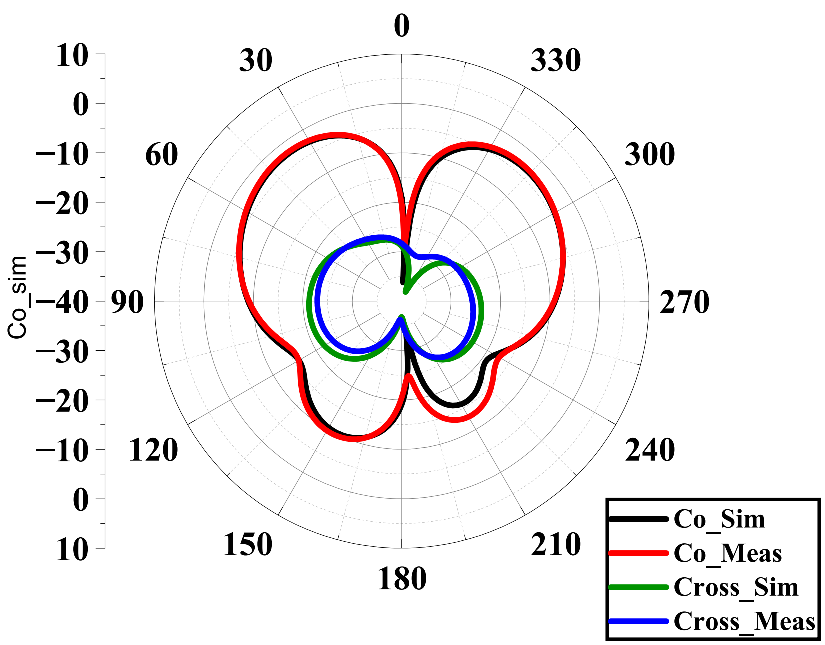


Fig. 6.9: Simulated and measured return loss curves of proposed antenna


0
30
330
60
300
90
270
120
240
150
210
180
10
0
−10
−20
−30
−40
−50
−40
−30
−20
−10
0
10
Co_Sim
Co_Meas
Cross_Sim
Cross_Meas

(a)


0
30
330
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120
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150
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180
Co_sim
10
0
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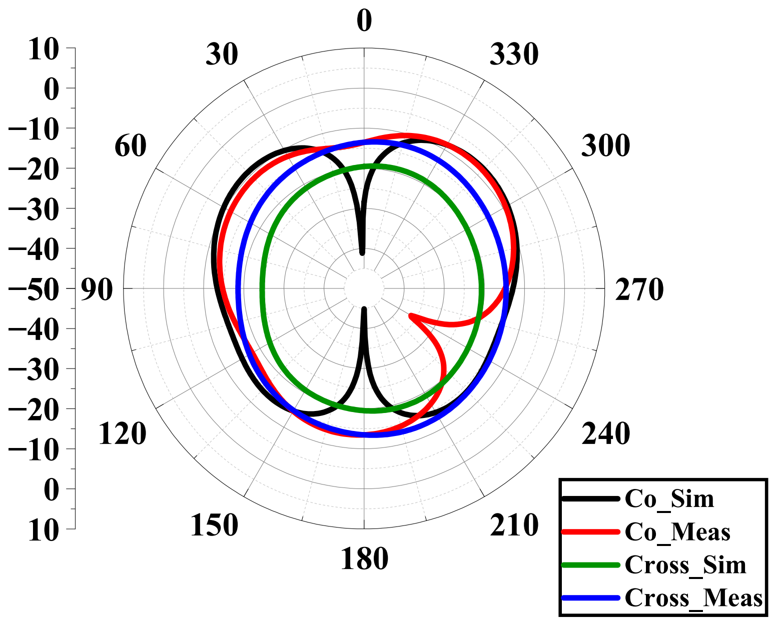
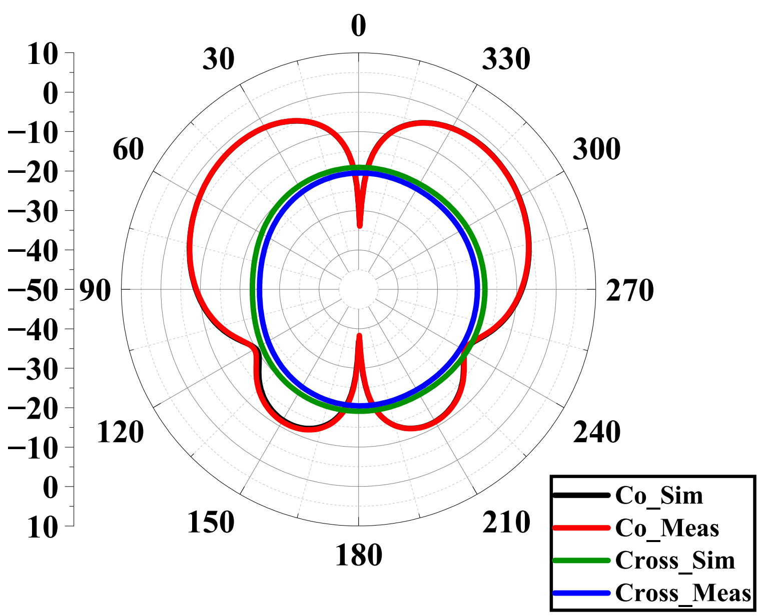
−20
−30
−40
−30
−20
−10
0
10
Co_Sim
Co_Meas
Cross_Sim
Cross_Meas

(b)



(c)



(d)

Fig. 6.10: Simulated and measured radiation patterns for (a) E plane at 2.47 GHz, (b) E plane at 3.65 GHz, (c) H plane at 2.47 GHz and (d) H plane at 3.65 GHz of designed antenna without copper plate at back side

Due to some fabrication errors such as dispute in etching process, improper soldering for connecting SMA connector to the patch, connector loss, cable loss etc. makes disparities between simulated and measured results. This antenna has novelty compared to some previously reported antennas which are mentioned in Table 6.2. The designed antenna provides dual band nature which is not provided by other reported antennas. This antenna provides more gain than many other reported antennas [18-21].

Table6.2. Comparison with Previously Reported Hexagonal Antennas

Ref.	**Operating Frequency (GHz)**	**Realized Gain (dBi)**
[18]	3.7	1.98
[19]	3.7	2.70
[20]	3.5	3.20
[21]	3.5	4.42
This Work	**2.47 GHz and 3.68 GHz**	**2.67 and 4.29**

6.5Conclusion

In this chapter, a peripheral slot based dual band hexagonal patch antenna has been designed. Here, copper is used as material of patch and ground and Arlon AD 430 is used as the material for substrate. This antenna was tuned to 2.94 GHz and 3.7 GHz. However, impedance matching is not good at 3.7 GHz compared to 2.94 GHz. However, our objective is to tune this antenna at sub- 6 lower band frequency band.

Therefore, matching should be better at 3.7 GHz than 2.94 GHz. An open-ended slot is incorporated in ground plane to achieve matching in second resonance i.e. at 3.7 GHz. A copper plate is placed at 20 mm distance from ground plane to increase the realized gain of the antenna. The proposed antenna is tuned to two frequencies – 2.47 GHz and 3.68 GHz. Therefore, this antenna can be utilized for 2.45 GHz ISM band WLAN and sub 6 GHz 5G.

This antenna is radiating over 2.46 – 2.48 GHz with realized gain 2.67 dBi and 3.69 – 3.71 GHz with 4.29 dBi realized gain. This antenna is fabricated and measured. The fabricated antenna is tuned to 2.52 GHz and 3.65 GHz. The simulated and fabricated results are quite similar. Therefore, it can be concluded that measured results validate the simulated results of this antenna.

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Chapter 7: Conclusions and Future Scope

7.1 Introduction

The aim of this work is to investigate hexagonal patch based antenna design and analysis for different applications especially for 5G application. In this work, Multiport Network Model (MNM) is used to analyze arbitrary shaped hexagonal patch antenna. Effects of size reduction, slot incorporation and ground reduction of the antenna are also investigated here for analyzing antenna performance.

7.2 Overall Summary of the work

In this initial phase, Multiport Network Model (MNM) is used for analysis of the irregular shaped hexagonal patch antenna characteristics. The irregular hexagonal patch antenna is decomposed into one rectangular and four right-angle triangular sections followed by multiple port incorporation along edges andthe input impedances are calculated for each port of each section using Green's functions of corresponding section. Finally ports of two different sections are connected using calculated impedances. The obtained surface current distribution from MNM analysis is verified with simulated surface current response of the antenna.

In next stage, characteristic studies between full and half hexagonal patch for regular and irregular shapes are performed. A circular slot has been added on patch also. This antenna has nine resonant frequencies viz. 1.81GHz, 2.36 GHz, 3.45 GHz, 3.65 GHz, 5.14 GHz, 5.49 GHz, 5.99 GHz, 7.15 GHz and 7.71 GHz with acceptable peak realized gain of 3.42 dBi, 2.69 dBi, 3.51 dBi, 1.15 dBi, 3.05 dBi, 4.66dBi, 6.20 dBi, 5.78 dBi and 9.68 dBi respectively. The antenna is covering Bluetooth, WLAN and point to point high speed wireless communication bands. This antenna also covers 5G sub-6 GHz lower band to support recent trends of communication facilities. On slot loading, it is found that the resonant frequencies of the unperturbed antenna are shifted downwards as the slot radius is increased.

Next, a defected ground hexagonal antenna is proposed for wireless communication and aeronautical navigation applications. This antenna has resonant frequency of 5.17 GHz. This antenna radiated over 4.66 GHz to 5.85 GHz with realized gain of 1.63 dBi at its resonant frequency. However, back lobe is present due to reduced ground. Therefore, a metal reflector is placed at the back side of the antenna which leads to enhance broad side realized gain of 5.98 dBi and fractional bandwidth of this whole structure is 22.97% around 5.17 GHz.

Finally, a peripheral slot based dual band hexagonal patch antenna has been designed. This antenna was tuned to 2.94 GHz and 3.7 GHz. However, impedance matching is not good at 3.7 GHz compared to 2.94 GHz. However, our objective is to tune this antenna at sub- 6 lower band frequency band. Therefore, matching should be better at 3.7 GHz than 2.94 GHz. An open-ended slot is incorporated in ground plane to achieve matching in second resonance i.e. at 3.7 GHz. A copper plate is placed at 20 mm distance from ground plane to increase the realized gain of the antenna. The proposed antenna is tuned to two frequencies – 2.47 GHz and 3.68 GHz. Therefore, this antenna can be utilized for 2.45 GHz ISM band WLAN and sub 6 GHz 5G. This antenna is radiating over 2.46 – 2.48 GHz with realized gain of 2.67 dBi and 3.69 – 3.71 GHz with 4.29 dBi realized gain.

7.3 Future Scope

There are some scopes of future work which can be outlined as follows,

1. Using hexagonal shaped patches for electromagnetic shielding can be an effective strategy. Hexagonal shapes offer certain advantages such as efficient use of space and reduced edge effects compared to other shapes of antennas.
2. Hexagonal Patches can be arranged in a closely packed array to cover the entire surface that needs electromagnetic shielding. This hexagonal lattice configuration can provide uniform coverage and minimize the formation gaps.
3. Analysis of planar microstrip antennas based on hexagonal geometries, particularly for utilizing the higher order modes for gain enhancement.
4. Use of hexagonal UWB patch antenna in IoT application
5. Use of hexagonal patch antenna in wireless camera for monitoring purpose.

Appendix I

List of Journals:

[1] M. Biswas, K. Patra, S. Ghosh and B. Gupta, "Circular Slotted Half Hexagonal Patch Multiband Antenna Design for 5G Applications," *European Journal of Science, Innovation and Technology*, vol. 3, no. 4, 2023.

[2] M. Biswas, S. Ghosh, S. Dey, K. Patra and B. Gupta, "Design and Analysis of Irregular Hexagonal Patch Antenna using Multiport Network Model (MNM)," *International Journal of RF and Microwave Computer-Aided Engineering*, July 2024, https://doi.org/10.1155/2024/8343100.

List of National/International Conferences:

[1] S. Dey, S. Ghosh, M. Biswas and B. Gupta, "Semi- Circular Ring slotted Circular Patch Antenna for 5G Applications," *2023 8th International Conference on Computers and Devices for Communication (CODEC)*, Kolkata, India, 2023, pp. 1-2, doi: 10.1109/CODEC60112.2023.10465705.

[2] M. Biswas, S. Ghosh, C. Mitra and B. Gupta, "Design and Performance Analysis of Defected Grounded Hexagonal Patch Antenna at 5.17 GHz," *2023 International Conference on Computer, Electronics & Electrical Engineering & their Applications (IC2E3)*, Srinagar Garhwal, India, 2023, pp. 1-4, doi: 10.1109/IC2E357697.2023.10262464.

[3] S. Dey, S. Ghosh, M. Biswas and B. Gupta, "Dual Band Slot loaded Hexagonal Patch Antenna for 5G Applications," *2024 Fourth International Conference on Advances in Electrical, Computing, Communication and*

Sustainable Technologies (ICAECT), Bhilai, India, 2024, pp. 1-5, doi: 10.1109/ICAECT60202.2024.10469049.

Appendix II

List of Presentations in National/International Conferences:

[1] S. Dey, S. Ghosh, M. Biswas and B. Gupta, "Semi- Circular Ring slotted Circular Patch Antenna for 5G Applications," *2023 8th International Conference on Computers and Devices for Communication (CODEC)*, Kolkata, India, 2023, pp. 1-2, doi: 10.1109/CODEC60112.2023.10465705.

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19/02/2024.

Gupta
19/02/24