DESIGN AND FABRICATION OF ANTENNA FOR SATELLITE APPLICATIONS WITH OPTIMIZED PARAMETERS

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DOCTOR OF PHILOSOPHY
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Electronics and Electrical Engineering
By
Gurpreet Singh Saini

(41400731)

Supervised By **Co-Supervised by**
Dr. Daljeet Singh **Dr. Rajeev Kumar**

LOVELY PROFESSIONAL UNIVERSITY
PUNJAB
2021

DECLARATION

I declare that the thesis entitled **"Design and Fabrication of Antenna for Satellite Applications with Optimized Parameters"** has been prepared by me under the guidance of **Dr. Daljeet Singh, Assistant Professor, School of Electronics and Electrical Engineering** at **Lovely Professional University, Punjab, India** and **Dr. Rajeev Kumar, Assistant professor at Chitkara University Institute of Engineering and Technology, Punjab, India**. No part of this thesis has been included in or has formed the basis for the award of any Degree or Diploma or Fellowship of any institution or university anywhere previously.

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Gurpreet Singh Saini

GURPREET SINGH SAINI
School of Electronics and Electrical Engineering
Lovely Faculty of Technology and Sciences
Lovely Professional University
Phagwara, -144411 (Punjab)

We endorse the above declaration of Ph.D. student

Daljeet Singh
14/9/2.21

Date: 14/9/2021

(Signature of the Ph.D. Supervisor)

14/09/2021

(Signature of the Ph.D. Co-Supervisor)

CERTIFICATE

We certify that **GURPREET SINGH SAINI** has prepared his thesis entitled **"Design and Fabrication of Antenna for Satellite Applications with Optimized Parameters"**, for the award of the Ph.D. degree of the Lovely Professional University, under our guidance. He has carried out the work at the **School of Electronics and Electrical Engineering**, Lovely Professional University.

Daljeet Singh
14/09/2021

Dr. DALJEET SINGH
Assistant Professor
School of Electronics and Electrical Engineering
Lovely Faculty of Technology and Sciences
Lovely Professional University,
Phagwara, Kapurthala-144411 (Punjab)

14/09/2021

Dr. RAJEEV KUMAR
Assistant Professor
Chitkara University Institute of Engineering and Technology
Chitkara University,
Rajpura, Patiala-140401(Punjab)

ABSTRACT

For the satellite communication application, the low profile patch antenna designs are appropriate due to its various advantages of the small size, single layer and light weight etc. But most of the designs for satellite communication applications are either aperture coupled or multi microstrip patch or multi-layered or proximity coupled. Due to the alignment issues and an air gap between the layers, these antennas are very difficult to realize. Also, these kinds of antennas are having more height and weight than the single patch and single layer antenna. Therefore in this thesis, two low profile antennas have been proposed to meet the necessity of a region -3 (ITU) for receive mode and transmit mode for FSS and DBS services. The design of the proposed antennas is low profile, small size and light weight antenna less complex and easy to integrate and realize

In the chapter 3, a low profile, small size, and lightweight dual-band antenna prototype is presented for satellite application (Ku- band). The frequency band of 11.69-13.24 GHz and 13.72-15.07 GHz are used for direct broadcast service (DBS) and fixed satellite service (FSS) in receive mode, and FSS in transmit mode, respectively. The antenna achieves the impedance bandwidth of 12.29 %, and 9.37 %, for first, and second band of frequency, respectively and also the axial ratio of 160 MHz (12.30-12.46 GHz) is achieved by the design. Moreover, the complexity in realizing the design is less due to its single patch and a single layer.

In chapter 4, a compact tri-band antenna is designed and analyzed to achieve both transmission and reception of direct broadcast service (DBS) and fixed satellite service (FSS) in Ku band. The proposed antenna design consists of truncated E shaped slot, eight rectangular slots, and two C shaped slots in the patch and eight defected ground structure (DGS) slots. The three frequency bands of 11.40-12.91 GHz, 13.86-14.53 GHz, and 17.20-17.86 GHz are achieved with impedance bandwidths of 12.32 %, 4.73 %, and 3.77 % respectively. Conversely, the measured frequency bands of 11.40-12.98 GHz, 14.21-14.86 GHz and 17.41-18.98 GHz with the impedance bandwidth of 12.70 %, 4.48 % and 8.63 % respectively are obtained. Moreover, the proposed antenna design can be used as an element in an array configuration to achieve high gain in both transmission and reception modes of FSS and DBS.

The simulated results of the proposed antennas are compared with the results of fabricated antenna and are found to be satisfactory for reflection coefficient, impedance bandwidth, polarization, efficiency, gain, and radiation pattern.

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High achievement always takes place in the framework of high expectation. The expectation was there and I begin with determined resolve and put in sustained hard work. It has been rightly said that every successful individual knows that his or her achievement depends on a community of persons working together but the satisfaction that accompanies the successful completion of any task would be incomplete without the mention of the people who made it possible.

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CONTENTS

ABBREVIATIONS

IEEE	Institute of Electrical and Electronics Engineering
ITU-R	International Telecommunication Union
MIMO	Multiple Input Multiple Output
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
FSS	Fixed Satellite Service
DBS	Direct Broadcast Service
Ku	Kurz unten
FR4	Flame Retardant
HFSS	High-frequency Structure Simulator
Wi-Fi	Wireless Fidelity
UMTS	Universal Mobile Telecommunications System
WiMAX	Worldwide Interoperability for Microwave Access
ISM	Industrial, Scientific and Medical
DGS	Defective Ground Structure
RA	Reflect Array
TM_{mn}	Transverse Magnetic Mode
LF	Lower Frequency
UF	Upper Frequency
RF	Resonant Frequency
BW	Bandwidth

LIST OF SYMBOLS

ε_r	Permittivity
ε_{reff}	Effective Permittivity
ΔL	Extended Incremental Length of the Patch
L_{eff}	Effective Length
c	Velocity of Light
λ_0	Centre Wavelength
S_{11}	Reflection Coefficient

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Chapter 1

INTRODUCTION

Since the establishment of human society, communication is considered to be a vital instrument in development. Humans have started using the electromagnetic spectrum for communication and have revolutionized the way we communicate with each other. The antenna is an important part of any such radio communication system. It allows the transmission and reception of signals. A large variety of antennas have been developed to optimize this process of transmission and reception. The antenna converts the radio waves into an electrical signal and vice-versa. With the change in the communication needs of customers, the requirement for smart antennas is escalating. A smart antenna is one with high-tech technology which makes it more powerful and consistent than its regular counterparts [1-3].

Antennas constitute a very large part of economic markets. In 2020, approximately 18.1 billion units of antenna shipment were observed and are projected to reach 30.84 units in 2026. The antenna market is growing at an incredible compound annual growth rate of 9.72% from 2021 to 2026 [4]. Most consumer electronic devices like mobile phones, tablets, laptops, wearable devices, etc. come with multiple antennas for cellular bands, WiFi, Bluetooth, GPS, and other applications. The growth rate of the antenna market by region is shown in Fig. 1.1 [5]. The design of these antennas mainly depends on the frequency of operation and requires substantial investment in research and development. The COVID-19 pandemic has a noteworthy influence on the telecommunication sector. Most of the governments around the world have imposed restrictions on the movements of people as a result of which, people are working from their homes thereby using more telecommunication devices.

1.1 Overview of Satellite Communication

The idea of satellite communication was commercialized in the late 80’s and soon it became one of the prominent routes for communication. When compared with its rival technologies, satellite-based communication offers a lot of unique advantages due to its massive coverage footprint, location, and height. The initial concept of satellite communication was proposed by Arthur C. Clarke in 1966 [6]. However, the first artificial satellite was successfully launched in 1957 named Sputnik 1 transmitting low-frequency signals which lasted only 22 days. Since then, there has been a huge rise in satellite communication and space technology.

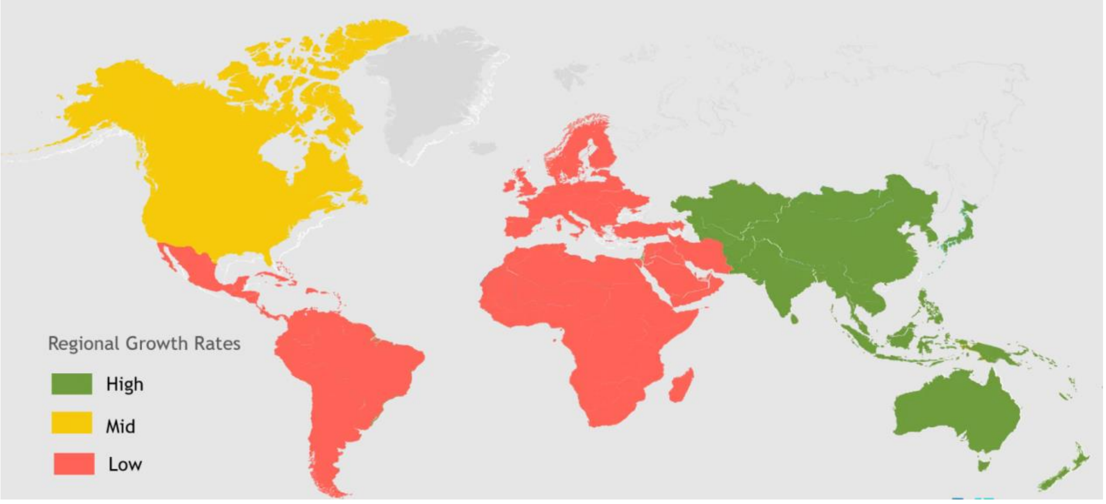


Fig. 1.1: Antenna Market: Growth rate by region

Satellite-based communication systems are more convenient, inexpensive, and easier to implement providing access to even the remotest areas with low local infrastructure support. Another major advantage of satellite communication is that it is unaffected by the effects of shadowing due to the presence of large buildings and natural obstacles. Currently, more than 2,000 artificial satellites are orbiting our planet and contributing to both analog and digital communications carrying audio, video, and data across the globe [7]. One of the major components in all these satellites is the antenna. An antenna acts as a transitional device converting radio signals into electrical pulses and vice-versa. A variety of antennas have been used in past for satellite communication which is described in the next section.

1.2 Evolution and Growth of Satellite Antennas

Due to the huge development in VLSI and signal processing technology, satellite antennas have evolved a lot in the last decades. Frequency bands for communication are changing for different satellite applications which have created a demand for updating the antenna designs. Further, the requirements of good signal performance and smaller devices have pushed the limits for antenna design optimization [8]. The work on antenna design started way back in 1887 by the German physicist Heinrich Rudolf

Hertz. He performed experiments on antenna systems for creating and observing radio waves and consequently verify the existence of electromagnetic radiations [3]. The system used by Hertz in his experiment is shown in Fig. 1.2. Another notable name in this field is the Scottish scientist James Clerk Maxwell. He is said to be the father of electromagnetic theory as his work proved to be the benchmark for upcoming works on electromagnetic waves.

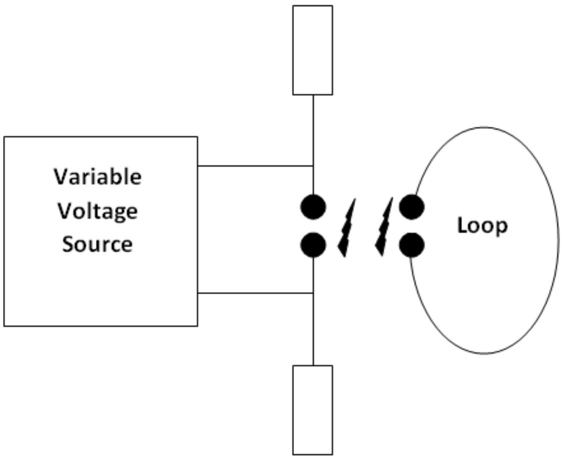


Fig. 1.2: Set-up of Hertz's Experiment [2]

Subsequently, the famous Italian inventor Guglielmo Marconi was able to establish and commercialize the communication technology with the aid of a radiotelegraph. Ever since antennas have become an inevitable part of our life. Initially, the communication devices and satellites were very heavy because of the usage of large external antennas. These devices were operating at low frequencies and utilized analog communication. These devices were having poor efficiency as most of the radiated signal was reflected and absorbed. Nowadays internal antennas are used in communication devices despite the external antenna. The main cause of that is the internal antenna has a good relation with specific absorption rate and also results in the decrease of device size. On the other hand, the size of satellites is also decreasing day by day. The invention of micro and pico satellites have resulted in a considerable decrease in size of satellites and consequently the size of antennas used at the satellite for communication purpose [9].

Further, the latest applications related to satellite communication require multiband antennas. Therefore, the need for antenna technology that can cover a band of a single frequency, twin band, wideband, and multi-band is the need of the hour. The extension of operating frequency bands is another key requirement. Traditional antennas have been stretched to their limits and the use of multiband reconfigurable antennas has proved to be a promising candidate. Further, the use of a directional reconfigurable antenna can decrease the collisions thereby improving the communication distance [10].

1.3 Antenna Classification

Wireless communication provides the benefits of hustle-free mobility but in turn, requires an antenna for transmitting or receiving the electromagnetic waves. The antenna acts as a transitional structure between the guiding device and free space. The process of transmission is shown in Fig. 1.3 [1].

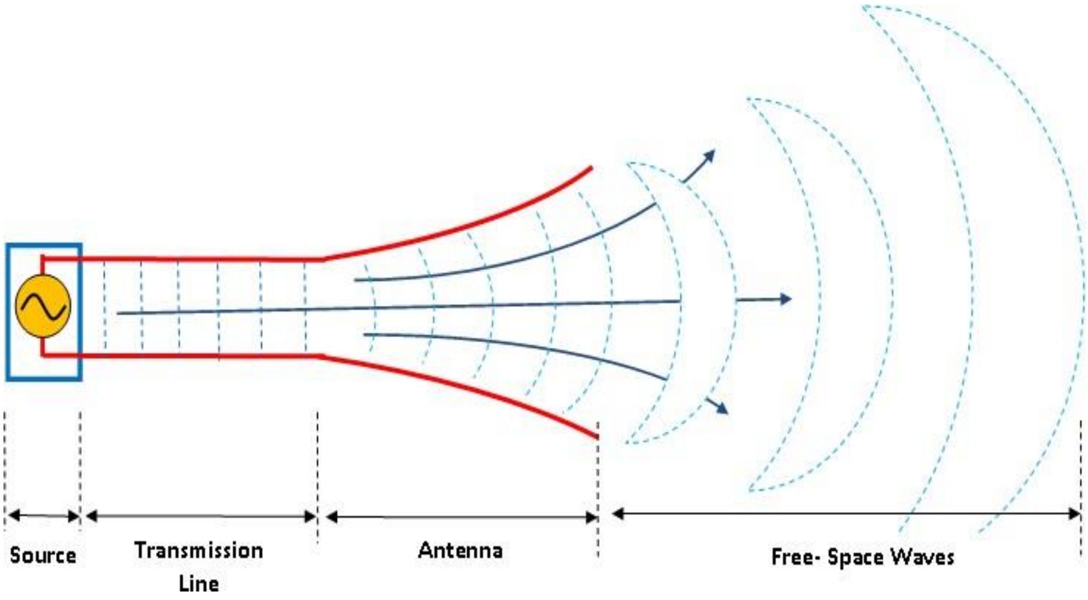


Fig.1.3: Antenna as a transitional device [1]

Antennas are classified into many categories depending upon their construction and working. Another method for antenna classification is based on their applications. For clear understanding, the antenna is classified into three major categories based on the following parameters [11]:

- Physical construction
- Frequency range
- Application areas

Further, based on the physical construction, there are various types of antennas. Some of the popular antenna designs based on their physical construction are:

- Aperture antenna
- Micro strip antenna
- Reflector antenna
- Lens antenna
- Array antenna
- Wire antenna

These antennas operate at different frequencies.

1.4 Frequency Bands for ITU

Allocation of frequency band involves international coordination and planning which is governed by International Telecommunication Union (ITU) [12]. For smooth and flawless operation, ITU has divided the earth into three different regions as follows:

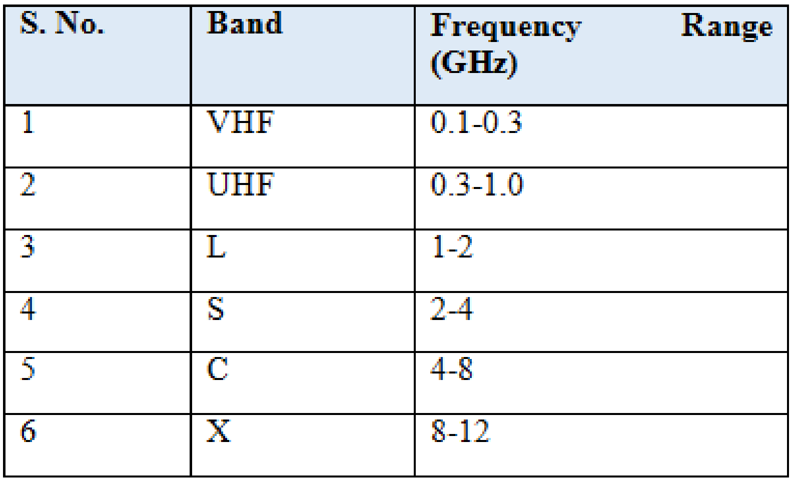
Region 1 consists of Europe, Africa, and Mongolia

Region 2 contains North and South America and Greenland

Region 3 includes Asia, Australia, and areas of the southwest Pacific.

Various frequency bands are allocated for satellite communication in these regions and are given in Table 1.1 [3].

Table 1.1: Description of frequency bands for satellite communication [3]



S. No.	Band	Frequency Range (GHz)
1	VHF	0.1-0.3
2	UHF	0.3-1.0
3	L	1-2
4	S	2-4
5	C	4-8
6	X	8-12

Antennas are designed for specific applications. For example, an antenna designed for satellite communication will not be suitable for underwater transmission. Therefore, based on their applications, antennas can be classified as:

- Point-to-point applications
- Broadcasting
- Radar/Sonar communications
- Satellite applications

1.5 Parameters of Antenna

To understand the working of the antenna and have a better insight into antenna design and fabrication, it is must to know about the parameters which govern the working of the antenna. Therefore, in this part, a brief overview of antenna parameters is presented as follows:

1.5.1 Radiation Pattern

The radiation pattern of the antenna consists of two parts. **Field pattern** is used to characterize the plot of the magnitude of the electric or magnetic field concerning the angular space. On the other hand, the **power pattern** is the plot of the square of the magnitude of electric or magnetic field versus angular space. Both of these patterns are represented in linear scale. The radiation pattern can be classified as Isotropic, Directional and Omnidirectional patterns as shown in Fig. 1.4. Power pattern is also represented in the dB scale to analyse the low values.

1.5.2 Radiation Power Density

The radiation power density of the antenna is described as $W = E \, X \, H$, where E and H are the instantaneous electric and magnetic field intensities respectively, and $W$is the instantaneous Poynting vector [2].

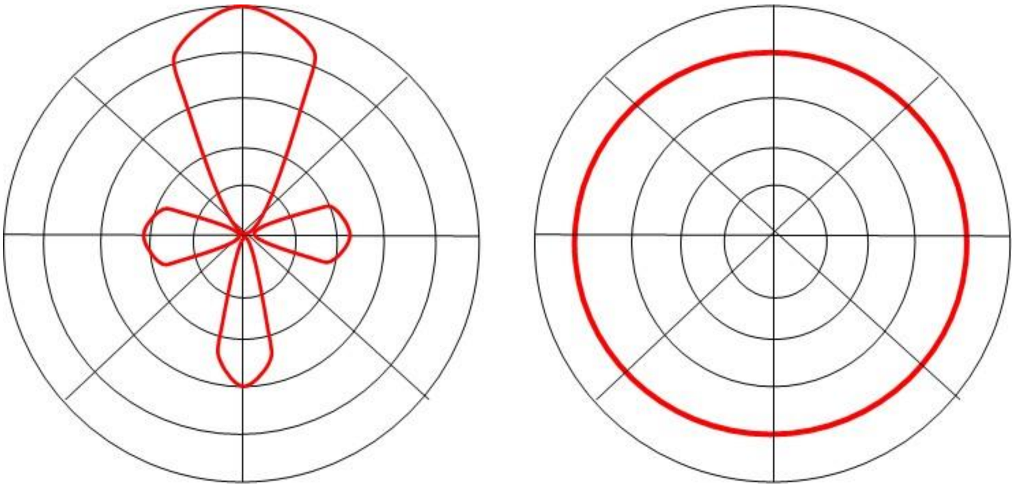


Fig. 1.4: Different types of radiation patterns.

1.5.3 Radiation Intensity

It is defined as the radiated power per unit solid angle for an antenna measured in W/unit solid angle. Mathematically, it is calculated as $U = r^2\mathrm{Wrad}$, where r is distance and Wrad is the radiation density.

1.5.4 Beamwidth

It is used to establish a trade-off between the levels of the main lobe and side lobes. For example, the higher the beamwidth, the lower will be the power in side lobes and vice versa. It is also considered as the resolution ability of the antenna that how well it can differentiate between two neighboring radiating sources or targets. Two different types of beamwidth are commonly defined for antennas i.e. Half Power Beamwidth and First Null Beamwidth as shown in Fig. 1.5 [1].

1.5.5 Gain

Gain of the antenna is a dimensionless quantity given by the ratio of radiation intensity in a specified direction to the intensity that would be obtained if power accepted by the antenna radiate isotropically. Gain is calculated as $Gain = \frac{4\,\pi\,U(\theta,\emptyset)}{P_{in}}$, where$U$ is the radiation intensity, P_{in} is the total input power, θ is elevation angle and, $\emptyset$ is azimuth angle [11].

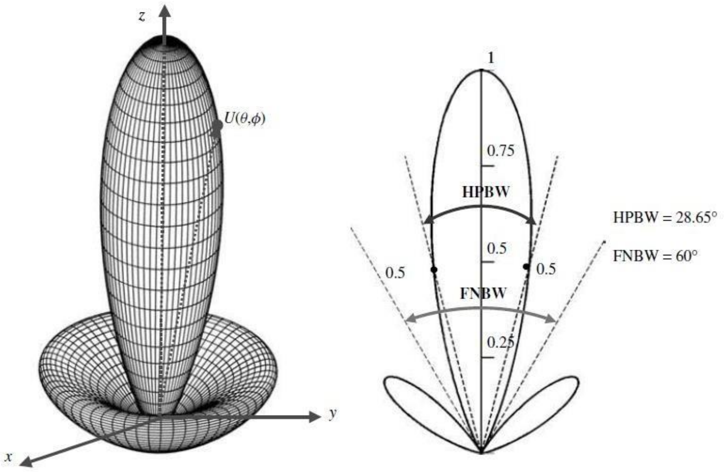


Fig.1.5: Half-Power Beamwidth and First-Null Beamwidth of antenna [4]

1.5.6 Directivity

It is a measure of the directional properties of a radiation pattern of the antenna. Mathematically, it is defined as $Directivity\ = \frac{4\,\pi\,U}{P_{rad}}$, where P_{rad} is the total radiated power measured in watts [13].

1.5.7 Efficiency

Efficiency relates the power given to the antenna with the radiated power. High values of efficiency are expected from a practical antenna system. Losses and mismatch of impedance are general causes of lower efficiency [2].

1.5.8 EFFECTIVE AREA

It relates the amount of power received by an antenna with the power delivered to its terminal. Mathematically, it is defined as: $A_e = \frac{\lambda^2}{4\,\pi} G$, where G is antenna gain.

1.5.9 Input impedance

The voltage at the terminal divided by the current flowing through the terminal is called input impedance. Mathematically, input impedance (Z_{in}) is defined as $Z_{in} = R_{in} + j\,X_{in}$, where R_{in} and $X_{in}$are resistance and reactance of antenna respectively.

1.5.10 Return loss

The return loss of antenna is the ratio of power radiated by the antenna to the power incident on the antenna and is calculated by S_{11}which is the plot of S_{11} v/s frequency. A dip in the plot of S_{11} v/s frequency represents low values of return loss at that particular frequency. Mathematically, return loss RL is defined as$RL_{dB} = 10\log_{10}\frac{P_r}{P_i}$, where P_r and P_i are the reflected and incident power respectively.

1.5.11 Polarization

The polarization of antenna is visualized by the field emitting through the antenna. It is a very parameter while designing an antenna. The “path traced by the tip of the electric field vector as a function of time” [14] is called polarization. Based on the path traced by the electric field, polarization can be linear, circular, or elliptic polarization. The polarization ellipse is depicted in Fig. 1.6 [14] where, E_{xo} and E_{yo} are the maximum magnitudes of the complex counterpart of the instantaneous electric field in x and y direction respectively.

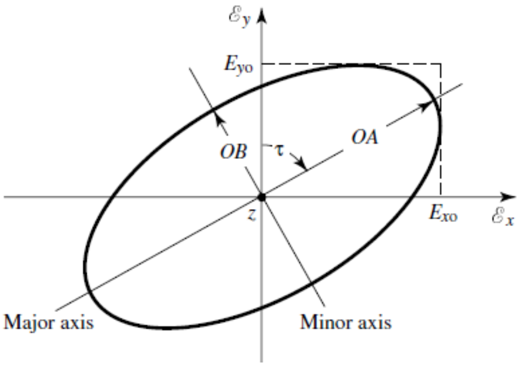


Fig. 1.6: Polarization ellipse [14]

1.6 Applications of Satellite Communication

In the last three decades, satellite communication has matured into a very useful commercial service. It is touching the lives of almost every human being. Applications of satellite communication are very vast. Some key applications of satellite communication are as follows [15]:

- **Telecommunication:** The very first application of satellites involves telecommunication in form of voice and data. It has become the prime source of communication, especially in remote locations. It also acts as the backup communication resource in times of natural disasters when other communication links fail. INSAT satellites in India are offering telecommunication services throughout the county. In order to accommodate these demands, Very Small Aperture Terminals (VSATs) are utilized.
- **Tele-Medicine:** Another important application of satellite communication is Tele-Medicine. Using telemedicine, doctors from key multi-specialty hospitals situated in large cities can connect to remote patients from remote locations very easily which otherwise is a tedious task.
- **Tele-Education:** Education is another sector that is affected by satellite technology. Delivery of real-time audio-video lectures, instructions, and information content to students globally is only possible using satellite technology.
- **Mobile Satellite Service:** Mobile Satellite Service (MSS) operating in the S band is small mobile satellite terminals used for voice/data communication at the time of disasters. For example, INSAT-3C launched in 2002 and GSAT-2 launched in 2003 are two such examples of MSS.
- **Radio Networking:** Satellite radio or Radio Networking (RN) is another application for satellite communication that provides consistent high-fidelity channels for a large geographical area.
- **Search and Rescue:** Satellites are also used extensively for search and rescue operations which prove to be life-saving and highly efficient. International COSPAS-SARSAT is a key program providing various services through LEOSAR satellite system.
- **Standard Time and Frequency Signal Dissemination:** Precise and accurate information of time is useful in maintaining synchronization among various applications. INSAT based standard time and frequency signal dissemination allow universal synchronization.
- **Television:** Satellites have proved to be vital instruments in the expansion of television services throughout the globe. Especially in developing and

underdeveloped countries where limited resources are available, the Direct To Home (DTH) service is utilized for television broadcasts using satellites.

1.7 Motivation

Every wireless communication system consists of an antenna responsible for transmitting and receiving the signals. Especially in satellite communication, the antenna becomes important in deciding the effectiveness of overall communication. Due to the shift in paradigm from traditional satellites to small miniature satellites and requirements of mobility and size restriction at a ground station, most of these antenna designs have been outdated. Current and future satellite communication applications demand small size antennas with multiband transmission and reception abilities. Therefore, microstrip patch antennas have become a very strong candidate for satellite communication. Microstrip antennas have numerous advantages like low profile, low fabrication cost, multiband operation, and simplicity in integration to other microwave circuits. Therefore, in this dissertation, multiband microstrip patch antennas for satellite applications are designed, fabricated, and analyzed for Ku band applications.

1.8 Objectives of proposed research

The major contribution of the work is as follows:

1. Comparative analysis of various designs of antenna for satellite applications.
2. Designing and optimization of the proposed antenna for different antenna parameters.
3. Fabrication, testing, and validation of the proposed antenna.
4. Comparative analysis of proposed antenna design with the various existing antenna of satellite application.

1.9 Organization of Thesis

This thesis is organized as follows:

In Chapter 1, an introduction to satellite communication is presented. Further, the evolution of satellite antennas and their classification is given. Thereafter, various parameters useful for the analysis of antenna working and performance are described.

Then, the applications of satellite communication are presented along with the motivation of work. Finally, the objectives of the dissertation are given in Section 1.5.

Chapter 2 presents an exhaustive literature review for the proposed work. In this review, different techniques for designing and optimization of Ku band satellite antennas are presented.

Chapter 3 presents a low-profile patch antenna for Ku-band applications with dual-band characteristics. The antenna is suitable for Ku band satellite applications of direct broadcast service (DBS) and fixed satellite service (FSS) in receive mode, and FSS in transmit mode. A detailed parametric analysis of the design is presented along with other performance parameters.

In Chapter 4, another antenna design for Ku-band applications of the satellite is presented. A tri-band antenna is designed which covers the frequency band for both transmission and reception of DBS and FSS in the Ku band. The practical implementation of the proposed antenna is also given.

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Chapter 2

Literature Survey

Conventionally, the antennas used in satellite applications are either bulky, having more height, more weight, aperture coupled, multi microstrip patch, multi-layered, or proximity coupled. Moreover, the co-axial feed has been used in some of the designs which are not appropriate for ICs environment and conformal surface antenna. Also, due to the alignment issues and an air gap between the layers, these antennas are very difficult to realize. To accomplish the above constraint of environment and space, the low profile, small size, and lightweight microstrip patch antenna is utilized. Microstrip patch antenna has multi-band performance, miniature dimensions, robustness against interference, and a cheap fabrication budget. In this chapter, an extensive literature survey has been carried out for Ku-band satellite antennas.

2.1 Multiband and Wideband Patch antennas for Ku band

A single layer, single patch rectangular antenna including double bent slots and slot in the centre of the patch has been designed by Sze et al. in 1999 [1]. The bandwidth of the proposed antenna is 2.8 times more than the conventional rectangular antenna. Moreover, the antenna achieved a good radiation pattern within the desired frequency range. In 2009, Misran et al. [2] proposed a patch antenna for dual Ku-band applications. In this design, 3 pair of thin slits along with microstrip feedline is used. The design gives a return loss of -23.8 dB and -14.0 dB at 12.5GHz and 14.15GHz respectively.

A patch antenna with notches and slits for the applications of Ku-band has been designed by Dubeyet al. in 2011 [3]. The three bands have been achieved by the proposed antenna. Moreover, the antenna average gain is 6.3 dB. In another work, an elliptical patch antenna with a thin foam substrate was proposed for the applications of Ku-band in 2011 by Sharma [4] et al. The antenna achieved the three different bands with the acceptable value of VSWR and the size of the antenna is compact i.e. 50×50 mm^2.

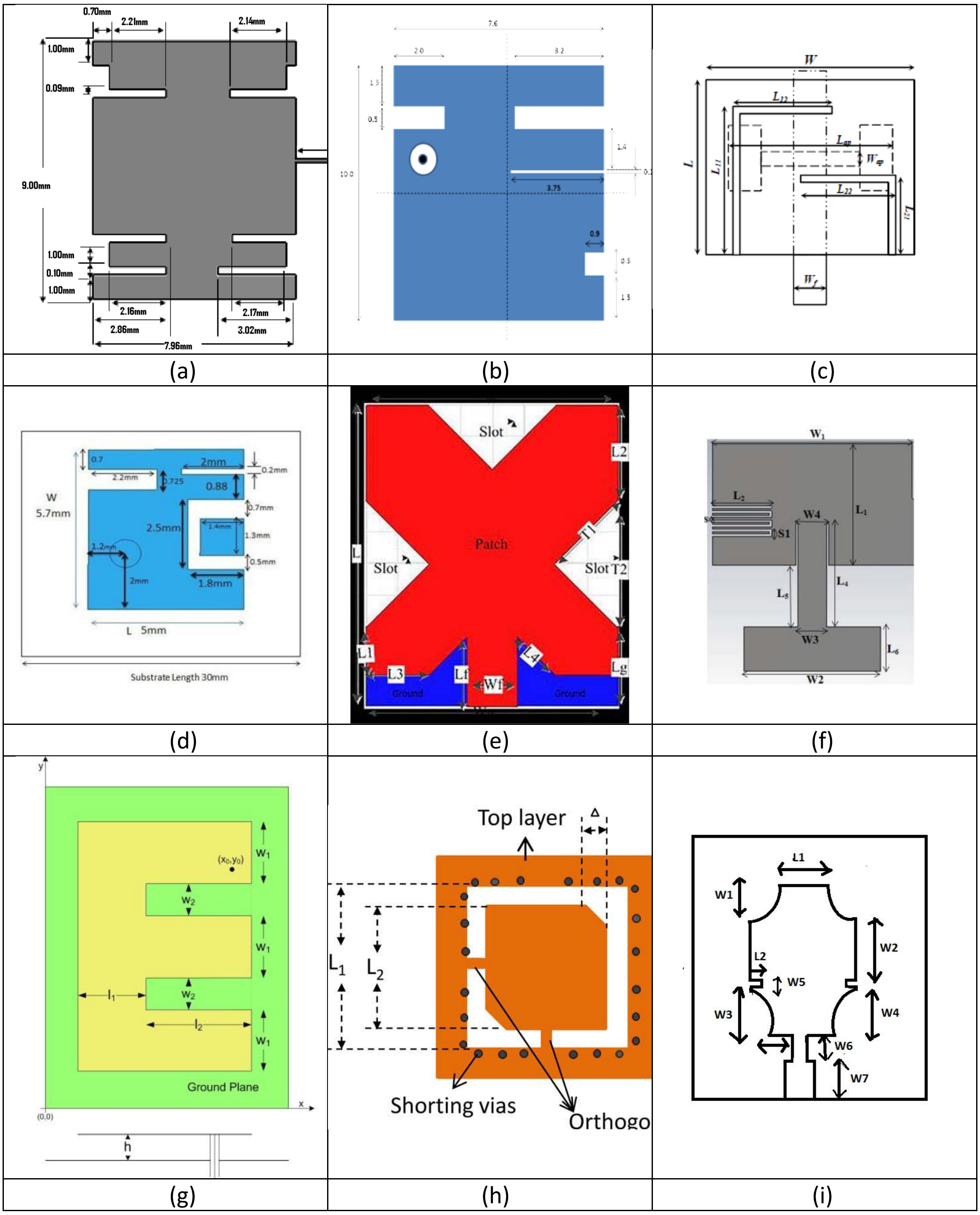
A Ku-band compact microstrip antenna was proposed by Sorouriand Rezaei [5] in 2012, for dual-band applications. In this design, the square patch of 4×4.15 mm^2 is used with 2 L-shaped inverted slots and aperture coupled feeding technique. The antenna achieves the gain of 6 dB at each band of the frequency i.e., 11.5 GHz and 14 GHz, and also for lower fabrication cost, the FR4 material has been used in the design. The antenna using coaxial feed has been designed for dual-band Ku- applications by Parikh et al. in 2012. Two slots are used in the patch to design an antenna. The return losses of -42 dB and -43 dB have been obtained at a frequency of 11.9 GHz and 14.28 GHz respectively. Moreover, a stable radiation pattern has been achieved and a 7.2 dB gain is obtained by the proposed design.

A multiband design has been achieved using notches and slits in the patch antenna by Prasad and Chattorajin in 2013 [6]. Glass PTFE substrate has been used to design an antenna. The antenna has been used for the non-geostationary orbit and FSS in Ku-band. Moreover, the gain of the antenna is 6 dB.

The X-shaped patch antenna on the ceramic PTFE substrate has been proposed for dual and triple-band application by Samsuzzaman and Misran [7] in 2013. The five rectangular slots are used in the design to produce the dual-band of operation for Ku band applications. Moreover, the three equilateral triangle slots have been introduced to achieve the tri-band operation. Also, the peak gain of 4.80 dBi, 6.42 dBi, and 3.91dBi with a stable radiation pattern has been achieved.

A tri-band E-shaped patch antenna with FR4 substrate has been designed by Ahmed and Islam in 2013 [8]. Moreover, the different characteristic of the antenna has been studied. A spidron fractal antenna with circular polarization has been designed for the dual-band by Thiet al. [9] in 2013. The bandwidth percentage of the proposed antenna is 8.7% and 6.6% for the frequency range of (11.44–12.48 GHz) and (13.47–14.39 GHz) respectively. Moreover, the resonant frequency ratio is small i.e., 1.15 only. The popular antenna geometries proposed in the literature for the Ku band are shown in Fig. 2.1. The detailed summary of antenna structures proposed for Ku band applications and their performance parameters is presented in Tables 2.1 and 2.2.

A low profile, multi-stack, dual-port, and H-shaped aperture slot antenna has been presented by Guodong et al. [10] in 2013. A parasitic patch is installed on the top layer. The values of VSWR, bandwidth, isolation, and beamwidth are less than 2.22%, higher than 30 dB, and greater than 70 degrees respectively. The compact, simple, and low-cost patch antenna has been presented by Hasan in 2013. The antenna can achieve the triple band of 7.7 GHz, 16.2 GHz, and 22 GHz with the S11 of -21 dB, -23.67 dB, and - 9.859 dB respectively. So that it is used for the C, Ku, and K bands.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 2.1: Different antenna geometries proposed in literature for Ku band

Table 2.1: Summary of antenna structures and their performance parameters-I

Ref. No.	Antenna Structure	Frequency Band (in GHz)	Performance Parameters
[1]	Double bent	1.864	○ Antenna bandwidth: 2.8 times conventional rectangular patch antenna without slots
[2]	Three Pairs of Thin Slot from the sides of Rectangular Patch	12.48 -12.57 and 14.13 - 14.19	○ Bandwidth Achieved: 90 MHz and 60 MHz ○ Reflection Coefficient (s11): -23.83 dB and -14.04 dB ○ Resonant Frequency: 12.545 GHz and 14.151 GHz
[3]	Loaded with Notches and Slits	12.108 - 12.708, 14.138 - 14.657 and 16.450 -16.832	○ Bandwidth: 600 MHz, 520 MHz and 382 MHz ○ Resonance frequency of 12.41 GHz, 14.44 GHz and 16.64 GHz. ○ Reflection Coefficient (s11): -23.60 dB, -21.40 dB, -24.61 dB ○ Gain (dB): 6.626, 7.771, 4.808
[4]	Elliptical patch with Slotted Ground	12.9 - 16.85 and 6.15 - 18.15	○ Return loss (S11): -22.98 dB ○ Resonant frequency: 14.6 GHz ○ Bandwidth: 3.95 GHz and 12.41 GHz ○ VSWR: < 2 and ≤ 2.3. ○ Variation in Gain: Less than 1 dB over the entire frequency range. ○ Proposed antenna: 50mm x 50mm x 3.162mm.
[5]	Inverted L shape slots and aperture coupled feeding	11.5 and 14	○ Gain: 6 dB ○ Front to back ratio: Over 15 dB ○ Reflection Coefficient (s11): -18 dB
[6]	loaded with notches and slit	11.16, 15.64 &17.73	○ Reflection Coefficient (s11): -18.99 dB, -23.026 dB, -18.16 dB ○ Bandwidth: 1 GHz, 930 MHz and 400 MHz
[7]	X- Shaped Patch Antenna	15.104 -15.632, 17.336-17.912 and 18.476-19.280	○ Center Frequency: 15.33 GHz, 17.6 GHz and 18.90 GHz ○ Bandwidth: 538 MHz, 576 MHz and 804 MHz ○ Peak Gain (dBi): 4.80, 6.42 and 3.91
[8]	E- Shaped Patch Antenna	12.4, 13.28 and 14.45	○ Reflection Coefficient (s11): -16, -27.7 and -11.6 ○ Bandwidth (MHz), 235,357 and 200 ○ Gain (dB): 4.7, 3.04 and 0.09 ○ Directivity (dBi): 8.6, 9.5 and 7.4
[9]	Spidron fractal patch	11.44–12.48 and 13.47–14.39	○ Antenna dimensions: 50×50×1.52 mm^3 ○ −10 dB reflection bandwidths: 8.7% and 6.6% ○ Resonant frequency ratio: 1.15. ○ 3 dB axial ratio bandwidths: 2.96 and 1.68%
[10]	Multi-stack micro-strip patch	12.25 -12.75 and 14 - 14.5	○ Bandwidths: 22% and 30.6% ○ VSWR: < 2

Table 2.2: Summery of antenna structures and their performance parameters-II

Ref. No.	Antenna Structure	Frequency Band (in GHz)	Performance Parameters
[11]	SIW Cavity-Backed Patch Antenna	11.7	○ Gain: 7.2 dB ○ beam width (3 dB): 85.5
[12]	U- Shaped Slot	4.9-7, 7.92-11.08 and 11.85-15.94	○ Wide Band: 5 to 16 GHz
[13]	Truncated corner square-ring slot	12.45	○ Axial Ratio: 1.5 ○ Directivity of Array: >13 dB
[14]	Rectangular Patch with internal (built-in) resonator	11.2 to 14.0	○ Bandwidth: 2.8 GHz ○ Average Gain: 4.65± 1 dB ○ Total efficiency: 82.0%
[15]	E- Shaped	12.25 13.4 and 14.5	○ Reflection Coefficient (s11): -17.5 dB, -26 dB and -15.5 dB ○ Bandwidth: 220 MHz, 250 MHz and 150 MHz
[16]	Rectangular Patch	11.86 - 15.58	○ Bandwidth: 3.72 GHz ○ Power Radiated (Watts): 0.00152835 ○ Effective Angle: 1.41639 ○ Directivity (dB): 9.48028 ○ Gain (dB): 8.57825 ○ Maximum intensity 0.00107905
[17]	Defected patch Antenna	15.27-16.5	○ Return Loss: -25 dB ○ Resonant Frequency: 15.8 GHz ○ VSWR: < 1.1 ○ Gain: 4.45 dB ○ Directivity: 5.17 dBi ○ Radiation Efficiency: 84.8%
[18]	Truncated Corner Patch with Circular Slots	10.8–13.2	○ Fractional bandwidth: 8.5 to 19% ○ Peak Gain: 7 dB
[19]	Rectangular Patch	15.88	○ Reflection Coefficient (s11): -30 dB ○ VSWR: near 1 ○ Gain: 5.5 dB
[20]	Radial Line Slotted Antenna	17.5	○ Bandwidth: 700 MHz ○ Return Loss: -43 dB ○ Gain: 15.2 dB
[21]	Bent Slot and Circular Slots	12.2–14.5	○ Bandwidth percentage: 10.2 and 8.2 ○ Frequency Ratio: 1.2 ○ Gain: 4.8- 7.4 dB ○ Radiation Efficiency: 0.68 to 0.72
[22]	Hexagonal Patch with Partial Ground	3.68 – 18.297	○ Bandwidth: 14.617 GHz ○ Size: 15×20 mm^2 ○ VSWR: 1.16 ○ Radiation Efficiency: 82%

A Ku-band cavity-backed patch antenna for the application of broadband was designed by Losito, et al. [11] in 2013. The corner of the rectangular patch has been truncated to achieve the operating bandwidth. Moreover, low-cost implementation, fast prototyping, and precise manufacturing have been achieved using substrate integrated waveguide (SIW) technology. A compact, low-priced and ultra-wideband, and multi-band antenna for satellite and radar applications was proposed by Nagharet al. [12] in 2014. The wideband of 5 to 16 GHz has been achieved by modifying the radiating element and the ground plane. Conversely, the C, X, and Ku bands are achieved by embedding the U-slot in the patch. A truncated corner square-ring slot, multi-layer, two-port, and the circularly polarized antenna has been designed, by Khan et al. [13] in 2014, for Ku-band applications. Moreover, due to the high isolation between the orthogonal ports, the prototype can be used to feed the reflector antenna for satellite application.

Oweis et al. [14] in 2014, proposed antenna covers the wide bandwidth of 2.8 GHz from 11.2 to 14.0 GHz. This is achieved by using a rectangular patch with a built-in resonator mounted on the FR4 substrate. The efficiency and an average gain of about 82% and 4.65± 1 dB at the resonant frequency. An E-shaped prototype was designed for the applications of Ku-band by Malisuwan et al. [15] in 2014. The proposed antenna achieves the three center frequencies of 12.25 GHz, 13.4 GHz, and 14.5 GHz with the help of a microstrip-based Cole-Cole diagram. A high gain Ku-band antenna with wide bandwidth has been proposed by Basra et al. [16] in 2014. To obtain the proper impedance matching, the proposed design is fed with an inset feed. The antenna has achieved a bandwidth of 3.72 GHz (from 11.86-15.58 GHz).

The DGS patch antenna with a compact size of $17 \times 17 \times 1.07$ mm^3 has been designed using FR4 substrate by Bhadouria and Kumar [17] in 2014. This design achieves a band of 15.27 to 16.51 GHz with a gain of 4.45 dB and a VSWR$\leq$ 1.1. A circular slot patch antenna for broadband applications has been designed by Baudha and Kumar [18] in 2015. The corners are truncated in this design. The bandwidth and the gain of 123% and 7 dB are achieved respectively. The compact size antenna for Ku-band applications of dual-band was proposed by Sayed et al. in 2015. The three pairs of thin slits have been used to achieve the characteristics of dual-band. The size of the antenna is very compact i.e., 9.5×10×0.254 mm^3. The values of the Reflection co-efficient (S_{11}) are -23.8 and -14.0 at the center frequency of 12.54 GHz and 14.15 GHz respectively.

The rectangular patch design has been proposed with a center frequency of 15.88 GHz for the satellite application by Ranjan [19] in 2016. The antenna has achieved a gain of 5.5 dBi with the compact size. Moreover, the edge cut feeding has been used for better impedance matching. A compact Radial Line Slot Antennas (RLSAs) with high efficiency and gain for Ku-band satellite application was proposed by Shalaby et al. [20] in 2016. The advantage of the design is low profile, simple design, and compact size.

The low profile, lightweight, and low-cost antenna were designed by Vijayvergiya and Panigrahi in 2016 [21]. The dual-band has been achieved for applications of the Ku-band. Moreover, the radiation pattern of the prototype is broadside. Also, the antenna has less complexity due to its structure of single-layer and single-patch. The receive mode of Fixed Satellite Services (FSS) and Direct Broadcasting Services (DBS) and transmit mode of FSS have been achieved for lower and higher bands respectively. The bandwidth of 10% and 8% has been found for the lower and higher bands respectively. Moreover, the frequency ratio is only 1.2.

A Hexagonal wide band Patch antenna has been proposed by Dhakad and Bhandari [22] in 2017 for the C Band, X Band, and Ku Band Applications. The bandwidth of 504% (3.68-18.297 GHz) has been achieved by the proposed antenna with compactness in size i.e., 15×20 mm^2. An X-shaped fractal antenna with defected ground structure (DGS) has been proposed by Gupta et al. [23] in 2017 for multiband and wideband applications (1-7 GHz). To achieve the multiple bands and wideband with compact size, the DGS technique is used by the proposed antenna, and for better impedance matching and better return loss, the X shaped has been implemented in the design.

The compact antenna with high directivity, efficiency, and wide bandwidth was proposed by Shailendra et al. [24] in 2017. The proposed design has an omnidirectional radiation pattern with stable gain. A corner truncated T- shaped antenna with DGS technique has been proposed for the C band, X band, and Ku band by Ashutosh [25] in 2017. The bandwidth of 12.69 GHz has been achieved by the design. A low-profile dual cavity antenna with high gain and efficiency has been reported for wideband applications in 2017 by YavuzAsci et al. [26]. The gain of 11.3 dBi and 12.4 dBi are achieved for the downlink and uplink frequency band respectively. Moreover, the efficiency of 65% is achieved throughout the frequency range (10-15 GHz).

A Simple and compact size antenna for the application of dual-band was proposed by Mao et al. [27] in 2018. The size of the antenna is only 14mm. This compact size has been achieved by folding the radiating element and restructuring the ground plane. The antenna has been used for two bands i.e., 34-3.6 GHz and 5.725-5.825 GHz. Moreover, the radiation pattern of the antenna is nearly omnidirectional. A miniaturized, wideband fractal antenna based on the hexagonal-triangular shape has been designed by Darimireddy and Prasad [28] in 2018. The proposed antenna covers a frequency range of 3–25.2 GHz which includes the Ku band of 12-18 GHz. The gain of the antenna varies from 3-9.8 dBi. The circularly polarized antenna using substrate integrated waveguide (SIW) cavity has been designed for the Ku-band satellite wireless applications. To achieve the left-hand CP radiation, the two different and orthogonal TE202 modes have been used. Moreover, two higher-order modes are deeply analyzed. The axial ratio (AR) bandwidth and impedance bandwidth of 1.6% and 4.2% are achieved respectively. Also, the peak gain of 7 dBi is achieved over the frequency of operation.

2.2 Array antennas for Ku band

Hyok et al. [29] proposed a Ku-band of 16x16 element array with dog-bone –aperture has been proposed in 1998. In this paper, the modular approach has been used to design the 16 x 16 element array for a resonant frequency of 12.5 GHz. The benefit of this modular approach is to evaluate the input impedance of the antenna array in a better way. The proposed antenna has attained good results with a gain of approx. -28 dB at a resonant frequency of 12.5 GHz.

A Ku-Band planar wideband antenna array with circular polarization has been designed in 1999 by Filipovic [30]. The bowtie antennas are used to design the array and fed by the corporate feed divider network. To give one-sided radiation, the dielectric substrate is coated with a metalized ground plane. This metalized layer is used to convert the linear to circular polarization. The antenna achieved an axial ratio of about 21%.

Table 2.3: Summary of array antenna structures and their performance parameters

Ref No	Antenna Structure	Frequency Band (in GHz)	Performance Parameters
[29]	16 x 16 Planar Array with Aperture Coupled Micro Strip-Patch Elements	12.5	○Gain: 28 dB ○Directivity: 31.8 dBi
[30]	Array of bow-tie antennas	11.5 and 14.25	○Gain(dBi): 15.90 and 19.32 ○Axial Ratio: 1.96 and 3.97
[31]	Array antenna Consists of one radiating patch and two parasitic patches	11.7-12.75 GHz and 14.0-14.5 GHz	○Gain: 10- 11 dBi
[32]	Airborne Ku-band phased array antenna system	10.7 to 12.75 GHz	○Return Loss (S11): < 10 dB ○Gain: 8 dBi
[33]	Spidron fractal slot array	10 to 15 GHz	○3 dB AR bandwidth: 10-15 GHz ○10 dB reflection bandwidth: 10-15 GHz ○Maximum Array Gain: 15.63 dB at 12.6 GHz
[34]	Parasitic array antenna using U Shaped patches	5.8 GHz to 18 GHz	○Bandwidth :12.2GHz ○Achieved gain :4 dBi to 11.8 dBi
[35]	Slotted Rectangular Patch	12.2 GHz and 13.1 GHz	○Gain: 12 dBi
[36]	CP antenna array	1.55 to 12.25 GHz	○Radiating elements: 16 X 16 ○Realized Gain (dBic): 26.4 ○Peak Radiation: 65%
[37]	17×17 Unit-Cells Transmit array	12 GHz and 17.5 GHz	○Peak gains 25.31 dBi and 27.1 dBi
[38]	Aperiodic transmit array units	12 GHz-18 GHz	○Peak Gain: 23.06 dBi ○Aperture efficiency: 42.3%
[39]	Conical-beam traveling-wave array antenna based on a slotted circular waveguide	12 GHz-18 GHz	○ -10 dB impedance bandwidth higher than 23% ○High-gain values :13.5 dB ○Total efficiency higher than 98%
[40]	Phased-array receive tile with 256 elements	10.6–12.5 GHz	○Axial ratio (AR) is 0.5 dB
[41]	MIMO antenna with 15 transmitting and 16 receiving antenna arrays	17.1 GHz	○Gain: 14.3 dBi ○Bandwidth: 300 MHz

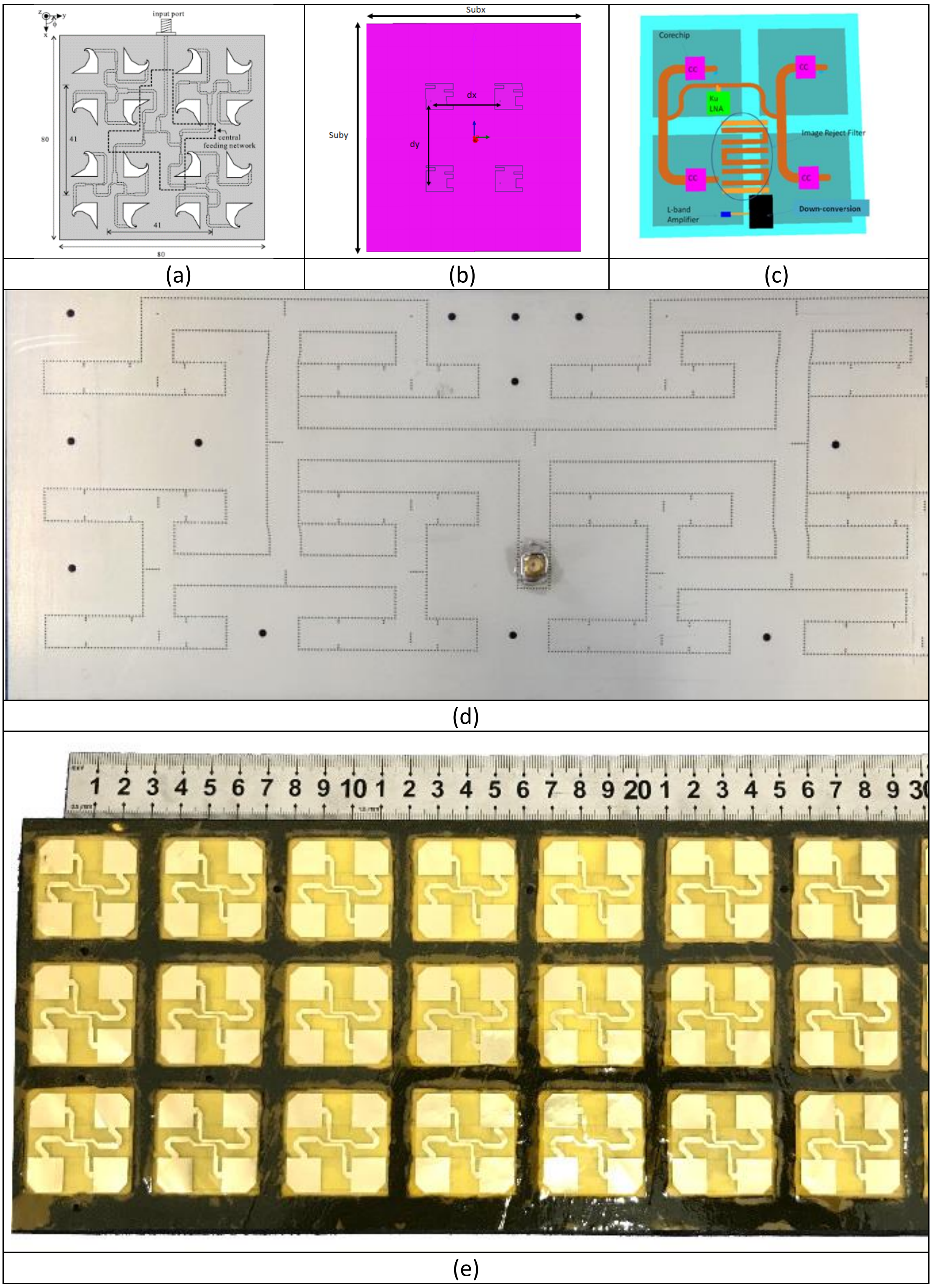
A high gain, wideband 1×8 array design for dual Ku-Band has been designed by HoengSook et al. [31] in 2004. The transmitting band of the antenna has horizontal polarization and on the other hand, for receiving band the antenna array achieves the vertical polarization. For the good impedance bandwidth and gain characteristics, the array comprises two parasitic patches and one radiating patch. Whereas, for bi-directional communication, Tx/Rx feed circuits have been used. The array of 1×8 has a gain of 18.l dBi at a frequency of 11.7-12.75 GHz and 14.0-14.5 GHz. Some of the popular geometries for array antennas proposed in the literature for Ku band are shown in Fig. 2.2. The detailed summary of array antennas for Ku band applications and their performance parameters is presented in Table 2.3.

An electronically steered phased array design was proposed for the Ku-band applications by Verpoorte et al. [32] in 2011. The array of the antenna comprises 1800 elements for the front end. This is used to steer the beam continuously around the geostationary satellites. The true-time delays with optical ring resonators are used to steer the sub-apertures of the proposed antenna. A high-efficiency Reflect Array (RA) antenna with a single layer has been proposed for a wide range of Ku-band applications. By adjusting the parameters of double square loops and an inner square patch, the element of the reflecting array has been considered. The wideband RA consist of the following approaches:

- Sub-wavelength spacing
- Multi-resonance structures on an electrically thick layer
- Multi-type elements
- Dual-frequency phase synthesis

The above approaches are used to attain high-efficiency wideband performance. The aperture efficiency of 60% has been achieved for the frequency range of 12.0–14.9 GHz.

A circularly polarized 4×4 array antenna was proposed for the applications of the Ku-band in 2013 by Trinh-Van et al. [33]. A single element of spidroin fractal slot is used to achieve the circular polarization radiations and also sequential feeding network was used with 4×4 array antenna to enhance the bandwidth of the antenna. The antenna array has attained the 3 dB axial ratio for a range of frequencies i.e., 10-15 GHz. Moreover, the gain of array at 12.6 GHz is 15.63 dB.



(a) (b) (c)

(d)

(e)

Fig. 2.2: Popular array antenna geometries proposed in literature for Ku band

An out of phase inductance geometry-based approach to the parasitic array antenna has been designed for multiple bands (C, X, Ku band) by Khare and Nema [34] in 2014.

Moreover, the gain and impedance bandwidth of 11.8 dBi and 102% have been achieved respectively.

A 2×2 array antenna was proposed by Kouhalvandi and Yagci [35] in 2015. In the design, the three slits are used in the patch for the satellite application. The frequency range of 12.2 GHz-13.1 GHz has been achieved with a gain of 12 dBi. A low profile antenna array with high efficiency and circular polarization has been designed for Ku-band satellite antenna in 2017 by Huang et al. [36]. Without occupying the additional area, the operating bandwidth of the antenna has been enhanced by the novel and compact sequential rotation (SQR) feeding technique. Moreover, to decrease the weight of the antenna (only 66.5 grams), a thin layer of Polyimide film backed by a piece of supporting foam was used. The gain and bandwidth of the antenna are 26.4 dBic and 700 MHz (11.55 to 12.25 GHz) respectively.

A transmitarray of broadband gain with a hybrid approach has been presented for the applications X and Ku band by Shalaby et al. [37] in 2017. In this paper, a dielectric block with four identical holes in the center of each quadrant is used to compose the elements of transmitarray. In addition to this, a circular hole is drilled to manage the frequency of the design. The gain of the design is 25.31 dBi and 27.1 dBi at the frequency of 12 GHz and 17.5 GHz respectively.

A reflect array using frequency selective surface (FSS) has been designed for dual-band and dual-polarized Ku/Ka-band satellite applications. The downlink and uplink frequency of 20 GHz and 30 GHz are achieved by the single-layer reflect array simultaneously. Moreover, the FSS band of 12 GHz is achieved using FSS. The gain of the reflectarray is 28.5 dBi at 20 GHz and 32.25 dBi at 30 GHz.

A Ku-band low profile transmitarray antenna (TA) for wideband application i.e., 12-18 GHz, has been proposed by the Mei-Yu et al. in 2020. To decrease the backward radiation of the transmitarray the three layers of aperiodic transmitarray units are placed periodically to design the transmitarray antenna. Moreover, the structure of TA is symmetrical. The TA has a gain, gain bandwidth, the backward radiation level is 23.06 dBi, 1 dB, and < -15 dB respectively [38].

A Ku-band conical-beam traveling-wave array antenna using a slotted circular waveguide with high gain has been proposed. A ring of eight equally spaced slots fed by a circular waveguide is used to form a single radiating element of the antenna. Each slot is fed by a uniform field. This generates an omnidirectional radiation pattern. The 48 rings of slots are used to design the array antenna. Each ring is appropriately designed to obtain the uniform power distribution and further maximum directivity antenna array has been achieved. Moreover, for improved input matching and mitigate the grating lobe appearance, generating high-gain conical-beam radiation, the distance between the elements has been adjusted. This makes the antenna suitable for satellite and 5G communication. Also, the 3-D printing and spray metallization process is used to fabricate the antenna. The efficiency, gain, and impedance bandwidth of 98%, 35.5 dB, and 23% are achieved. A corrugated conical horn antenna was designed for the applications of Ku-band. This design achieves the gain of 12-28 dB for the band of 12-18 GHz and VSWR value is less than 1.5 for the range of 1-23 GHz [39].

A 256 element transmit phased array antenna with dual polarization was proposed for the applications of Ku-band. This design having the advantage of a lightweight and ultralow profile which makes the antenna suitable for SATCOM terminals. The array achieves the almost ideal pattern in both E and H planes. The axial ratio (AR) is less than 1.1 is achieved between the frequency range of 14-14.5 GHz. Moreover for QPSK, 8-PSK, and 16-PSK waveform, the error vector magnitude (EVM) of 2.8%–3.5% is found. [40]

A wideband MIMO antenna with a low sidelobe level has been designed by the et al. [41] in 2021. This is made up of an array of 15 transmitting and 16 receiving antenna element (which is arranged in two parallel straight lines). The spacing between the transmitting and receiving elements are λ and 4λ respectively. To reduce the level of SLL (low sidelobe level) and to obtain a broad bandwidth, a traveling wave feeding with center excitation has been used. The advantage of the design satisfies the requirement of GB-SAR (Ground-based synthetic aperture radar).

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Chapter 3

Dual-Band Patch Antenna for Ku-Band Satellite Applications

Since the inception of radio communication, the demand for small-sized antennas with versatile characteristics is aspiring the academic as well as industrial fraternities. Researchers around the world are working on designing multiband patch antennas for the applications of the satellite. Due to its low cost, compact size, low power consumption, readiness for mass production using VLSI technology, availability of integration with other electronic circuitry on the same chip, patch antennas have become popular candidates for satellite-based communication systems [1-2].

For satellite applications, the ITU splits the world into three regions for efficient organization of spectrum. In region 3, the allotted frequency band for fixed-satellite service (FSS) in receive mode and transmit mode is 12.2–12.7 GHz and 14–14.5 GHz, respectively. Whereas, the allotted frequency band for direct broadcast service (DBS) in receive mode and transmit mode is 11.7–12.2 GHz and 17.3–17.8 GHz, respectively. The proposed design meets the spectrum necessity of region 3 for FSS and DBS in receive mode and FSS in transmit mode.

3.1 Related works

In the recent past, several dual/wideband designs have been reported in the Refs. [1-3]. Similarly, many patch designs have been investigated for Ku-band, such as rectangular patch with edge side cut feeding technique [4], slotted patch antenna using coaxial feed [5-8], transmit array [9-10], Patch antenna of E-shape [11], fractal patch antenna with microstrip feed [12], multi-layer ring slot antenna [13],multi-layer microstrip patch array antenna [14-17], proximity-coupled patch antenna array [18-19], aperture coupled planar array antenna [20-21], cross-type antenna array [22], parasitic microstrip patch antenna with multiple layers [23], antenna array with waveguide and hybrid microstrip feed [24], slot antenna with microstrip feed [25-27], stacked microstrip antenna [28-29], dual cavity antenna [30], microstrip patch antenna with orthogonal feed [31], defected ground structure slot antenna [32], Substrate integrated array antenna [33], a polygonal antenna with circular slot and coaxial feed [34] and cross shape patch antenna with microstrip feed [35].

Most of the designs for satellite communication applications as discussed above are either aperture coupled or multi microstrip patch or multi-layered or proximity coupled. Due to the alignment issues and an air gap between the layers, these antennas are very difficult to realize. Also, these kinds of antennas are having more height and weight than the single patch and single-layer antenna. Moreover, the co-axial feed has been used in some of the designs which are not appropriate for ICs environment and conformal surface antenna.

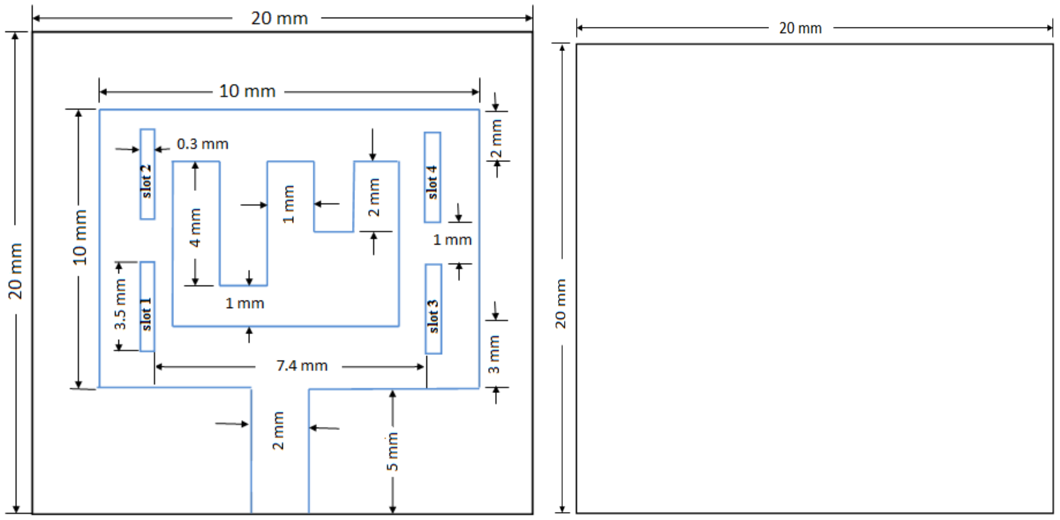
Keeping all these constraints in mind, we propose a low profile, small size, and lightweight antenna to meet the necessity of a region -3 (ITU) for dual-band function completely (receive mode for FSS and DBS services and transmit mode for FSS service). These requirements have not been covered by any of the above-discussed antennas. Furthermore, the design of the proposed design is less complex and simple to integrate and realize.

This chapter is prepared as follows: Introduction and the literature review are described in Section 3.1. The detail of the design is presented in Section 3.2. The parametric analysis of the design is given in Section 3.3. The result and discussion are explained in Section 3.4. Finally, the proposed work is concluded in Section 3.5.

3.2 Proposed antenna design

Usually the bandwidth of a single patch, a single layer is very less. In [38], the antenna achieves the bandwidth of 10% and 8% for the first and second band with the help of the circular slot along with the rectangular slot and the microstrip line. But in the proposed design, the impedance bandwidth of 12.29% and 9.37% are achieved for the first and second band, respectively. Moreover, the resonant frequency ratio is less than the above antenna which is useful in the implementation of an antenna for satellite application. A modified method is used to improve the bandwidth of the design. In the modified method, the nearly symmetric E-shaped slot and rectangular slots are used to achieve the greater impedance bandwidth and less resonant frequency ratio.

In this work, the FR4 substrate has been used to design the antenna having a 1.6 mm of thickness, and the design is simulated by Ansoft HFSS software. The dimensions of the design are given in Table 3.1. The design dimension and the fabricated antenna are presented in Fig. 3.1 and Fig. 3.2, respectively. There is a total of five slots used in the proposed design, out of which one slot is an E-shape and all others are rectangular.



(a) (b)

Fig. 3.1: The design of proposed antenna (a) Front view and (b) back view

To achieve the high accuracy of the antenna, a symmetrical radiation pattern is a key parameter. For this purpose, the configuration of the antenna must be symmetrical. Therefore, in the proposed antenna, an almost symmetrical configuration/slot has been adopted. Figure 3.3 (a) and 3.3 (b) show the current distribution of the design at a band of 12.38 GHz and 14.40 GHz, respectively. The arrow sign is used to indicate the direction of the current. However, the current distribution seems to be almost regular at the different parts of the antenna.

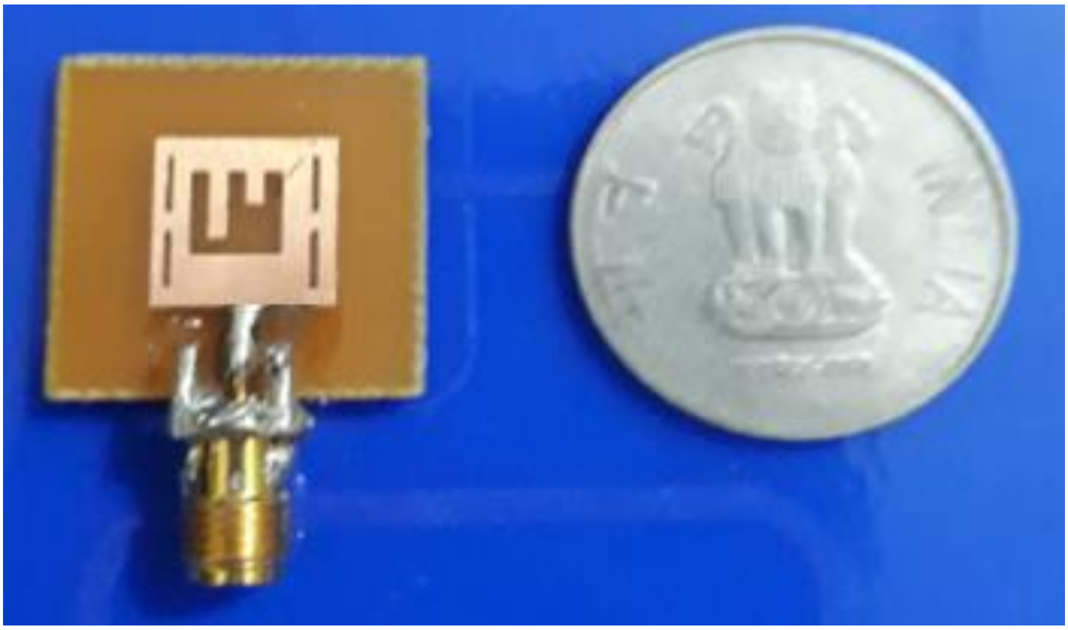


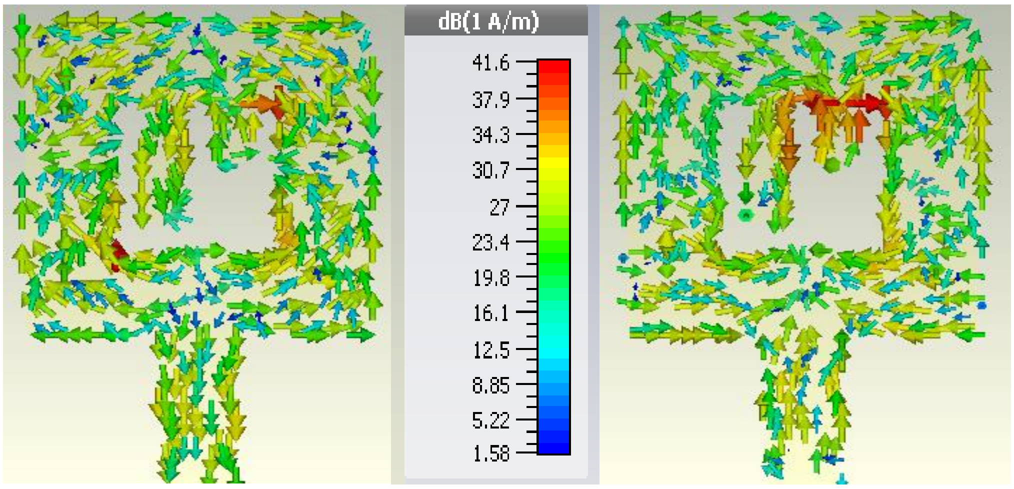
Fig. 3.2: Fabricated antenna of size 20×20 mm^2

Table 3.1: Dimensions of the proposed design

S.No	**Design Parameters**	**Dimensions**
1.	Substarte’s length and width	20×20 mm^2
2.	Patch’s Length and width	10×10 mm^2
3.	Length of slot1, slot2, slot 3 and slot4	3.5 mm
4	Width of slot1, slot2, slot 3 and slot4	0.3 mm
5.	Length and width of E-slot	5×5 mm^2
6.	Length and width of feedline	5×2 mm^2

3.3 Parametric analysis

Initially, the design parameters of the proposed antenna are determined from the design equations of the rectangular patch antenna [38]. Then the symmetric E-slot is made on the rectangular patch of the proposed antenna which generates the two bands of resonant frequency i.e., 13.20 GHz and 15.60 GHz and subsequently, one arm of E-slot is truncated by 2 mm for fine-tuning of these resonant frequencies to achieve the ITU’s bands as shown in Fig. 4. For finer tuning of the antenna, slot 1 and slot 2 are introduced into the patch, and then slot 3 and slot 4 are introduced for bandwidth and S_{11} enhancement of the design.



(a) **(b)**

Fig. 3.3: Current distribution of the design at (a) 12.38 GHz and (b) 14.40 GHz

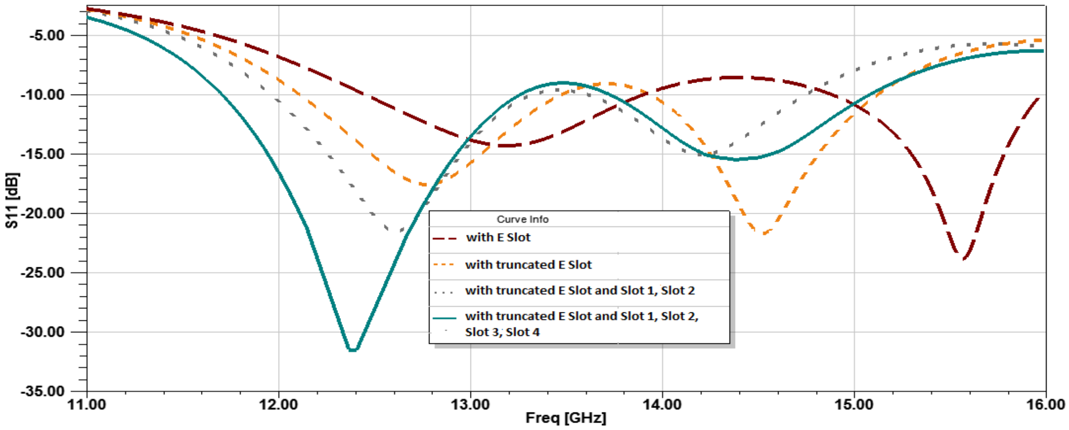


Fig. 3.4: Parametric analysis of the antenna with different slots

3.4 Results and Discussion

All of the aforesaid parameters have a notable effect on the performance of the antenna. For this design, Ansoft HFSS has been used to optimize the antenna parameters in terms of reflection coefficient, operation bandwidth, and gain and radiation pattern. The parameters of the structure are decided by changing the dimension of one slot at a time and fixing the others. In this chapter, we discussed that how the slot's dimension impact the various parameters of the antenna.

3.4.1 S_{11} Parameters of the proposed antenna

The plot of the simulated and measured reflection coefficient (S_{11}) of the design with optimized parameters is shown in Fig. 3.5. The simulated values of reflection co-efficient and bandwidth, (as shown in Fig. 3.4), are obtained by optimization of the antenna's dimension and the frequency ranges of 11.69-13.24 GHz and 13.72- 15.07 GHz are obtained for first and second band respectively. Conversely, the measured frequency ranges for the first and second band are 11.64-12.81 GHz and 13.78-14.57 GHz, respectively. The measured and simulated results are good with each other except for a small change in the resonant frequency due to various reasons such as the tolerance in the value of dielectric constant, fabrication losses, connector losses, etc.

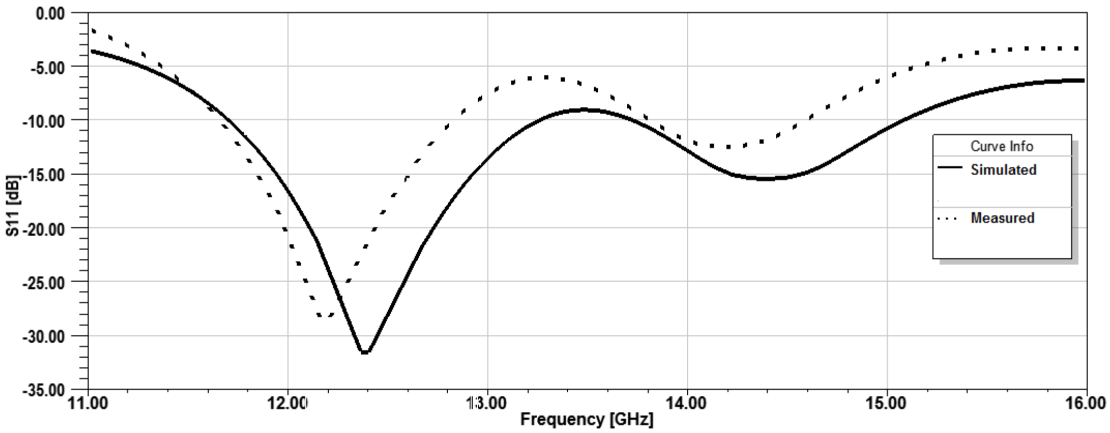


Fig. 3.5 Simulated and measured S_{11} of the proposed design

3.4.2 Gain and radiation pattern of the proposed antenna

Fig. 3.6 shows the measuring setup of the gain and radiation pattern of the proposed design. Whereas the left-hand side and right-hand side of Fig. 3.7 illustrates the simulated and measured radiation pattern of the E-plane and H-plane at a frequency band of 12.38 GHz and 14.40 GHz, respectively, which has been performed in an anechoic chamber of the antenna laboratory of BanasthaliVidyapith University (Rajasthan, India). It has been noticed from Fig. 7 that the broadside radiation patterns are achieved by the proposed design at a frequency of 12.38 GHz and 14.40 GHz, respectively. Due to manual alignment, cable and connector losses, and higher mode excitation, a small difference is observed between simulated and measured radiation patterns of E and H-plane. Furthermore, for more efficient radiation, a low-dielectric-loss substrate can be used.

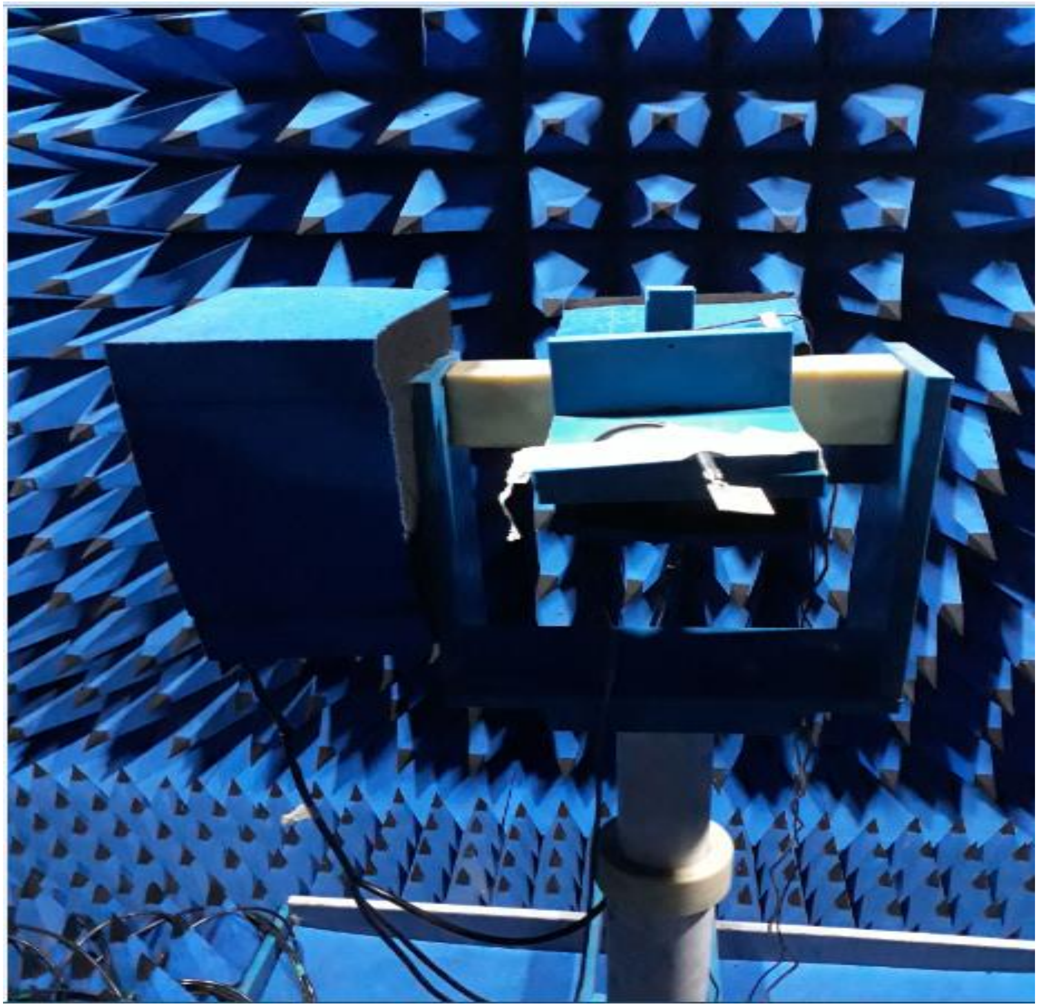
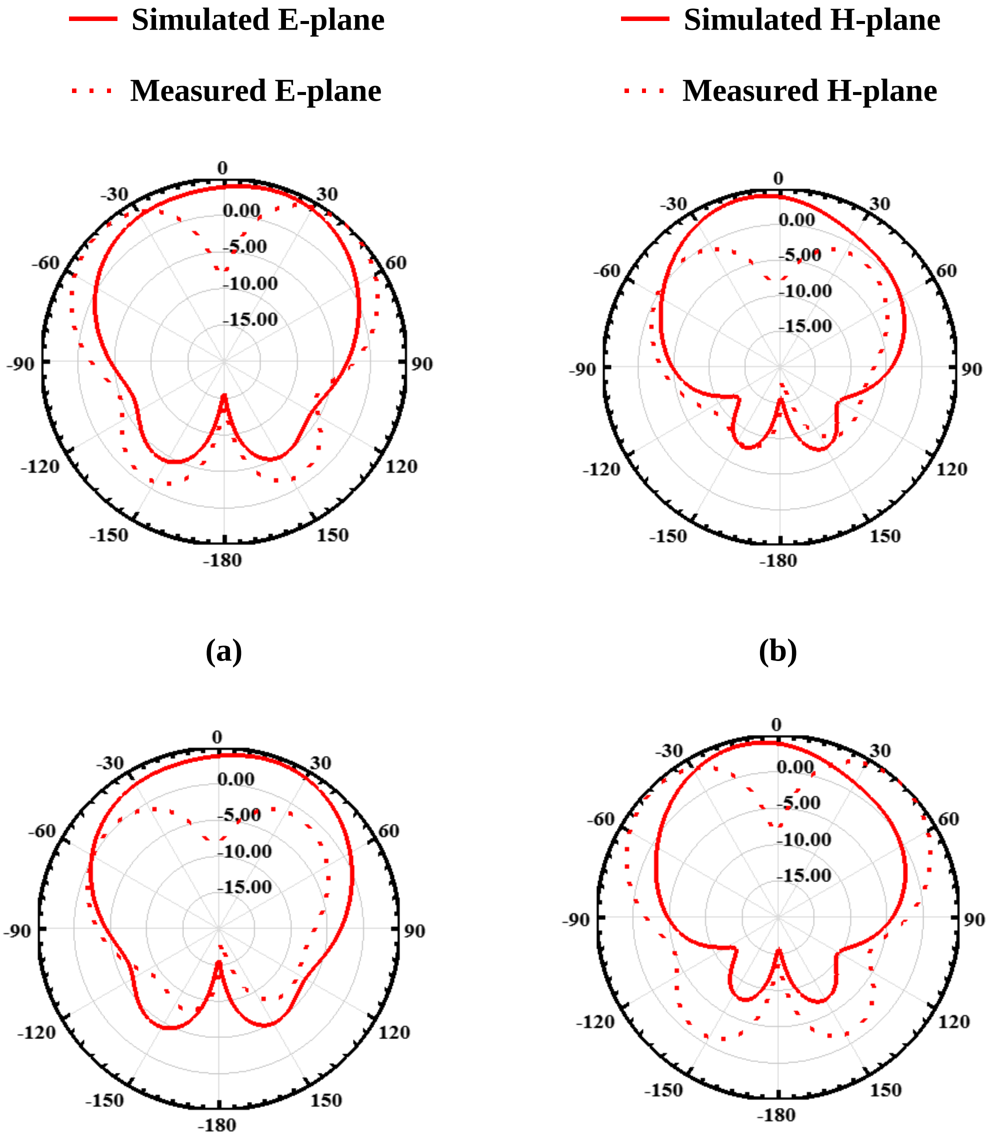


Fig. 3.6: Setup of measuring gain and radiation pattern of the proposed antenna

Fig. 3.8 presents the gain analysis of design with different slots and it can be noticed from the fig.8 that the gain with truncated E slot and slot 1, slot 2, slot 3, and slot 4 is more than the other cases (Which is mentioned in curve info of Fig.8). Whereas Fig. 3.9 illustrates the gain v/s. frequency plot and it is noticed that the simulated gain of the design varies from 1.84 to 4.38 dBi. Moreover, the Vector Network Analyzer (VNA) has been recalibrated each time separately to enhance the accuracy agreement between the simulated and measured gain.



(a) (b)

(c) (d)

Fig. 3.7: Simulated and Measured radiation pattern of E and H-plane (a) at 12.38 GHz (b) 12.38 GHz (c) 14.40 GHz (d) 14.40 GHz

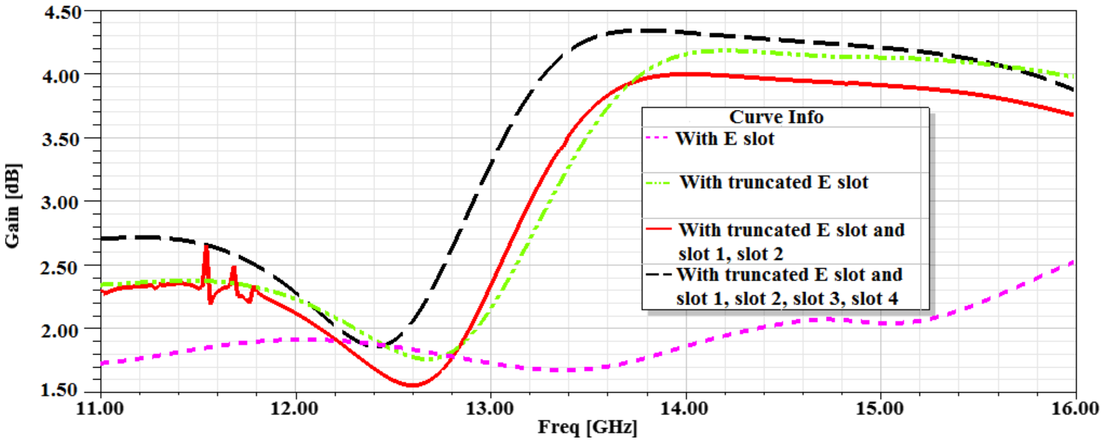


Fig. 3.8: Gain analysis of the antenna with different slots

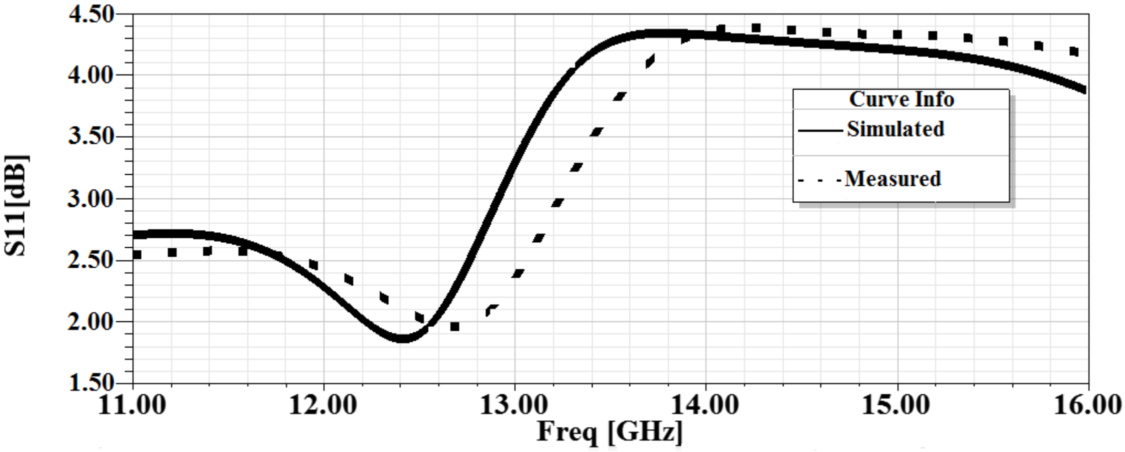


Fig. 3.9: Gain of the proposed antenna

3.4.3 Comparison of the proposed antenna with reference antennas

Table 3.2 gives the comparison of reference antennas with the proposed design and it is seen that the bandwidth percentage of the proposed design is more than all the references used in Table 2. Moreover, the resonant frequency ratio, gain, efficiency are acceptable for the application of the proposed antenna with the compactness in design.

Table 3.2: List of the comparison of various studies with proposed antenna for the same application

Refs.	**Resonant frequency of lower band (GHz)**	**Resonant frequency of Upper band (GHz)**	**Frequency ratio of resonant frequency**	**Lower band band width in %**	**Upper band bandwidth in %**	**Size of the patch in mm^2**	**Gain (dBi)**	**Efficiency**
Parikh et al. (2012)	11.95	14.25	1.19	4.2	3.6	9.4×7.1	5.7-7.2	----
Thi et al. (2013)	11.96	13.93	1.16	8.7	6.6	50×50	3.7-3.8	----
Sayed et al. (2015)	12.72	14.4	1.13	5.3	6.9	5.7×8	5-5.5	----
Samsuzzaman et al. (2013)	15.33	17.61	1.14	3.4	3.3	9.5×8	4.8-6.4	----
Vijayvergiya and Panigrahi (2017)	12.07	14.44	1.19	10.2	8.2	10.13×9.9	4.8-7.4	0.68-0.78
Proposed	**12.38**	**14.40**	**1.16**	**12.29**	**9.37**	**10×10**	**1.6-4.2**	**0.69-0.80**

3.5 Conclusions

The single layer and single patch antenna have been designed with a microstrip feed line for Ku band satellite applications. The antenna is designed for dual-band operation with wide bandwidth. The first band covers the receive mode of FSS and DSS services; whereas the second band covers the transmit mode of FSS service (ITU region-3). In addition, the design achieved an axial ratio of 160 MHz. Moreover, the proposed antenna is the first candidate in this field which is having a small resonant frequency ratio and wide bandwidth which fulfil the requirement of ITU region 3.

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CHAPTER 4

COMPACT TRI-BAND PATCHANTENNA FOR KU BAND APPLICATIONS

With the developments in satellite technology, the use of satellite antennas in various applications like cellular communication, weather forecasting, TV broadcasting, navigation, monitoring, and surveillance, etc. has exponentially increased. At earth station, generally, a bulky and large parabolic reflector antenna is used for this task. Such an antenna is not desirable due to space and environmental constraints. Also, the radio is not static in one position in most satellite applications. Therefore, a low-profile patch antenna is utilized for multi-band performance, miniature dimensions, robustness against interference, and cheap fabrication budget [1].

Conventionally, the antennas used in such applications were single-band antennas i.e. operating at a single frequency. But, due to the proliferation in several possible applications originating in a single system and space constraints, multiband antennas have become a strong candidate for present and future Ku-band satellite communication systems [2]. In the literature, many antennas have been proposed to fulfill the requirement of multiband applications [1-3]. A lot of patch antennas have been designed for Ku-band satellite applications such as dual-band antenna with single-layer and single-patch for Ku-band satellite application, low profile patch antenna, and loaded slot patch antenna for applications in Ku-band [4-10].

4.1 Related Works

Researchers around the world have worked on the design, fabrication, and optimization of antennas for FSS and DBS according to ITU norms. In [11], a dual-band antenna with 3.4-3.6 GHz and 5.725-5.825 GHz for 5G and 5.8G Wi-Fi are achieved respectively. A Spidron-Fractal antenna operating in the Ku band of 11.44-12.48 GHz and 13.47-14.39 GHz is proposed by Nguyen et al. in [12]. In [13], a triple-band parasitic array antenna has been designed to optimize the total inductance of geometry for achieving C, X, and Ku bands. Mathew et al. [14] presented a tri-band antenna using a circular disc sector for UMTS, WiMAX, and ISM band applications.

In [15], an X-shaped patch antenna containing five rectangular slots is presented. The design is proposed for frequency ranges of 15.104-15.632 GHz, 17.336-17.912 GHz, and 18.476-19.280 GHz. Naghar et al. in [16] have proposed an antenna for C (4.9-7 GHz), X (7.92-11.08 GHz), and Ku (11.85-15.94 GHz) bands. This design comprises a modified rectangular element with U-shaped slots along with the deformed ground plane. In [17], the authors proposed a C, X, and Ku band hexagonal patch microstrip antenna using FR4 substrate. Partial ground planes along with unsymmetrical slots are used in the design.

In [18], a defected patch and ground-based antenna are proposed for 15.27-16.51 GHz. A defected ground structure (DGS) based fractal antenna design is studied in [19]. The frequency range of operation is given to be 1-7 GHz. In [21], a three-dimensional meandering probes-based antenna is proposed for the Ku band. The technology of a multilayer printed circuit board is utilized in [21]. Deng et al. [22] proposed a reflectarray (RA) type antenna for Ku band applications. An aperture efficiency of 60% is measured for the frequency bands of 12.0-14.9 GHz.

Huang et al. [23] proposed a planar patch antenna array having circular polarization. The proposed antenna is claimed to have a bandwidth of 700 MHz from 11.55 to 12.25 GHz (Ku band). In [24], a 25×30 mm^2 hexagonal-triangular fractal antenna is designed for 3–25.2 GHz. Using this design, a gain of 3-9.8 dBi has been achieved [24]. The Ku band for FSS transmission and reception as well as DBS reception is achieved for region 3 by [4]. The authors in [4] claim that the dual-band with impedance bandwidth of 10% and 8% are achieved for the lower band and the upper band respectively. Recently, in [7], the bands 11.69–13.24 GHz and 13.72–15.07 GHz are achieved by a patch antenna.

To summarize, only a few antenna designs are proposed for FSS and DBS to achieve both transmission and reception completely. Moreover, most of the designs for this purpose utilize multi-patch, multi-layered, aperture coupled, or proximity coupled structures. Practical implementation of these structures is very difficult because they face alignment issues and the air gap between layers. Further, the height and weight of these antennas (Multi-layered design with co-axial cable) are more than the patch antenna. This is incompatible to use as a conformal surface antenna. To achieve this target, a tri-band antenna is analyzed which covers the frequency band for both transmission and reception of DBS and FSS in the Ku band and is compact.

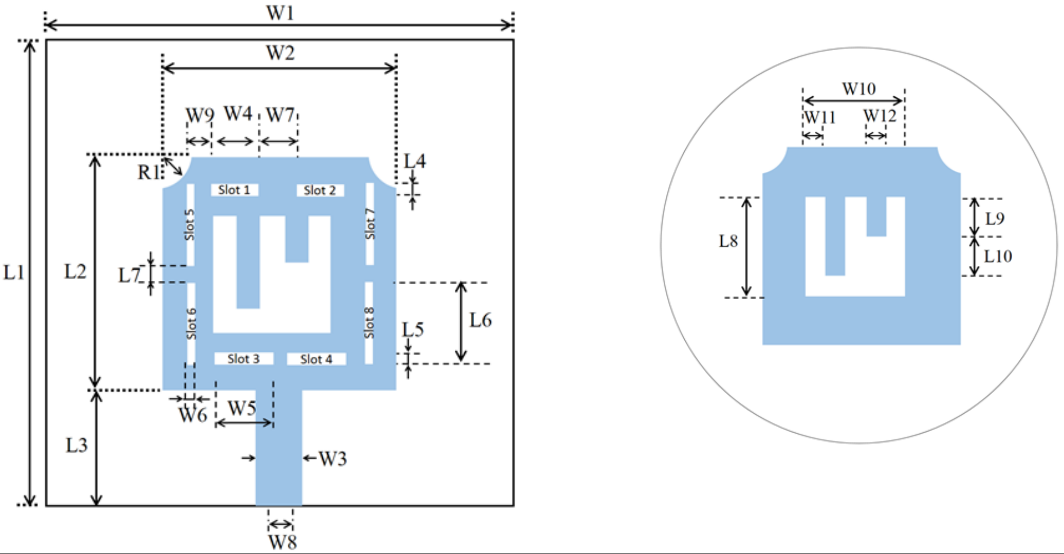
The design consists of truncated E-slots, C-shaped slots, and defected ground structure (DGS) slots. The fabricated antenna results are compared with the simulated results obtained from the proposed design and are found satisfactory for the radiation pattern, impedance bandwidth, polarization, efficiency, gain, and reflection coefficient. Moreover, the proposed design can be used as an element in an array configuration to achieve high gain in both transmission and reception modes of FSS and DBS. This gain can be further enhanced using more refined and costly materials like RT Duroid substrate. The remaining chapter is arranged as follows: the details about the proposed design are described in Section 4.2. Section 4.3 presents the parametric analysis of antenna design. The simulated and measured results with extensive discussions are presented in Section 4.4. Section 4.5 concludes the chapter.

4.2 Proposed antenna design

The geometrical design of the prototype is shown in Fig. 4.1 and Fig. 4.2. Fig. 4.1 (a) shows the front view and the zoomed view of the E slot is shown in Fig. 4.1 (b). Fig. 4.2 presents the back view of the proposed antenna. The description of the dimensions (mm) of the proposed design is listed in Table 4.1. The total dimensions of the proposed design are 20×20 mm^2. The design is constructed with a 1.6 mm thick ($h1$) FR-4 substrate due to its cost-effectiveness. The dielectric loss tangent and relative permittivity of used FR-4 are 0.025 and 4.3 respectively. The software tool used for simulation of the antenna design is Ansoft HFSS.

Patch antenna acts as a resonant cavity therefore multimode are present with different cut-off frequencies. But in the proposed design, the direction of the E-field is towards the y plane. So, the length of the design is selected to transmit $TM_{0\delta}$ along with dominant mode TM_{01}, where the range of δ is from 1 to 3. In this mode, there is a half-wave change along the y-axis while there are no changes along the x-axes. Higher modes above the range of δ are not desirable since they have a higher loss and the field pattern may change over the transmission.

Initially in the proposed design, a truncated E-shaped slot is etched from the patch which gives the frequency bands of 12.08 to 13.20 GHz and 13.96 to 15.05 GHz with a center frequency of 12.65 GHz and 14.5 GHz respectively. For finer tuning, the eight rectangular slots are used to attain the bands of 11.7 GHz to 12.7 GHz and 14 to 14.5 GHz. The patch design is further modified with two C-shaped corner truncated slots to achieve transmit and receive mode of DBS. As a consequence, the third band of 16.93-17.5GHz is achieved by this step. But, this band requires finer tuning as the actual band for DBS transmission is 17.3-17.8 GHz. Therefore, eight DGS slots are used in the design to achieve all the bands of FSS and DBS (transmission and reception) with enhanced bandwidth. Fig. 3 gives the final fabricated antenna.



(a)(b)

Fig. 4.1: Proposed antenna design: (a) Front view and (b) Zoomed view of E slot

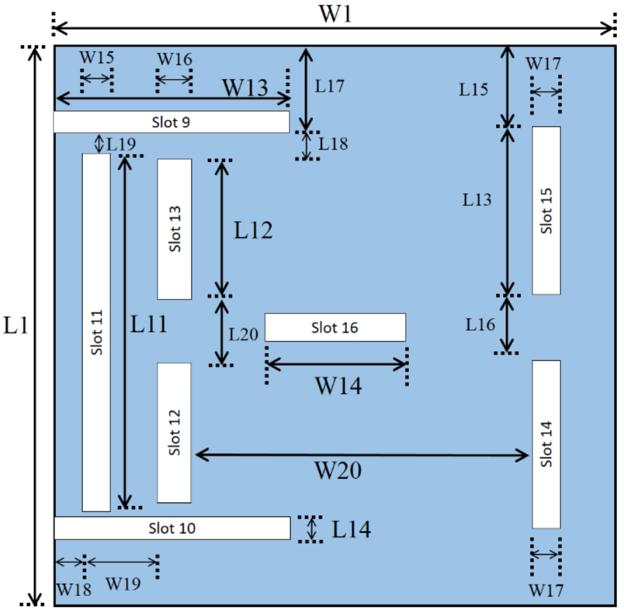
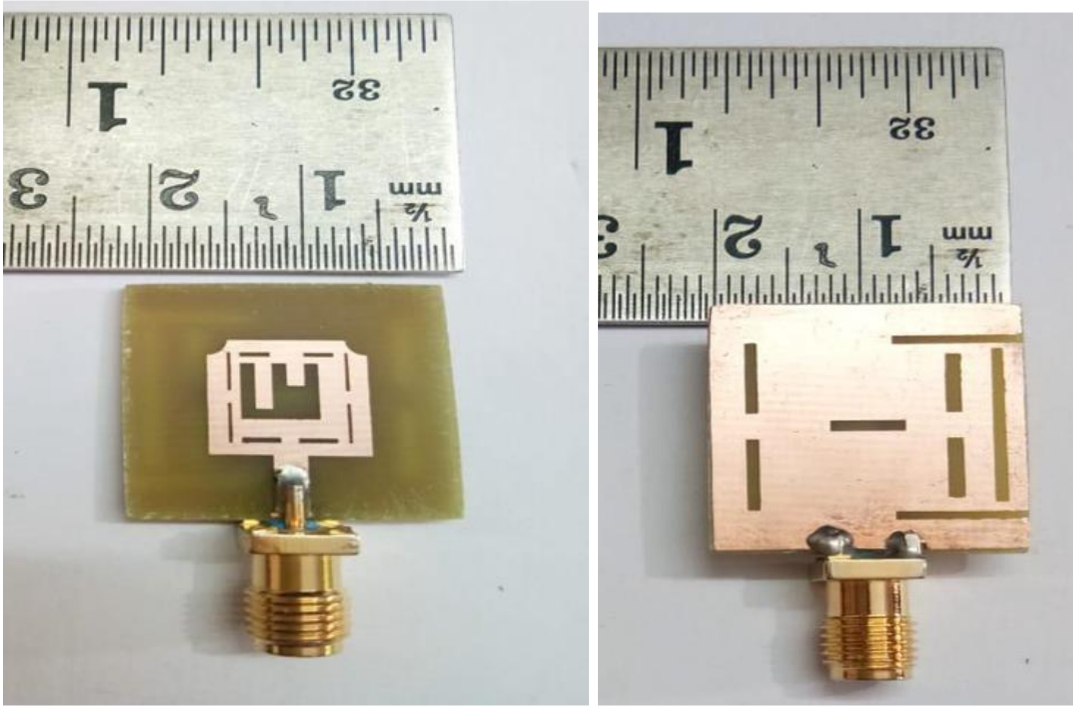


Fig. 4.2: Proposed antenna design: Back view

Table 4.1: Dimensions (in mm) of proposed design

Length	Dimension	Width	Dimension	Length	Dimension	Width	Dimension
L1	20	W1	20	L11	12.8	W12	1
L2	10	W2	10	L12	5	W13	8.4
L3	5	W3	2	L13	6	W14	5
L4	0.5	W4	2	L14	0.8	W15	1
L5	0.5	W5	2.5	L15	3	W16	1.2
L6	3.5	W6	0.3	L16	2	W17	1
L7	1	W7	2	L17	3	W18	1
L8	5	W8	1	L18	1	W19	2.8
L9	2	W9	0.5	L19	0.6	W20	12
L10	2	W10	5	L20	2	H1	1.6
R1	1.3	W11	1				

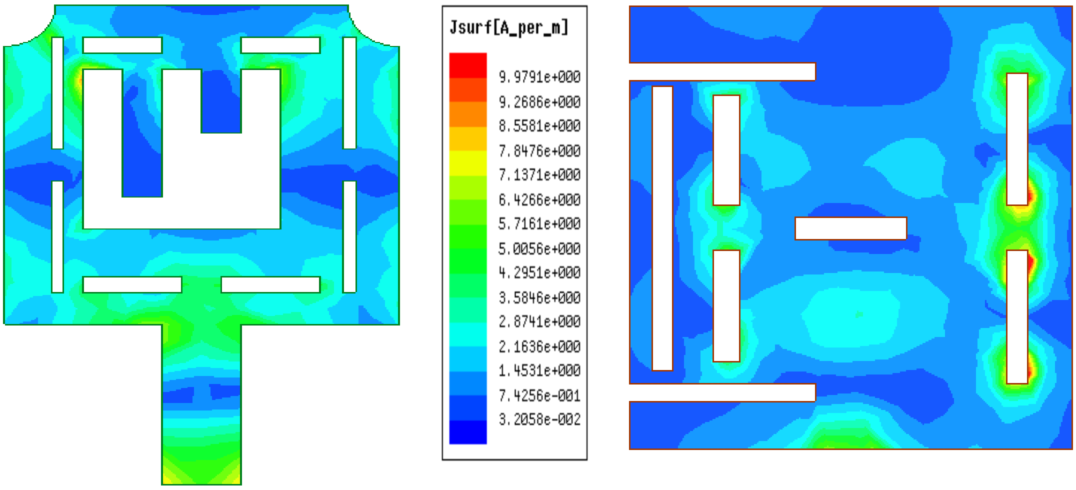


(a) Front view (b) back view

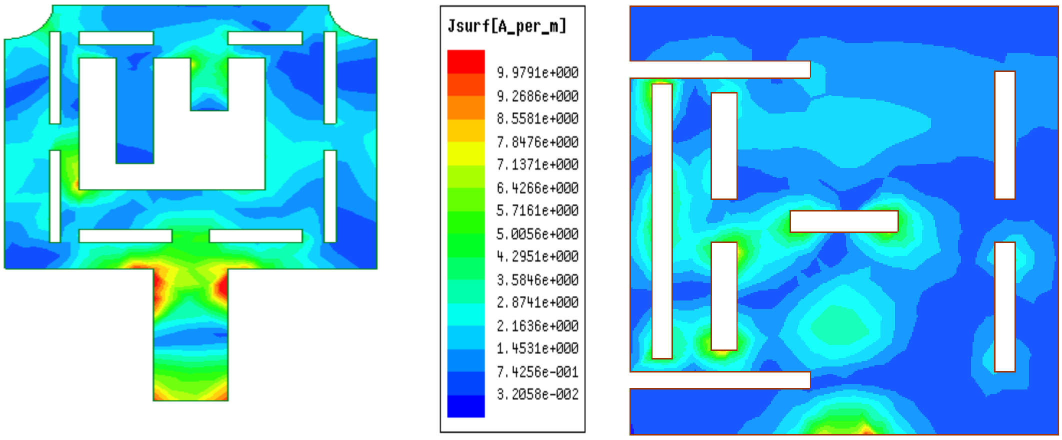
Fig. 4.3: Fabricated antenna (20×20 mm^2)

The simulated surface current distribution of the design can be visualized from Fig. 4.4. Fig. 4.4(a) and 4.4(b) gives the current distribution for 12.25 GHz, whereas, 4.4(c) and 4.4(d) are for 14.16 GHz; 4.4(e) to 4.4(f) are for 17.50 GHz. The rainbow color spectrum shows the intensity of current in ampere/meter. Fig. 4.4(a), 4.4(c), and 4.4(e) show the surface current distribution for the top view of the patch with truncated E-shaped slot, slot 1-8, and truncated corners conversely; the Fig. 4.4 (b), 4.4(d) and 4.4(f) shows the surface current distribution for the ground plane with slots 9 to 16 for clear understanding.

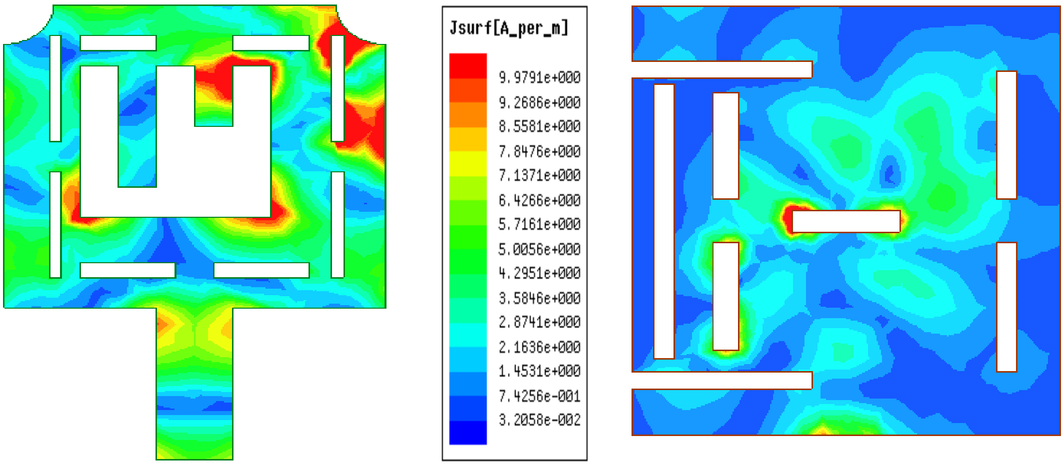
By analyzing Fig 4.4(a) and 4.4(b), it has been noticed that the first center frequency of 12.25 GHz is mainly due to the current concentration on the upper part of the E-shaped slot, slot 3 to slot 5, slot 12 to slot 15. Whereas from Fig. 4.4(c) and 4.4(d), it has been noticed that the resonant frequencies of 14.16 GHz is mainly due to the current concentration on the lower part of E-slot, left corner of the patch, slot 3, slot 4, slot 11, slot 12 and slot 16. Further, the current concentration on the E-slot, slot 7, slot 12, and slot 16, Fig. 4.4(e) and 4.4(f) are responsible for 17.50 GHz.



(a) Front view (b) Back view



(c) Front view (d) Back view



(e) Front view (f) Back view

Fig. 4: Distribution of current across the proposed design at (a), (b) 12.25 GHz, (c), (d) 14.16 GHz, and (e), (f) 17.50 GHz

4.3 Parametric analysis

The following general equations have been utilized to compute the preliminary measurements of the design. The proposed design starts with operating frequencyf_1, required permittivity ε_r, substrate thickness h_1. Based on the transmission line model, the length $L_1$and width $W_1$of the patch is calculated as [25-27]:

$$\Delta L = 0.412 \frac{(\varepsilon_{reff}+0.3)\left(\frac{W1}{h1}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W1}{h1}+0.8\right)} h_1 \tag{1}$$

The effective length of the patch becomes

$$L_1 = L_{eff} - 2\Delta L \tag{2}$$

The effective length (L_{eff}), for resonant frequency (f_1), is given as

$$L_{eff} = \frac{c}{2f_1\sqrt{\varepsilon_{reff}}} \tag{3}$$

and

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h_1}{W_1}\right]^{-\frac{1}{2}} \tag{4}$$

The center frequency corresponds to any TM_{mn} mode is given as

$$f_1 = \frac{c}{2\sqrt{\varepsilon_{reff}}}\left[\left(\frac{m}{L_1}\right)^2 + \left(\frac{n}{W_1}\right)^2\right]^{\frac{1}{2}} \tag{5}$$

Here, m and n are modes with respect to $L_1$and W_1 respectively. For resonance, the width is given as:

$$W_1 = \frac{c}{2f_1\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{6}$$

The $L_1 \times W_1$are 10×10 mm^2 which is $\lambda_0/2\times\lambda_0/2$ mm where λ_0 is the center wavelength. Initially, we have obtained frequency bands with central frequencies 13.85 and 15.55 GHz. This square patch is modified with an asymmetric E-shaped slot centered at the origin, result in a shift in resonant frequency to 13.2 GHz and 15.6 GHz, which can be used for transmitting and receiving mode of fixed satellite services. It has been observed that there is a minor shift in upper resonant frequency. Therefore, the E-shaped slot is truncated to achieve resonant frequency at 12.65 GHz and 14.5 GHz. This results in a significant change in upper resonant frequency. But, unfortunately, the introduction of the E slot requires fine-tuning in bandwidth which is thereafter enhanced using eight rectangular slots on the patch of antenna design.

The insertion of slots 1-4 results in minor shifting of resonant frequency to 12.8 GHz and 14.5 GHz. Finally, fine-tuning is done by inserting slots 5-8 into the proposed structure in order to achieve dual-frequency peaks at 12.5 GHz and 14.1 GHz. The result of reflection coefficient (S_{11}) v/s frequency with a different configuration of proposed antenna design like with rectangular patch and ground, E slot and ground, truncated E slot and ground, truncated E slot with slot 1-4, and truncated E slot with slot 4-8 are given in Fig. 4.5. The fact that two bands are achieved with truncated E slot and slot1 to slot8 can be visualized from Fig. 4.5.

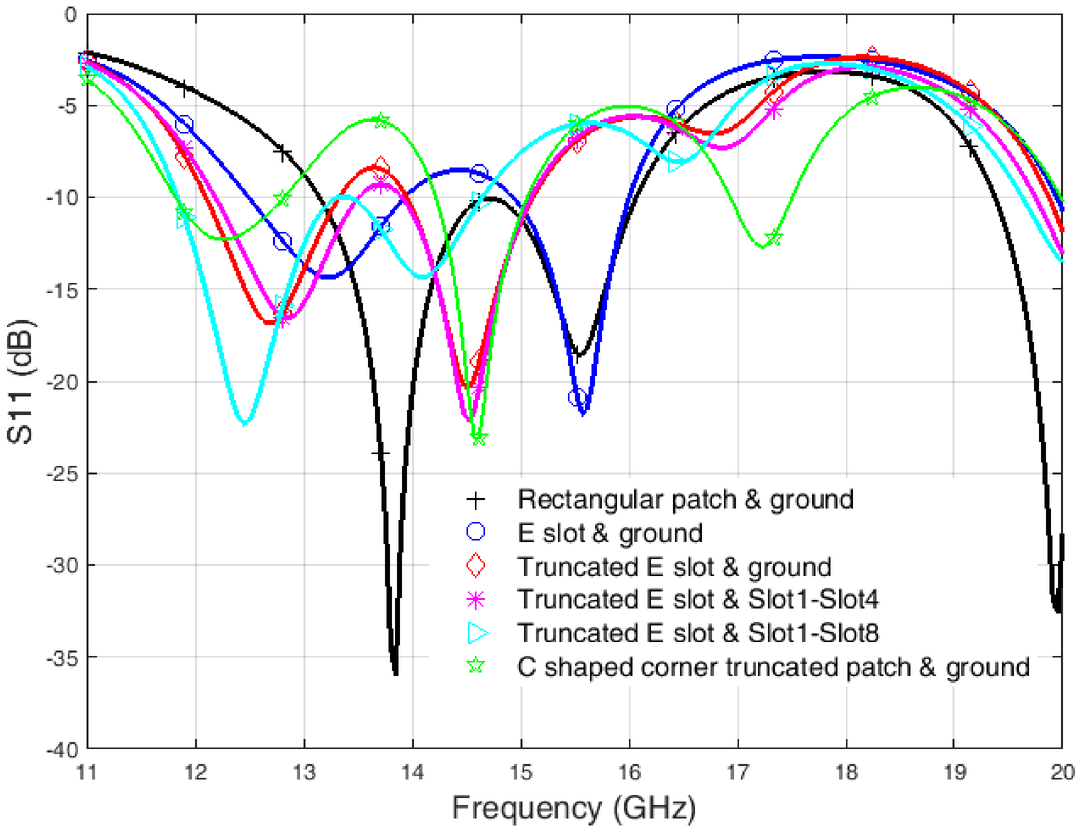


Fig. 4.5: Reflection Co-efficient (S11 (dB)) v/s frequency (GHz) with E-Slot, Truncated E slot, Slot1-Slot8, and C shaped truncated patch and ground.

Further, in order to achieve transmit and receive mode of DBS, antenna design is modified with C-shaped corner truncated slots. As a consequence, three bands of 11.84-

12.79 GHz, 14.19-15.05 GHz, and 16.93-17.5 GHz are now achieved and results are shown in Fig. 4.5. The first band is found to be very close to DBS receive mode frequency (11.7 GHz-12.2 GHz). Also, the third band is close to DBS transmit mode frequency (17.3 GHz -17.8 GHz).

Lastly, to achieve desired DBS bands defected ground structure (DGS) technique is utilized. Slots 9, 10, and 11 are embedded into the ground plane resulting in the generation of desired DBS receive band but with very poor S_{11}. To overcome these problems slots 12, 13, 14, and 15 are introduced. Finally, with slot 16, the exact desired bands i.e. transmit and receive mode of DBS and FSS with better S_{11} and enhanced bandwidth have been achieved. The plots of S_{11} (dB) as a function of frequency for the cases of C shaped corner truncated patch with the ground, DGS with slot 9-10, DGS with slot 11, DGS with slot 12-13, DGS with slot 14-15, and finally, DGS with slot 16 are shown in Fig. 4.6

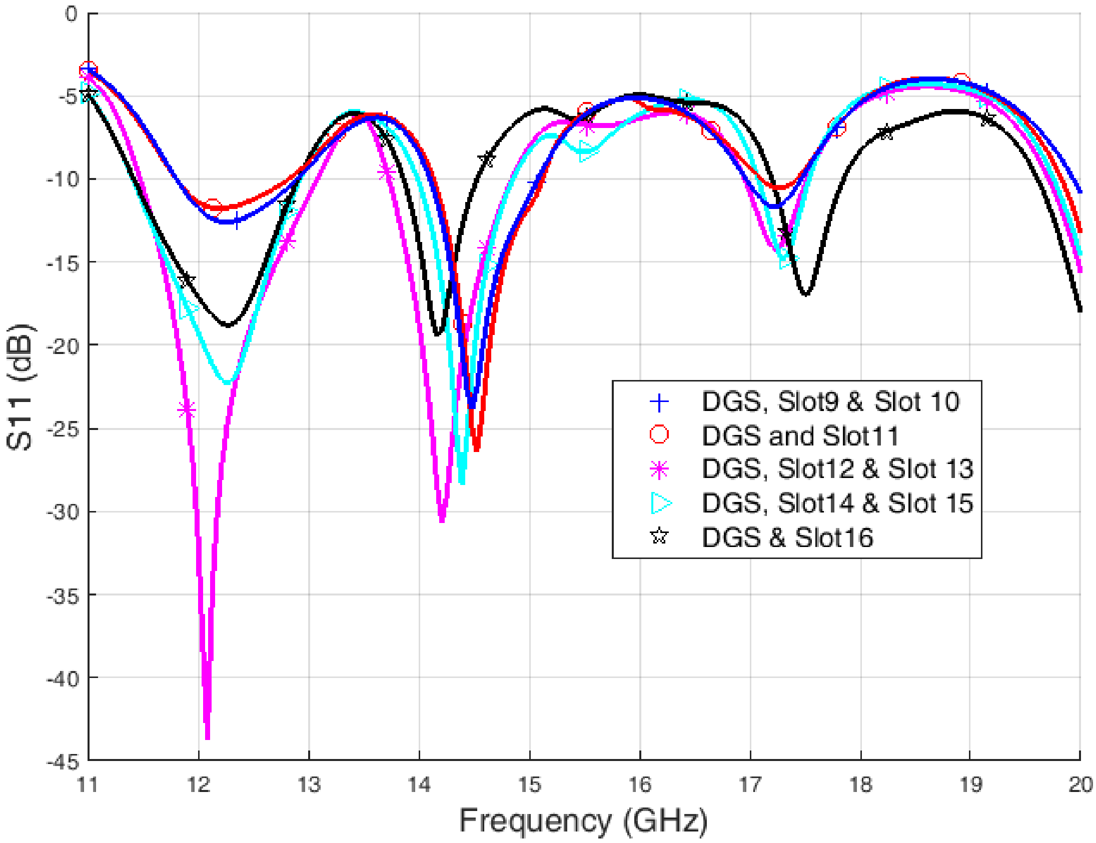


Fig. 4.6: Reflection Co-efficient (S11 (dB)) v/s frequency (GHz) with DGS and Slot 9-Slot 16.

4.4 Results and discussion

The obtained results from the simulation are presented and compared with the results of the hardware prototype of the proposed design. For simulation, High-Frequency Structure Simulator (HFSS) is utilized to enhance different parameters of the antenna. The effect of changing different slot dimensions on the performance of the antenna is studied by varying dimensions of one slot and keeping all other slot dimensions are constant. This resulted in the allocation of optimal dimensions for a superlative performance of the proposed design.

4.4.1 S_{11} Parameters of proposed antenna

Fig. 4.7 shows the S_{11}v/s frequency plots for both simulation and measured results. Observations from Fig. 4.7 conclude that the proposed design works satisfactorily for the bands 11.40-12.91 GHz, 13.86-14.53, and 17.20-17.86 GHz formally introduced by ITU for transmission and reception of DBS and FSS.

Another important observation can be made from Fig. 4.7 that the simulation results are in accordance with measured results except in a few instances. The reason behind this ambiguity may be the fabrication loss, connector loss, and tolerance in the dielectric constant. Further, the dependency of dielectric constant (ε_r) on operational frequency is also a key factor that generally decreases with an increase in frequency.

The numerical values of three frequency bands obtained by simulated and measured results are given in Table 4.2. Lower frequency (LF), upper frequency (UF), resonant frequency (RF), and bandwidth (BW) are taken as parameters for Table 4.2.

4.4.2 Gain and radiation pattern of the proposed antenna

The measured results are calculated using the setup given in Fig. 4.8. Measurements were performed inside an anechoic chamber situated in the research lab of the Indian Institute of Technology (IIT), Roorkee, India. Fig. 4.9 presents the radiation pattern of co and cross-polarization. The frequencies of 12.25 GHz, 14.16 GHz, and 17.50 GHz are taken for observation in Fig. 4.9 for both simulation and measured results. It can be noticed from Fig. 4.9 that the radiation patterns of co polarization are comparatively higher values than the cross-polarization. Therefore, it can be noted that the radiation pattern of the design is almost broadside. For further improvement in radiation efficiency, a substrate with low dielectric losses can be utilized. The slight difference between simulated and measured results of Fig. 4.9 may be due to high mode excitation, the losses due to the cable/connector and the manual positioning, etc.

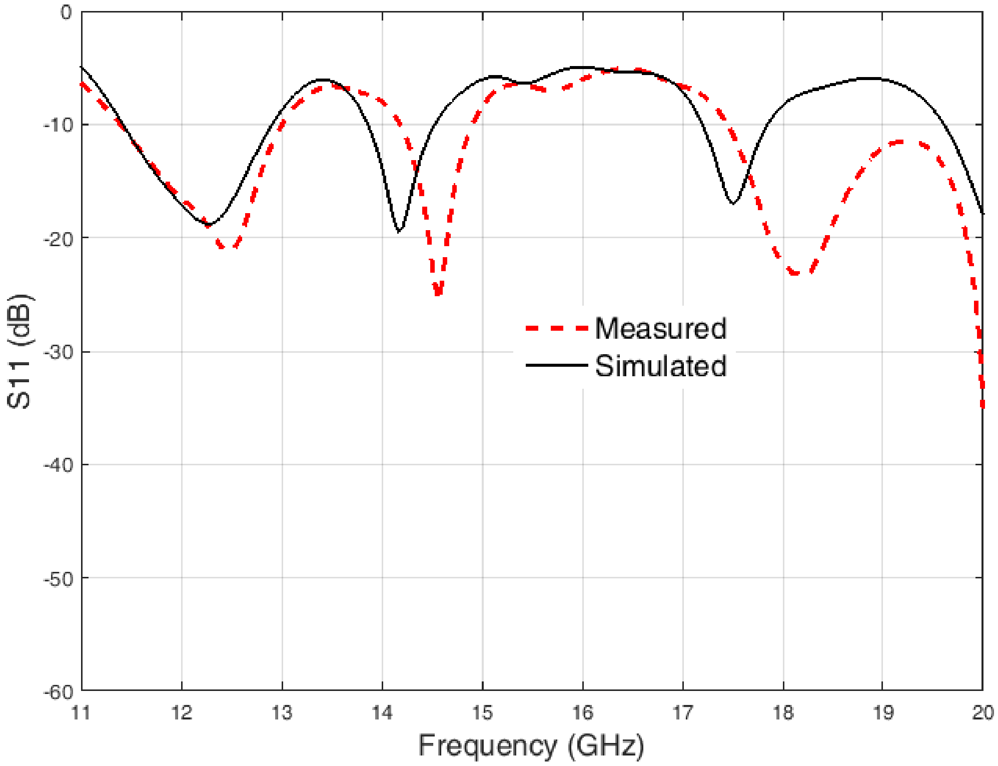


Fig. 4.7: Simulated and measured results of S_{11}v/s frequency for the proposed design

Table 4.2: Simulated and measured results of the first, second and third band for DBS and FSS

Frequency band (GHz)	Simulated Results				Measured Results			
	LF	UF	RF	BW	LF	UF	RF	BW
First band	11.40	12.91	12.25	1.51	11.40	12.98	12.44	1.58
Second band	13.86	14.53	14.16	0.67	14.21	14.86	14.5	0.65
Third band	17.20	17.86	17.50	0.66	17.41	18.98	18.18	1.57

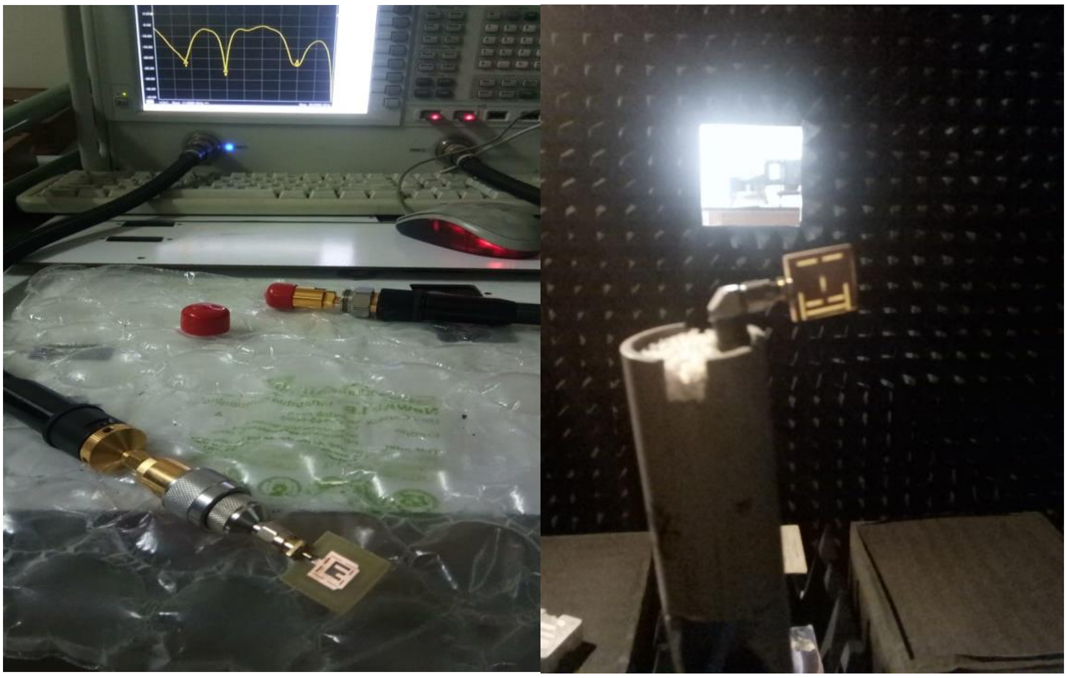
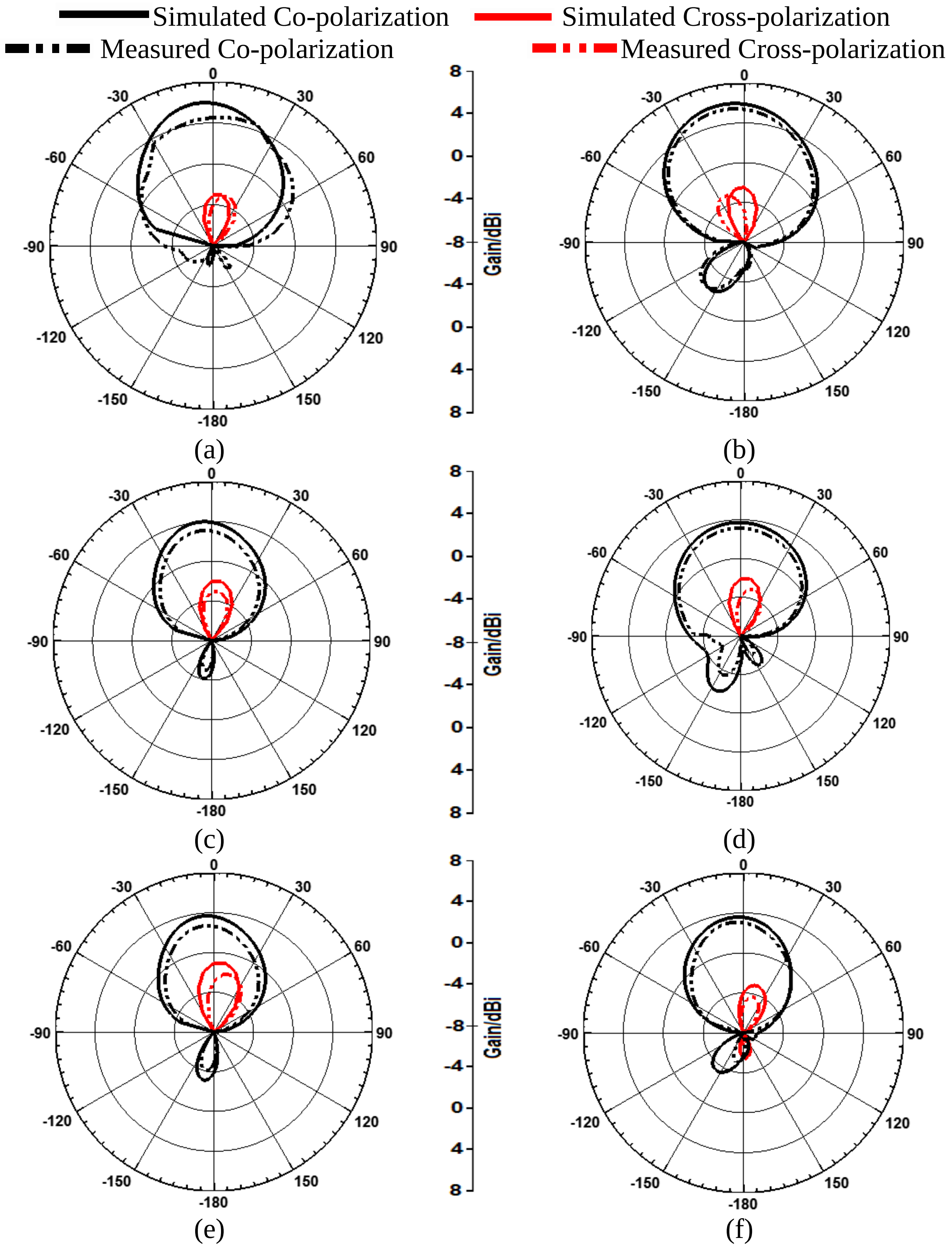


Fig. 4.8: Gain and radiation pattern measurement setup

Fig. 10 shows the plot of simulated and measured results for gain v/s frequency. The simulated values of gain vary from 3.18 to 6 dBi, 2.08 to 4 dBi, and 2.10 to 3.70 dBi at the frequency bands 11.40-12.98 GHz, 14.21-14.86 GHz, and 17.41-18.98 GHz respectively. Conversely, the measured gain varies from 2.78 to 5.76 dBi, 1.70 to 3.48 dBi, and 1.10 to 3.05 dBi at the frequency bands 11.40-12.98 GHz, 14.21-14.86 GHz, and 17.41-18.98 GHz respectively. For every reading, the Vector Network Analyzer (VNA) was recalibrated in order to further enhance the precision of measured results.

4.4.3 Radiation efficiency of the proposed antenna

The radiation efficiency (%) v/s frequency (GHz) plot is given in Fig. 11. It has been observed from Fig. 11 that the simulated values of the efficiency vary from 53 to 70%, 54 to 67% dB, and 67 to 69% at the frequency bands of 11.40-12.98 GHz, 14.21-14.86 GHz, and 17.41-18.98 GHz respectively. Conversely, the measured efficiency changes from 51 to 66%, 48 to 61%, and 61 to 64% at the frequency bands of 11.40-12.98 GHz, 14.21-14.86 GHz, and 17.41-18.98 GHz respectively.



(a) (b) (c) (d) (e) (f)

Fig. 4.9: Simulate and measured Co and Cross- polarization radiation patterns:(a) E-plane at 12.25 GHz (b) H-plane at 12.25 GHz (c) E-plane at 14.16 GHz (d) H-plane at 14.16 GHz (e) E-plane at 17.50 GHz (f) H-plane at 17.50 GHz

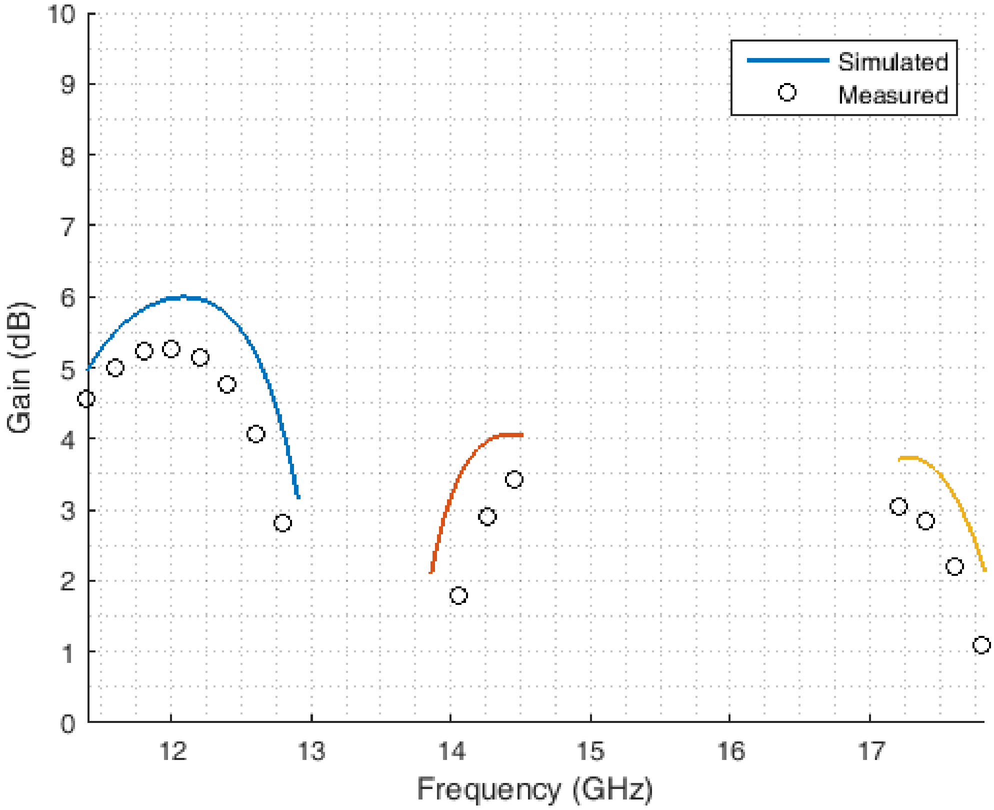


Fig. 4.10: Gain (dBi) v/s frequency (GHz) plot

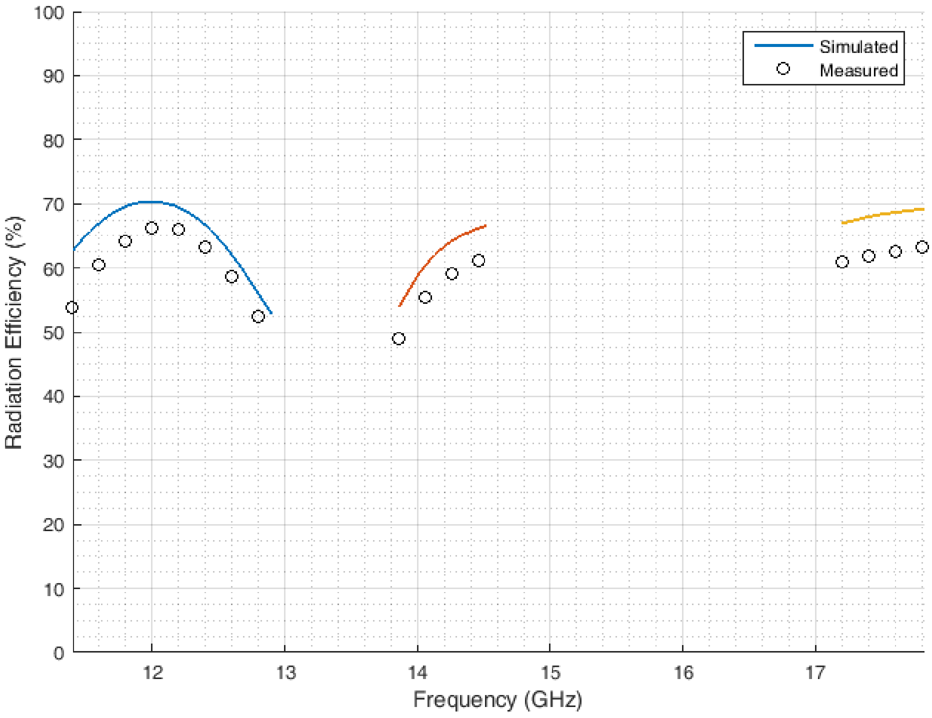


Fig. 4.11: Radiation efficiency (%) v/s frequency (GHz) plot

4.4.4 Comparison of proposed antenna with reference antennas

Table4.3 gives the comparison of different antenna designs given in literature with the proposed design for the same application of interest. The proposed design achieves the three desired bands with the resonant frequencies of 12.25 GHz, 14.16 GHz, and 17.50 GHz with the percentage impedance bandwidth of 12.70%, 4.48%, and 8.63% respectively. Moreover, the gain and efficiency are also found to be satisfactory.

Table 4.3: Proposed antenna design as compared to previously published designs

(RF: Resonant Frequency, BW: Bandwidth)

Design	RF of 1st Band (GHz)	RF of 2nd Band (GHz)	RF of 3rd Band (GHz)	BW of 1st Band	BW of 2nd Band	BW of 3rd Band	Patch size (mm^2)	Gain (dBi)	Efficiency (%)
Samsuzzaman et al. (2013) [15]	15.33	17.61	----	3.4	3.3	----	9.5×8	4.8-6.4	----
Vijayvergiya and Panigrahi (2017) [4]	12.07	14.44	----	10.2	8.2	----	10.1×9.9	4.8-7.4	68-78
Saini and Kumar (2019) [7]	12.38	14.40	----	12.29	9.37	----	10×10	1.6-4.2	69-80
Sayed et al. (2015) [10]	12.72	14.4	----	5.3	6.9	----	5.7×8	5-5.5	----
Thi et al. (2013) [12]	11.96	13.93	----	8.7	6.6	----	50×50	3.7-3.8	----
Parikh et al. (2012) [6]	11.95	14.25	----	4.2	3.6	----	9.4×7.1	5.7-7.2	----
Proposed	**12.25**	**14.16**	**17.50**	**12.70**	**4.48**	**8.63**	**10×10**	**2.08-6**	**53 to 70**

4.5 Conclusion

In this work, a low profile, small size tri-band antenna has been proposed and fabricated for Ku band applications. The frequency bands required for the transmission and reception of DBS and FSS have been achieved using the proposed design. For this task, truncated E-shaped slots, eight rectangular slots, two C-shaped slots in the patch and eight defected ground structure (DGS) slots have been utilized. The results of the antenna design are verified by comparing them with fabricated antenna results. Certain key parameters for satellite antennas like reflection coefficient, impedance bandwidth, polarization, efficiency, gain, and radiation pattern were taken for this analysis. The antenna design presented in this chapter lays the groundwork for array antennas. It can be used as an element in an array configuration to achieve enhanced gain suitable for transmission and reception modes of FSS and DBS which can be taken as a future endeavor for this study. This gain can be further enhanced using more refined material like RT Duroid substrate in future studies. Also, the proposed antenna fulfills the spectrum necessity of ITU region 3.

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Chapter 5

Conclusions and Future Research

5.1 Conclusions

Modern wireless devices are becoming smaller, lighter, and thinner day by day which has pushed the requirements for smaller antenna sizes. Another key concern with current satellite communication systems is to achieve multi-band operation. Low-profile patch antennas are proving to be the most suitable candidates for this task. Therefore the main objective of this dissertation is to design and fabricate multiband low-profile patch antennas for satellite applications with Optimized Parameters.

In order to accomplish this objective, two highly optimized patch antennas have been presented for satellite applications. The frequency band of operation of these antennas is Ku band. The proposed antennas are fabricated using FR4 as the substrate and cover both transmission and reception bands of FSS and DBS.

The first antenna design presented in Chapter 3 is of a dual-band patch antenna which meets the spectrum necessity of region 3 for FSS and DBS in receive mode and FSS in transmit mode. The impedance bandwidth of 12.29 % and 9.37% are achieved for the first and second band, respectively by the antenna. A nearly symmetric E-shaped slot and rectangular slots have been utilized to achieve greater impedance bandwidth and less resonant frequency ratio which is useful for satellite applications. A detailed parametric analysis of design has resulted in optimized values of performance parameters i.e. S_{11}, Gain, radiation pattern of E, and H-plane. Further, the current distribution is observed to be almost regular at the different parts of the proposed antenna. The design achieved an axial ratio of 160 MHz.

The second antenna design demonstrated in Chapter 4 further optimizes the performance of the antenna presented in Chapter 3. A tri-band antenna is proposed in Chapter 4 which covers the frequency band for both transmission and reception of DBS and FSS in the Ku band. As compared to the designs available in the literature that achieve this task by utilizing multi-patch, multi-layered, aperture coupled or proximity coupled structures; the proposed antenna design is small and lightweight. The practical implementation of the proposed antenna is also very easy as compared to these designs as they face alignment issues and air gaps between layers. The proposed design achieves the three desired bands with the resonant frequencies of 12.25 GHz, 14.16 GHz, and 17.50 GHz with the percentage impedance bandwidth of 12.70%, 4.48%, and 8.63% respectively.

The proposed antenna design consists of truncated E-slots, C-shaped slots, and defected ground structure (DGS) slots. The fabricated antenna results when compared with the simulated results are found satisfactory. The radiation pattern, impedance bandwidth, polarization, efficiency, gain, and reflection coefficient of the antenna are analyzed to check its suitability for practical applications.

5.2 Future Works

Gain is a key parameter while designing an antenna for satellite applications. The proposed designs in this work can be used as an element in an array configuration to achieve higher gain. Another important aspect that affects the overall performance of the antenna is the material used for fabrication. FR4 has been used in the antenna designs in this work which is considered to be a lossy material. Therefore, in order to increase the efficiency of these antennas, more refined and costly materials like RT/Duroid 5880, RO3003, RO4003, Taconic TLC, and Epoxy Kevlar, etc. can be used. Finally, the proposed antenna designs can be further optimized to achieve higher-order bands for other applications of satellite communication.

List of Publications

Journal

[1] G. S. Saini and R. Kumar, “A low profile patch antenna for Ku-band applications,” International Journal of Electronics Letters, pp.1-11, 2019.

[2] R. Kumar, G. S. Saini, and D. Singh, “Compact Tri-Band Patch Antenna for Ku Band Applications,” Progress in Electromagnetics Research C, vol. 103, pp. 45-58, 2020.

Patent

[1] R. Kumar, G. S. Saini, D. Singh, P. Kaur, M. Sharma, et. al, “Compact Tri-Band Patch Antenna for Ku Band Applications and Methods Thereof,” The Patent Office issued on January 1, 2021.