DESIGN AND IMPLEMENTATION OF SWB ANTENNA FOR 5G

A PROJECT REPORT

Submitted by

KARTHIK G	**921619106028**
MURALI M	**921619106039**
SAMUEL EBINEZER R	**921619106048**
SATHEES R	**921619106054**

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BONAFIDE CERTIFICATE

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SIGNATURE	**SIGNATURE**
Mr. R. SANKARANARAYANAN, M.E.,	**Ms. A. ROSARIYO, M.E.,**
HEAD OF THE DEPARTMENT,	**SUPERVISOR,**
ASSISTANT PROFESSOR	**ASSISTANT PROFESSOR**
Department of Electronics and	Department of Electronics and
Communication Engineering	Communication Engineering
SBM College of Engineering and	SBM College of Engineering and
Technology,	Technology,
Dindigul-624005.	Dindigul-624005

Submitted for the project **VIVA-VOCE** held on ______________

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ABSTARCT

This work investigates the design and practical implementation of a novel Super Wide Band (SWB) antenna on a flexible substrate. The antenna is designed on the Ultralam 3850 substrate having a compact dimension of 60 × 40 × 0.1 mm3. This antenna has an operating frequency band from 1.74 to 100 GHz with a bandwidth (BW) ratio of approximately 57.47:1. Such an extended frequency coverage makes this antenna operable in a wide variety of wireless application areas, including 5G and the Internet of Things (IoT).The simulated performance of the designed antenna is analyzed here with respect to different antenna parameters, including reflection coefficient, radiation pattern, gain, efficiency, and surface current. The proposed antenna prototype is fabricated, and experimental validation is provided through the measurement using a programmable network analyzer (PNA).

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LIST OF ABBREVIATIONS

BDR	-Bandwidth Dimension Ratio
CPW	-Coplanar Waveguide
EMBB	-Enhanced Mobile Broadband
FCC	-Federal Communication Commission
GPP	-Generation Partnership Project
ITU	-International Telecommunication Union
MIMO	-Multiple Input and Multiple Output
MMTC	-Massive Machine Type Communications
NOMA	-Non-Orthogonal Multiple Access
SWB	-Super Wide Band
URLLC	-Ultra Reliable Low Latency Communications
UWB	-Ultra Wide Band
PNA	-Programmable Network Analyzer
IOT	-Internet of Things

CHAPTER 1

INTRODUCTION

1.1 5G COMMUNICATION

In telecommunications,5G is the fifth–generation technology standard for broadband cellular networks, which cellular phone companies began deploying worldwide in 2019, and is the planned successor to the 4G networks which provide connectivity to most current cellphones. 5G networks are predicted to have more than 1.7 billion subscribers worldwide by 2025, according to the GSM Association. Like its predecessors, 5G networks are cellular networks, in which the service area is divided into small geographical areas called cells. All 5G wireless devices in a cell are connected to the Internet and telephone network by radio waves through a local antenna in the cell. The main advantage of the new networks is that they will have greater bandwidth, giving higher download speeds, eventually up to 10 gigabits per second (Gbit/s). In addition to 5G being faster than existing networks, 5G can connect more different devices, and even if people are in crowded areas, the servers will be more unified, improving the quality of Internet services. Due to the increased bandwidth, it is expected the networks will increasingly be used as general internet service providers (ISPs) for laptops and desktop computers, competing with existing ISPs such as cable internet, and also will make possible new applications in internet-of-things (IoT) and machine-to-machine areas. Cellphones with 4G capability alone are not able to use the new networks, which require 5G-enabled wireless devices.

1.2 OVERVIEW

5G networks are cellular networks, in which the service area is divided into small geographical areas called cells. All 5G wireless devices in a cell communicate by radio waves with a cellular base station via fixed antennas, over frequency channels assigned by the base station. The base stations, termed gNodeBs, are connected to switching centers in the telephone network and routers for Internet access by high-bandwidth optical fiber or wireless backhaul connections. As in other cellular networks, a mobile device moving from one cell to another is automatically handed off seamlessly to the current cell. 5G can support up to a million devices per square kilometer, while 4G supports only one-tenth of that capacity.

Several network operators use millimeter waves called FR2 in 5G terminology, for additional capacity and higher throughputs. Millimeter waves have a shorter range than microwaves, therefore the cells are limited to a smaller size. Millimeter waves also have more trouble passing through building walls. Millimeter-wave antennas are smaller than the large antennas used in previous cellular networks. Some are only a few centimeters long.

The increased speed is achieved partly by using additional higher-frequency radio waves in addition to the low- and medium-band frequencies used in previous cellular networks. However, higher-frequency radio waves have a shorter useful physical range, requiring smaller geographic cells. For wide service, 5G networks operate on up to three frequency bands – low, medium, and high.

5G can be implemented in low-band, mid-band or high-band millimeter-wave 24 GHz up to 54 GHz. Low-band 5G uses a similar frequency range to 4G cellphones, 600–900 MHz, giving download speeds a little higher than 4G: 30–250 megabits per second (Mbit/s).Low-band cell towers have a range and coverage area similar to 4G towers. Mid-band 5G uses microwaves of 2.3–4.7 GHz, allowing speeds of 100–900 Mbit/s, with each cell tower providing service up to several kilometers in radius. This level of service is the most widely deployed and was deployed in many metropolitan areas in 2020. Some regions are not implementing the low band, making Mid-band the minimum service level. High-band 5G uses frequencies of 24–47 GHz, near the bottom of the millimeter wave band, although higher frequencies may be used in the future. It often achieves download speeds in the gigabit-per-second (Gbit/s) range, comparable to cable internet. However, millimeter waves (mmWave or mmW) have a more limited range, requiring many small cells. They can be impeded or blocked by materials in walls or windows. Due to their higher cost, plans are to deploy these cells only in dense urban environments and areas where crowds of people congregate such as sports stadiums and convention centers. The above speeds are those achieved in actual tests in 2020, and speeds are expected to increase during rollout. The spectrum ranging from 24.25–29.5 GHz has been the most licensed and deployed 5G mmWave spectrum range in the world.

The industry consortium setting standards for 5G is the 3rd Generation Partnership Project (3GPP). It defines any system using 5G NR (5G New Radio) software as "5G", a definition that came into general use by late 2018. Minimum standards are set by the International Telecommunication Union (ITU).

Rollout of 5G technology has led to debate over its security and relationship with Chinese vendors. It has also been the subject of health concerns and misinformation, including discredited conspiracy theories linking it to the COVID-19 pandemic.

1.3 APPLICATION AREAS

The ITU-R has defined three main application areas for the enhanced capabilities of 5G. They are Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type

Communications (mMTC). Only eMBB is deployed in 2020; URLLC and mMTC are several years away in most locations.

Enhanced Mobile Broadband (eMBB) uses 5G as a progression from 4G LTE mobile broadband services, with faster connections, higher throughput, and more capacity. This will benefit areas of higher traffic such as stadiums, cities, and concert venues.

Ultra-Reliable Low-Latency Communications (URLLC) refer to using the network for mission critical applications that require uninterrupted and robust data exchange. The short-packet data transmission is used to meet both reliability and latency requirements of the wireless communication networks.

Massive Machine-Type Communications (mMTC) would be used to connect to a large number of devices. 5G technology will connect some of the 50 billion connected IoT devices.[10] Most will use the less expensive Wi-Fi. Drones, transmitting via 4G or 5G, will aid in disaster recovery efforts, providing real-time data for emergency responders. Most cars will have a 4G or 5G cellular connection for many services. Autonomous cars do not require 5G, as they have to be able to operate where they do not have a network connection. However, most autonomous vehicles also feature teleoperations for mission accomplishment, and these greatly benefit from 5G technology.

1.4 PERFORMANCE

Speed

5G speeds will range from ~50 Mbit/s to over 1,000 Mbit/s (1 Gbit/s). The fastest 5G speeds would be in the mmWave bands and can reach 4 Gbit/s with carrier aggregation and MIMO.

Sub-6 GHz 5G (mid-band 5G), by far the most common, will usually deliver between 100 and 4,400 MBit/s but will have a much further reach than mmWave, especially outdoors. C-Band (n77/n78) will be deployed by various U.S. operators in 2022. C-Band had been planned to be deployed by Verizon and AT&T in early January 2022 but was delayed due to safety concerns raised by the Federal Aviation Administration.

The Low-band spectrum offers the greatest range, thereby a greater coverage area for a given site, but its speeds are lower than the mid and high bands.The work on 5.5G technology is expected to offer 20 Gbit/s downstream and 10 Gbit/s upstream rates, possibly between 2025 and 2030.The theoretical throughput of 5G, with only one device connected, is as high as 1000 Gbit/s and real life demos have shown wireless speeds over 70 Gbit/s.

Latency

In 5G, the "air latency" is of the order of 8–12 milliseconds. The latency to the server must be added to the "air latency" for most comparisons. Verizon reported the latency on its 5G early deployment is 30 ms: Edge Servers close to the towers can reduce latency to 10–20 ms; 1–4 ms will be extremely rare for years outside the lab. The latency is much higher during handovers; ranging from 50–500 milliseconds depending on the type of handover. Reducing handover latency is an ongoing area of research and development.

Error rate

5G uses adaptive modulation and coding scheme (MCS) to keep the bit error rate extremely low. Whenever the error rate crosses a (very low) threshold the transmitter will switch to a lower MCS, which will be less error-prone. This way speed is sacrificed to ensure an almost zero error rate.

Range

The range of 5G depends on many factors; frequency is the most important of all. mmWave signals tend to have a range of only a couple of hundred meters whilst low band signals generally have a range of a couple of kilometers. Since there is a lot of marketing hype on what 5G can offer, simulators and drive tests are used for the precise measurement of 5G performance.

Standards

Initially, the term was associated with the International Telecommunication Union's IMT-2020 standard, which required a theoretical peak download speed of 20 gigabits per second and 10 gigabits per second upload speed, along with other requirements. Then, the industry standards group 3GPP chose the 5G NR (New Radio) standard together with LTE as their proposal for submission to the IMT-2020 standard.

5G NR can include lower frequencies (FR1), below 6 GHz, and higher frequencies (FR2), above 24 GHz. However, the speed and latency in early FR1 deployments, using 5G NR software on 4G hardware (non-standalone), are only slightly better than new 4G systems, estimated at 15 to 50% better.

The standard documents for 5G are organized by 3GPP.

The packet protocol for session mobility (establishing connection and moving between base stations) and session management (connecting to networks and network slices) is described in TS 24.501. Specifications of key data structures are found in TS 23.003.

Spectrum

Large quantities of new radio spectrum (5G NR frequency bands) have been allocated to 5G. For example, in July 2016, the U.S. Federal Communications Commission (FCC) freed up vast amounts of bandwidth in underused high-band spectrum for 5G. The Spectrum Frontiers Proposal (SFP) doubled the amount of millimeter-wave unlicensed spectrum to 14 GHz and created four times the amount of flexible, mobile-use spectrum the FCC had licensed to date. In March 2018, European Union lawmakers agreed to open up the 3.6 and 26 GHz bands by 2020.

1.5 5G DEVICES

In March 2019, the Global Mobile Suppliers Association released the industry's first database tracking worldwide 5G device launches.[58] In it, the GSA identified 23 vendors who have confirmed the availability of forthcoming 5G devices with 33 different devices including regional variants. There were seven announced 5G device form factors: (telephones (×12 devices), hotspots (×4), indoor and outdoor customer-premises equipment (×8), modules (×5), Snap-on dongles and adapters (×2), and USB terminals (×1)). By October 2019, the number of announced 5G devices had risen to 129, across 15 form factors, from 56 vendors.

In the 5G IoT chipset arena, as of April 2019 there were four commercial 5G modem chipsets and one commercial processor/platform, with more launches expected in the near future.

Cell types		Deployment environment	Max. number of users	Output power (mW)	Max. distance from base station
5G NR FR2	Femtocell	Homes, businesses	Home: 4–8 Businesses: 16–32	indoors: 10–100 outdoors: 200–1,000	tens of meters
	Pico cell	Public areas like shopping malls, airports, train stations, skyscrapers	64 to 128	indoors: 100–250 outdoors: 1,000–5,000	tens of meters
	Micro cell	Urban areas to fill coverage gaps	128 to 256	outdoors: 5,000−10,000	few hundreds of meters
	Metro cell	Urban areas to provide additional capacity	more than 250	outdoors: 10,000−20,000	hundreds of meters
Wi-Fi (for comparison)		Homes, businesses	fewer than 50	indoors: 20–100 outdoors: 200–1,000	few tens of meters

Fig 1.1 TABLE OF IOT DEVICE

1.6 MASSIVE MIMO

MIMO systems use multiple antennas at the transmitter and receiver ends of a wireless communication system. Multiple antennas use the spatial dimension for multiplexing in addition to the time and frequency ones, without changing the bandwidth requirements of the system.

Massive MIMO (multiple-input and multiple-output) antennas increases sector throughput and capacity density using large numbers of antennas. This includes Single User MIMO and Multi-user MIMO (MU-MIMO). Each antenna is individually-controlled and may embed radio transceiver components.

1.7 EDGE COMPUTING

Edge computing is delivered by computing servers closer to the ultimate user. It reduces latency and data traffic congestion.

Small cell

Small cells are low-powered cellular radio access nodes that operate in licensed and unlicensed spectrum that have a range of 10 meters to a few kilometers. Small cells are critical to 5G networks, as 5G's radio waves can't travel long distances, because of 5G's higher frequencies

Beamforming

There are two kinds of beamforming: digital and analog. Digital beamforming involves sending the data across multiple streams (layers), while analog beamforming shaping the radio waves to point in a specific direction. The analog BF technique combines the power from elements of the antenna array in such a way that signals at particular angles experience constructive interference, while other signals pointing to other angles experience destructive interference.

This improves signal quality in the specific direction, as well as data transfer speeds.

1.8 CONVERGENCE OF WI-FI AND CELLULAR

One expected benefit of the transition to 5G is the convergence of multiple networking functions to achieve cost, power, and complexity reductions. LTE has targeted convergence with Wi-Fi band/technology via various efforts, such as License Assisted Access (LAA; 5G signal in unlicensed frequency bands that are also used by Wi-Fi) and LTE-WLAN Aggregation (LWA; convergence with Wi-Fi Radio), but the differing capabilities of cellular and Wi-Fi have limited the scope of convergence. However, significant improvement in cellular performance specifications in 5G, combined with migration from Distributed Radio Access Network (D-RAN) to Cloud- or Centralized-RAN (C-RAN) and rollout of cellular small cells can potentially narrow the gap between Wi-Fi and cellular networks in dense and indoor deployments. Radio convergence could result in sharing ranging from the aggregation of cellular and Wi-Fi channels to the use of a single silicon device for multiple radio access technologies.

1.9 NOMA (NON-ORTHOGONAL MULTIPLE ACCESS)

NOMA (non-orthogonal multiple access) is a proposed multiple-access technique for future cellular systems via allocation of power.

SDN/NFV

Initially, cellular mobile communications technologies were designed in the context of providing voice services and Internet access. Today a new era of innovative tools and technologies is inclined towards developing a new pool of applications. This pool of applications consists of different domains such as the Internet of Things (IoT), web of connected autonomous vehicles, remotely controlled robots, and heterogeneous sensors connected to serve versatile applications. In this context, network slicing has emerged as a key technology to efficiently embrace this new market model.

Channel coding

The channel coding techniques for 5G NR have changed from Turbo codes in 4G to polar codes for the control channels and LDPC (low-density parity check codes) for the data channels.

Operation in unlicensed spectrum

In December 2018, 3GPP began working on unlicensed spectrum specifications known as 5G NR-U, targeting 3GPP Release 16.[78] Qualcomm has made a similar proposal for LTE in unlicensed spectrum.

5G-Advanced

5G-Advanced is a name for 3GPP release 18, which as of 2021 is under conceptual development.

1.10 ANTENNA CONSIDERATIONS FOR 5G

Owing to the remarkable development of wireless communication, there has been an increasing trend of growing network and data traffic. To comply with this demand, the Fifth generation (5G) wireless system is being deployed, which can offer an enhanced frequency spectrum and unprecedented data rates as high as multi-Gigabit per second (Gbps).

5G technology would use the existing 4G band along with the newly de_ned 5G frequency ranges, including millimeter wave(mmWave) bands (26, 28, 40, 50, and 66 GHz). 5G communication systems will have the ability to support the Internet of Things (IoT) applications, and therefore Io devices need to be 5G enabled. This requirement, along with the usage of mmWave applications, instigate the necessity of integrating small-sized enhanced bandwidth (BW)antennas in 5G communication devices.

An antenna is one of the most crucial parts of any radiocommunication platform. Evolution in communication electronics has made it easier to develop compact, reliable, and advanced antenna systems (AAS). Since the emergence of RF (radio frequency) communication, there has been an ever-increasing demand for compact and ubiquitous antennas. The modern-day communication systems require.

versatile multi-antenna technologies, which further escalates the necessity for small mobile terminals. Such small-scale equipment, including cellular phones, navigation devices, radio frequency identification (RFID) tag or sensors, as well as connected IoT and 5G devices, instigate the adoption of pervasive, high data capacity antennas with increased bandwidth. The widespread use of such devices and the constant growth of mobile network technology will continue to challenge researchers to design and develop compact, high performance, and cost-effective AAS on an ongoing basis.

Ultra-Wide Band (UWB) is a radio communication protocol that can use low power to offer short-range connectivity with an increased data rate. This technology is beneficial for a wide range of applications, including multimedia services, home networking, medical, wireless personal area network (WPAN), and many others. However, due to its universal applicability through both short and long-distance data communication, in recent years, the super wideband (SWB) technology has drawn an increased amount of attention.

This technology includes all the sophisticated features of UWB. Besides, compared to that of the UWB, it offers better channel capacity with a higher data rate and an increased resolution. SWB implies a ratio bandwidth equals to or greater than 10:1, which means a broader frequency range than the decade bandwidth. SWB antennas can be designed to occupy a very high bandwidth, which can cover most of the existing and proposed frequency bands specified for 5G applications. These antennas can also facilitate the wireless body area network (WBAN) applications by incorporating low-cost, flexible designs. WBAN requires wearable wideband antennas that can exchange digital information by using the human body as a data network. To ensure the comfort of users, such on-body antennas need to be designed on flexible textile or plastic substrates.

CHAPTER 2

LITERATURE SURVEY

[1] Dual-band microstrip patch antenna array for 5Gmobile communications

U. Raque, H. Khalil, and R. S. Ur, presents the design of an 8-element microstrip patch antenna (MPA) array for dual-band 5G communications. The proposed antenna array is compact with size of 16× 16 mm2 at 28 and 38 GHz, respectively. The dual-band response is achieved by etching an inverted U-shaped slot from the main radiator. It is observed from the results that the proposed array is able to provide resonance for desired frequency bands. Furthermore, the proposed antenna array exhibits omni-directional radiations and offer an acceptable gain for both frequency bands.

[2] A compact monopole antenna for super wideband applications

K.-R. Chen, C.-Y.-D. Sim, and J.-S. Row proposed A planar microstrip-fed super wideband monopole antenna is initially proposed. By embedding a semi elliptically fractal-complementary slot into the asymmetrical ground plane, a 10-dB bandwidth of 172% (1.44-18.8 GHz) is achieved with ratio bandwidth >;12:1. Furthermore, the proposed antenna also demonstrated a wide 14-dB bandwidth from 5.4 to 12.5 GHz, which is suitable for UWB outdoor propagation. This proposed antenna is able to cover the DVB-H in L-band (for PMP), DCS, PCS, UMTS, Bluetooth, WiMAX2500, LTE2600, and UWB bands.

[3] Super wide band wearable antenna: Assessment of the conformal characteristics in terms of impedance matching and radiation properties,"

S. Mahmud, S. Dey, and N. Saha, illustrates the design and competence investigation of a novel conformal super wide band (SWB) wearable textile antenna. The design of this flexible antenna is employed on a material named Dacron fabric whose substrate permittivity is 3. This antenna occupies a bandwidth of almost 35 GHz and ranges between frequencies from 1.76 GHz to 36.80 GHz. The designed antenna is bended at different angles to study its conformal nature in terms of return loss and radiation characteristics.

[4] Textile antennas for on-body communications: Techniques and properties

J. G. Santas, A. Alomainy, and Y. Hao, proposed that Due to the increased demand on multi-frequency and multi-function antenna to be utilized in smart clothing and future consumer-centric communication technologies, fabric and textile antenna designs have received a vast amount of attention in the last few years. The fabrication techniques and materials used in designing textile antennas play a significant role in defining and determining the overall performance. This paper investigates different methods of fabrications applying various material types to analyse the effect those parameters have on a rectangular microstrip patch antenna to be deployed in general wearable applications providing cost-effectiveness, ease of system integration and immunity to performance degradation when placed on the body.

[5] Super-wideband printed asymmetrical dipole antenna

X.-H. Jin, X.-D. Huang, C.-H. Cheng, and L. Zhu, proposed dipole antenna consists of two printed strips with unequal lengths and is fed by a coplanar strip (CPS) line. As the antenna parameters and port impedance are properly selected, a super wide operating band (|S11|<-10 dB) of 3.5 to 20.0 GHz is realized. Antenna samples were fabricated using standard PCB process. The area of the constructed dipole antenna is 40.0x5.0 mm2. The S-parameter measurement was performed via a transition (CPS to double-sided parallel strip line) and transformer (190 to 50

Ohm). The measured fractional bandwidth achieved 139.3% (from 3.4 to 19.0 GHz) as predicted, over which the antenna peak gain is better than 0 dBi.

[6] Design of a novel super wide band circular-hexagonal fractal antenna

M. A. Dorostkar, M. T. Islam, and R. Azim proposed a novel circular-hexagonal Fractal antenna is investigated for super wide band applications. The proposed antenna is made of iterations of a hexagonal slot inside a circular metallic patch with a transmission line. A partial ground plane and asymmetrical patch toward the substrate are used for designing the antenna to achieve a super wide bandwidth ranging from 2.18GHz to 44.5GHz with a bandwidth ratio of 20:4 : 1. The impedance bandwidth and gain of the proposed antenna are much better than the recently reported super wideband antennas which make it appropriate for many wireless communications systems such as ISM, Wi-Fi, GPS, Bluetooth, WLAN and UWB. Details of the proposed antenna design are presented and discussed.

[7] Compact super-wideband asymmetric monopole antenna with dual-branch feed for bandwidth enhancement

J. Liu, K. P. Esselle, S. G. Hay, and S. S. Zhong proposed A novel compact super-wideband (SWB) antenna with an optimised feed is presented. The antenna is composed of an asymmetric trapezoid ground plane and a modified rectangular monopole patch. It is demonstrated that the bandwidth of the antenna is significantly enhanced by introducing an asymmetric dual-branch feed with an L-shaped feed branch. The measurements indicate that the 2:1 VSWR bandwidth is from 1.05 to 32.7 GHz with a ratio bandwidth of 31:1. Since the antenna features an extremely wide bandwidth and the entire size is only 74 × 80 mm, it is useful for modern wireless communication applications.

[8] Stacked stepped-fed super wideband antenna performance in free space and liquid medium for biomedical applications.

M. A. Jamlos, W. A. Mustafa, W. Khairunizam, I. Zunaidi, Z. M. Razlan, proposed A new design of compact Super Wideband (SWB) antenna for performance comparison between in free space and in plain water is presented in this paper. The proposed antenna consists of basic circular patch as radiating element associated with partial ground and a zinc reflector to realize high gain and wide bandwidth. Dimension of 20 mm × 30 mm made the proposed antenna as a compact antenna. The significant feature of this design is the cautious manufacturing of the feed line with additional of two microstrip lines between the patch and the feed line known as stepped transmission line that altering the capacitance between the radiating element and the ground plane. The patch is directly connected with SMA connector using 50 Ohm microstrip feed line through side feeding and deploy the air gap stacked. The antenna exhibits high performance in free space indicated by operated frequency ranged from 4.3 GHz until more than 15 GHz (<-10dB) with maximum gain of 9.79 dB. On the other hand, plain water medium degraded the antenna performance yet still within acceptance limit associated with resonant frequency ranged from 4.7 GHz until more than 15 GHz (<-6dB) and 2.2 dB for the maximum gain. The results reflect the reliability of the SWB antenna operated within liquid medium for various related applications especially for biomedical related applications such as microwave imaging for cancer detection.

[9] Super wideband antenna with single band suppression

M. Manohar, R. S. Kshetrimayum, and A. K. Gogoi proposed a band-notched compact printed monopole super wideband (SWB) antenna has been designed and fabricated. The SWB antenna composed of a radiating patch with a

50 Ω triangular tapered feed line which is connected through a feed region, and a chamfered ground plane (CGP), that covers the frequency band from 0.9–100 GHz (ratio bandwidth of 111.1:1) with a reflection coefficient |S11| < −10 dB, except in the notched band of 4.7–6 GHz for Wireless local area network IEEE 802.11a and HIPERLAN/2 WLAN band. To realize the band notch characteristics a C-shape parasitic element is employed near the CGP etched with two symmetrical L-slots and placed under the radiating patch. Proposed antenna structure occupies a relatively small space (30 × 40 × 0.787 mm3) and achieved much wider impedance bandwidth as well as higher gain compared with the existing ultra-wideband and SWB antennas.

[10] A compact super-wideband antenna pair with polarization diversity

J. Liu, K. P. Esselle, S. G. Hay, Z. Sun, and S. Zhong proposed A low-profile, planar, super-wideband (SWB) antenna pair has been developed to achieve polarization diversity. Its unique configuration brings superior compactness and bandwidth. A novel technique is developed to force one printed patch to play two roles and hence to achieve polarization diversity using only three printed patches, as opposed to four in a conventional diversity pair, to maximize the usage of the limited area available in a compact wireless device. The measurements confirm extremely wide impedance bandwidths of 0.86-30 and 1.04-27.2 GHz at the two ports. That means the ratio bandwidth for each polarization is greater than 26:1. Moreover, the antenna displays sufficient isolation between the two ports and good envelope correlation coefficient for diversity over its operating frequency range. The measured radiation patterns corresponding to each port are also presented.

CHAPTER 3

EXISTING SYSTEM

3.1 SLOTTED ANTENNA

A slot antenna consists of a metal surface, usually a flat plate, with one or more holes or slots cut out.[1] When the plate is driven as an antenna by an applied radio frequency current, the slot radiates electromagnetic waves in a way similar to a dipole antenna. The shape and size of the slot, as well as the driving frequency, determine the radiation pattern. Slot antennas are usually used at UHF and microwave frequencies at which wavelengths are small enough that the plate and slot are conveniently small. At these frequencies, the radio waves are often conducted by a waveguide, and the antenna consists of slots in the waveguide; this is called a slotted waveguide antenna. Multiple slots act as a directive array antenna and can emit a narrow fan-shaped beam of microwaves. They are used in standard laboratory microwave sources used for research, UHF television transmitting antennas, antennas on missiles and aircraft, sector antennas for cellular base stations, and particularly marine radar antennas. A slot antenna's main advantages are its size, design simplicity, and convenient adaptation to mass production using either waveguide or PC board technology.

Operating principle

Slot antennas operate on the principle that whenever a high-frequency field is present across the slot in a metallic sheet, then energy is radiated.

This is the reason when a slot is cut from the surface of the conductive plate then on energizing the slot, the electromagnetic wave is radiated thus acts as an antenna. Due to the presence of a slot, it is named as a slot antenna.

Thus, we can say a conductive surface with a slot of particular dimensions is referred as a slot antenna.

Working of Slot Antenna

Suppose we have a rectangular conductive sheet over which a horizontal slot is cut having length $\lambda/2$ and the breadth extremely less than $\lambda/2$, let it be ω.

This half wavelength slot resembles a half-wave dipole according to radiation and gain. However, the slot antenna and half-wave dipole antenna show variation according to the polarization.

The slot antenna follows Babinet's principle.

Babinet proposed that two complementary screens generate a similar diffraction pattern. This is known as Babinet's principle. According to this principle, the structure of the slot antenna and the half-wave dipole structure cut out from the conducting sheet are complementary to each other.

3.2 MEANDER STRUCTURE ANTENNA

Meander line antenna (MLA) is an electrically small antenna. Electrically small antennas pose several performance related issues such as narrow bandwidth, high VSWR, low gain and high cross polarization levels. In this paper overview on properties, parameter consideration and design of MLA is proposed. The proposed antenna is designed for USB based application. The antenna performance parameters are optimized to achieve reasonably wide impedance bandwidth, high gain, VSWR < 2 and an omni directional radiation pattern.

Fig.3.1 Meander Line Structure

The meander line element consists of vertical and horizontal line, so it formed a series of sets of right-angled bends. The polarization of antenna depends on radiations from the bend. The spacing between two bends is very vital, where if the bends are too close to each other, then cross coupling will be more, which affects the polarization purity of the resultant radiation pattern. In other case the spacing is limited due to the available array grid space and also the polarization of the radiated field will vary with the spacing between the bends, and the spacing between the micro strip lines [8]. The width of etch (line etch on PCB) is used here is 0.5 mm.

In this work, design of a compact single element planar antenna system operating in the ISM frequency band was presented. Due to size reduction proposed antenna useful for wireless communication. The antenna system operates in the 2.44GHz - 2.68GHz frequency band with a bandwidth is 240 MHz. Return loss is – 39.1 dB is obtained. The proposed research work is suitable for USB application.

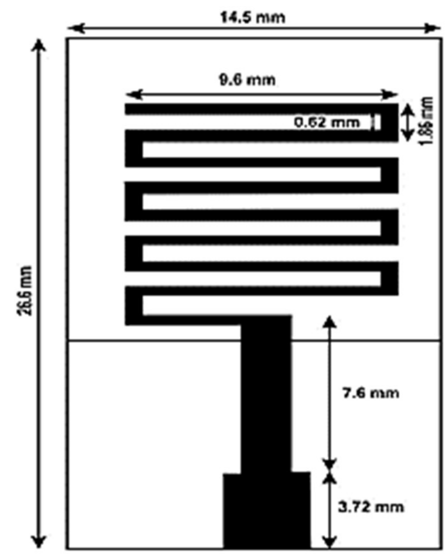

Fig.3.2 Meander antenna structure

The MLA is created using meander line and shaped ground as shown in Figure 3.2; on rectangular FR4 substrate. Height of the substrate is 1.59 mm with relative permittivity 4.4 and ground of size 13.33 mm x 10.04 mm. The total USB dongle PCB area is typically about 14.5mm×26.6 mm where the antenna area. Quarter Wave Transformer is used for impedance matching purpose.

Disadvantages:

- Low Return loss
- Low gain
- weak transmission
- No required frequency

CHAPTER 4

PROPOSED SYSTEM

4.1 PROPOSED ANTENNA

- This work presents compact and slotted antennas for high data wireless applications.
- The antenna is designed on the Ultralam 3850 substrate having a compact dimension of 60 × 40 × 0.1 mm3 as shown in Fig 3.1.
- . This antenna has an operating frequency band from 1.74 to 100 GHz with a bandwidth (BW) ratio of approximately 57.47:1.
- Such an extended frequency coverage makes this antenna operable in a wide variety of wireless application areas, including 5G and the Internet of Things (IoT).
- The proposed antenna prototype is fabricated, and experimental validation is provided through the measurement using a programmable network analyzer (PNA).
- This proposed antenna has resonating frequencies such as 2.34 GHz,3.6 GHz,4.3 GHz,6.6GHz and 8 GHz.
- The proposed antennas have low return loss, high gain and high directivity and low VSWR.
- The simulated performance of the designed antenna is analyzed here with respect to different antenna parameters, including reflection coefficient, radiation pattern, gain, efficiency, and surface current.

- These patch antennas are suitable not only for 5G applications but also for WiFi, WiMAX, Bluetooth and WLAN applications.

. Here, the EM solver software CST Microwave (MW) Studio is used to perform the entire design and simulation. The designed antenna prototype is fabricated, and a thorough measured analysis is carried out to provide an experimental validation. A programmable network analyzer (PNA) with a maximum range of 67 GHz is utilized to perform this measurement. A thorough investigation of frequency response, radiation characteristics, and surface current is conducted to demonstrate that the simulated and measured results conform well with each other.

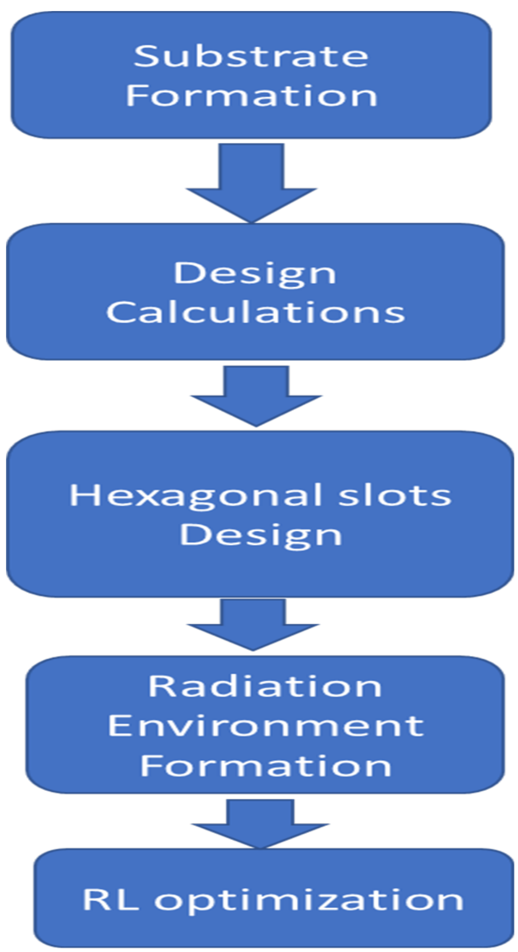

Fig 4.1 System flow diagram

4.3 ANTENNA DESIGN AND OPERATIONAL MECHANISM

Antenna design plays a vital role in determining its performance. Microstrip patch antenna is simpler to construct as it provides easy feeding and has low profile when compared to other type of antennas. It has a patch supporting radiation, along with a ground plane and the substrate. In the proposed designs the ground plane is made of copper andFR4 material is used for making the substrate. The patch can be of any shape, here the shape of patch chosen to be rectangle instead of circular because it provides high gain. The antenna has slots within the patch and is provided with an inset feed. The antenna design parameters are calculated using various formulae. In order to get efficient radiation, a practical rectangular patch width *W* can be given

as,

$$W = \frac{c}{2fr}\sqrt{\frac{2}{\varepsilon_r+1}}$$ …..…………………………. (1)

where *fr*is the antenna's resonant frequency and *c* is the speed of light in vacuum. The effective dielectric constant *εreff*is expressed as,

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{W}}}\right)$$ ………………………… (2)

where h is the substrate height, the effective lengthLeff is obtained as,

$$L_{eff} = \frac{c}{2fr\sqrt{\varepsilon_{reff}}}$$ ……………………………. (3)

Patch's actual length is estimated using the equation 4.

$$L = L_{eff} - 2\Delta L \quad \text{.....................................} (4)$$

where ΔL is extension length of the patch and is given by,

$$\Delta L = 0.412h\frac{\left(\varepsilon_{reff}+0.3\right)\left(\frac{W}{h}+0.264\right)}{\left(\varepsilon_{reff}-0.258\right)\left(\frac{W}{h}+0.8\right)} \quad \text{.........................} (5)$$

There are number of feeding techniques present in operating an antenna such as aperture-coupled coaxial feed, proximity-coupled feed, inset feed, microstrip feed, and coplanar waveguide feed. Any of these techniques can be used ensuring the efficient power transfer between the radiating structure and feeding structure.

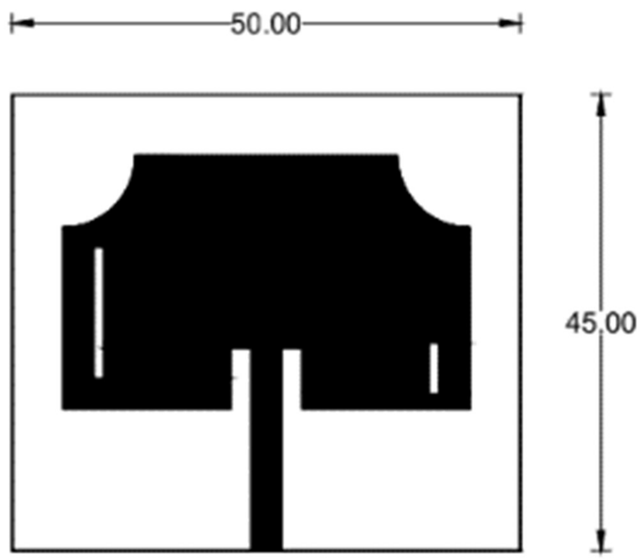

Fig 4.2 Proposed antenna

The length and width of the ground plane are 50 × 45 mm. The height of the substrate is chosen as 1.6 mm. The square patch dimensions are 30× 26 mm. The design includes the removal of square of unit size and circle of radius of 0.75mm from the patch as shown in the figure. The slot width and length are 0.5 mm and 3.99 mm respectively. The overall length of the feed line is 26 mm as shown in Fig.4.1 These design parameters are calculated using the above-mentioned formulae and the proposed antennas are connected with 50Ωtransmission feed line.

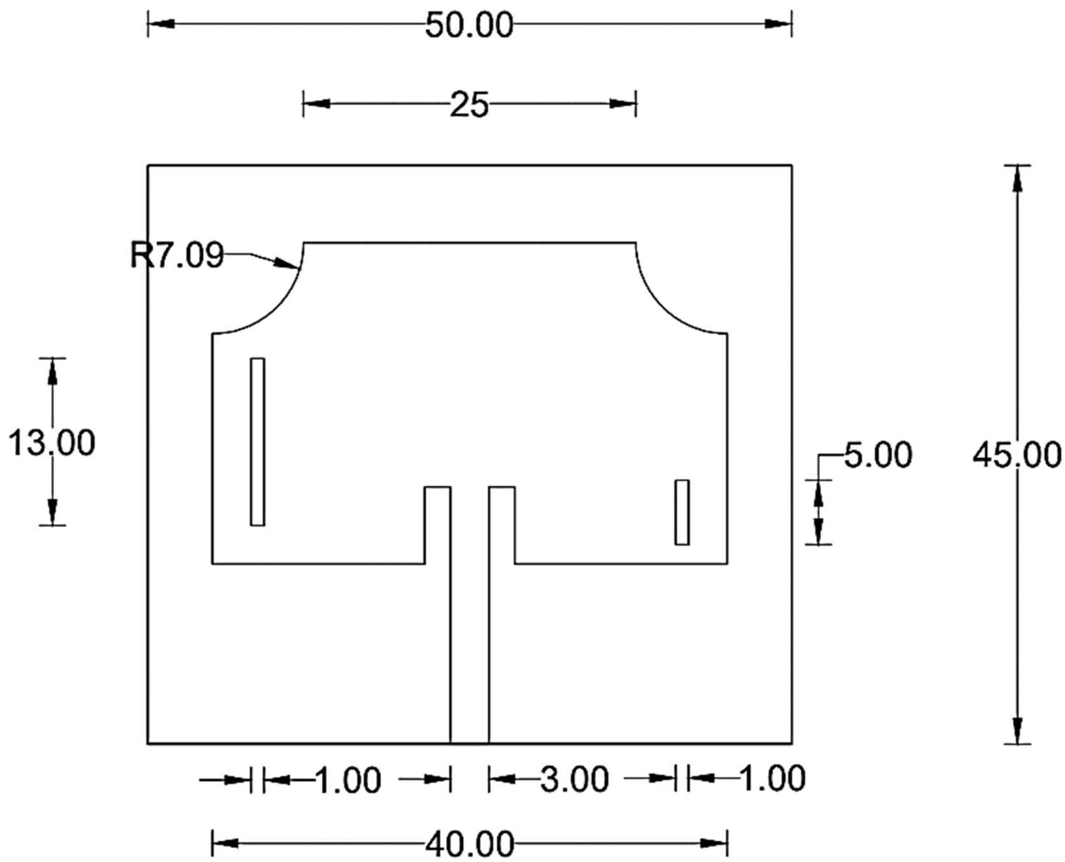

Fig 4.3 Proposed antenna with dimensions

CHAPTER-5

INTRODUCTION OF DOMAIN

5.1 ANTENNA

Antennas are a very important component of communication systems. By definition, an antenna is a device used to transform an RF signal, traveling on a conductor, into an electromagnetic wave in free space. Antennas demonstrate a property known as *reciprocity*, which means that an antenna will maintain the same characteristics regardless of if it is transmitting or receiving. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band of the radio system to which it is connected, otherwise the reception and the transmission will be impaired. When a signal is fed into an antenna, the antenna will emit radiation distributed in space in a certain way. A graphical representation of the relative distribution of the radiated power in space is called a *radiation pattern*.

Antenna Glossary

Before we talk about specific antennas, there are a few common terms that must be defined and explained:

Input Impedance

For an efficient transfer of energy, the impedance of the radio, of the antenna and of the transmission cable connecting them must be the same. Transceivers and their transmission lines are typically designed for 50 Ω impedance. If the antenna has an impedance different from 50Ω, then there is a mismatch and an impedance matching circuit is required.

Return loss

The return loss is another way of expressing mismatch. It is a logarithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna from the transmission line. The relationship between SWR and return loss is the following:

$$\text{Return Loss (in dB)} = 20\log_{10}\frac{SWR}{SWR-1} \qquad \text{…………………} (6)$$

5.2 BANDWIDTH

The bandwidth of an antenna refers to the range of frequencies over which the antenna can operate correctly. The antenna's bandwidth is the number of Hz for which the antenna will exhibit an SWR less than 2:1.

The bandwidth can also be described in terms of percentage of the center frequency of the band.

$$BW = 100 \times \frac{F_H - F_L}{F_C} \qquad \text{……………………………} (7)$$

where F_H is the highest frequency in the band, F_L is the lowest frequency in the band, and F_C is the center frequency in the band. In this way, bandwidth is constant relative to frequency. If bandwidth was expressed in absolute units of frequency, it would be different depending upon the center frequency. Different types of antennas have different bandwidth limitations.

Directivity and Gain

Directivity is the ability of an antenna to focus energy on a particular direction when transmitting, or to receive energy better from a particular direction when receiving. In a static situation, it is possible to use the antenna directivity to concentrate the radiation beam in the wanted direction. However, in a dynamic system where the transceiver is not fixed, the antenna should radiate equally in all directions, and this is known as an omni-directional antenna. Gain is not a quantity which can be defined in terms of a physical quantity such as the Watt or the Ohm, but it is a dimensionless ratio. Gain is given in reference to a standard antenna. The two most common reference antennas are the isotropic antenna and the resonant half-wave dipole antenna. The isotropic antenna radiates equally well in all directions. Real isotropic antennas do not exist, but they provide useful and simple theoretical antenna patterns with which to compare real antennas. Any real antenna will radiate more energy in some directions than in others. Since it cannot create energy, the total power radiated is the same as an isotropic antenna, so in other directions it must radiate less energy.

The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. Usually, we are only interested in the maximum gain, which is the gain in the direction in which the antenna is radiating most of the power. An antenna gains of 3 dB compared to an isotropic antenna would be written as 3 dBi. The resonant half-wave dipole can be a useful standard for comparing to other antennas at one frequency or over a very narrow band of frequencies. To compare the dipole to an antenna over a range of frequencies requires a number of dipoles of different lengths. An antenna gains of 3 dB compared to a dipole antenna would be written as 3 dBd.

The method of measuring gain by comparing the antenna under test against a known standard antenna, which has a calibrated gain, is technically known as a gain transfer technique. Another method for measuring gain is the 3 antennas method., where the transmitted and received power at the antenna terminals is measured between three arbitrary antennas at a known fixed distance.

Radiation Pattern

The radiation or antenna pattern describes the relative strength of the radiated field in various directions from the antenna, at a constant distance. The radiation pattern is a reception pattern as well, since it also describes the receiving properties of the antenna. The radiation pattern is three-dimensional, but usually the measured radiation patterns are a two-dimensional slice of the three-dimensional pattern, in the horizontal or vertical planes. These pattern measurements are presented in either a *rectangular* or a *polar* format. The following figure shows a rectangular plot presentation of a typical 10 element Yagi. The detail is good, but it is difficult to visualize the antenna behavior at different directions.

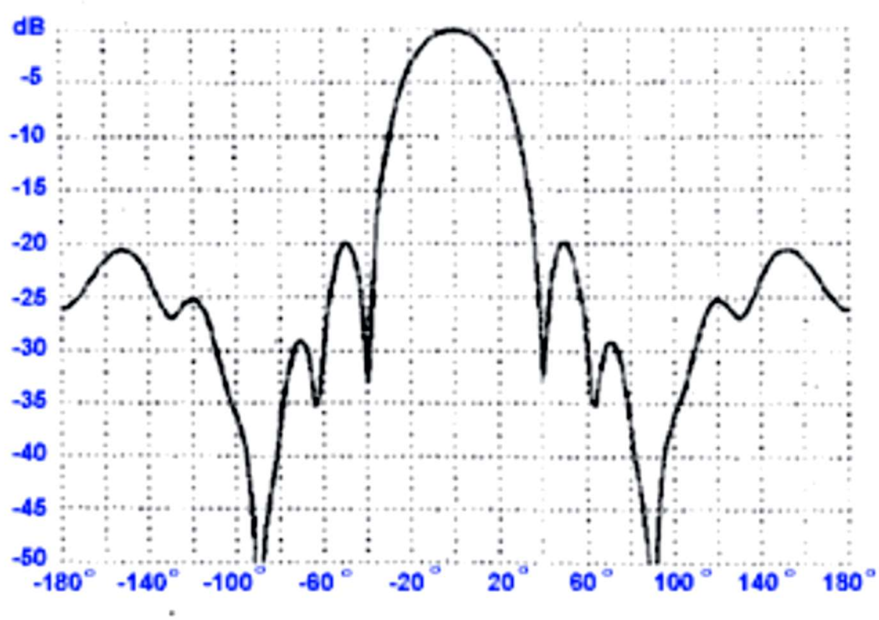

Fig.5.1 Behavior of antenna

Polar coordinate systems are used almost universally. In the polar coordinate graph, points are located by projection along a rotating axis (radius) to an intersection with one of several concentric circles. Following is a polar plot of the same 10 element Yagi antenna.

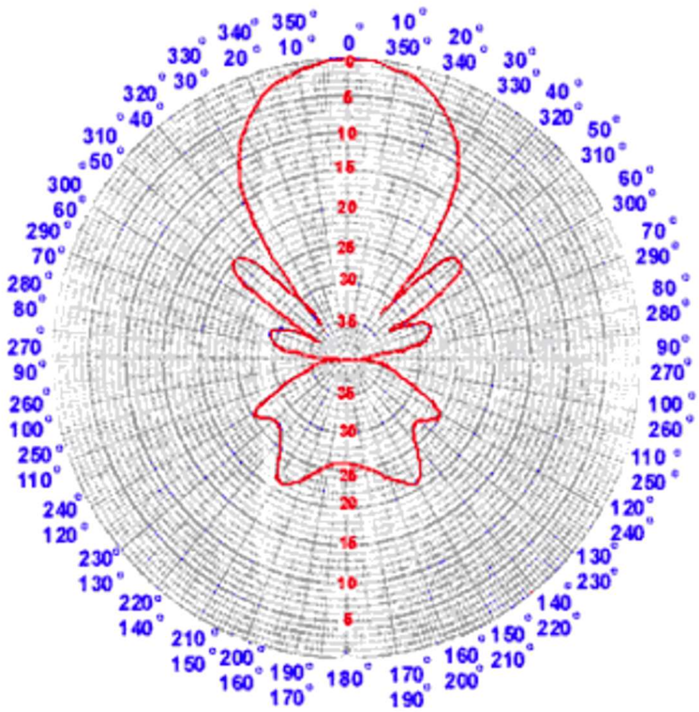

Fig.5.2 Polar for Yogi antenna

Polar coordinate systems may be divided generally in two classes: *linear* and *logarithmic*. In the linear coordinate system, the concentric circles are equally spaced, and are graduated. Such a grid may be used to prepare a linear plot of the power contained in the signal. For ease of comparison, the equally spaced concentric circles may be replaced with appropriately placed circles representing the decibel response, referenced to 0 dB at the outer edge of the plot. In this kind of plot the minor lobes are suppressed. Lobes with peaks more than 15 dB or so below the main lobe disappear because of their small size. This grid enhances plots in which the antenna has a high directivity and small minor lobes. The voltage of the signal, rather than the power, can also be plotted on a linear coordinate system. In this case, too, the directivity is enhanced and the minor lobes suppressed, but not in the same degree as in the linear power grid.

5.3 BEAMWIDTH

An antenna's beamwidth is usually understood to mean the half-power beamwidth. The peak radiation intensity is found and then the points on either side of the peak which represent half the power of the peak intensity are located. The angular distance between the half power points is defined as the beamwidth. Half the power expressed in decibels is —3dB, so the half power beamwidth is sometimes referred to as the 3Db beamwidth. Both horizontal and vertical beamwidths are usually considered.

Assuming that most of the radiated power is not divided into sidelobes, then the directive gain is inversely proportional to the beamwidth: as the beamwidth decreases, the directive gains increases.

Sidelobes

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. The peaks are referred to as sidelobes, commonly specified in *dB down from the main lobe*.

Nulls

In an antenna radiation pattern, a *null* is a zone in which the effective radiated power is at a minimum. A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as suppression of interfering signals in a given direction.

Polarization

Polarization is defined as the orientation of the electric field of an electromagnetic wave. Polarization is in general described by an ellipse. Two special cases of elliptical polarization are linear polarization and circular polarization. The initial polarization of a radio wave is determined by the antenna. With linear polarization the electric field vector stays in the same plane all the time. Vertically polarized radiation is somewhat less affected by reflections over the transmission path. Omni directional antennas always have vertical polarization. With horizontal polarization, such reflections cause variations in received signal strength. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.

In circular polarization the electric field vector appears to be rotating with circular motion about the direction of propagation, making one full turn for each RF cycle. This rotation may be righthand or lefthand. Choice of polarization is one of the design choices available to the RF system designer.

5.4 TYPES OF ANTENNAS

A classification of antennas can be based on:

Frequency and size

Antennas used for HF are different from the ones used for VHF, which in turn are different from antennas for microwave. The wavelength is different at different frequencies, so the antennas must be different in size to radiate signals at the correct wavelength. We are particularly interested in antennas working in the microwave range, especially in the 2.4 GHz and 5 GHz frequencies. At 2.4 GHz the wavelength is 12.5 cm, while at 5 Ghz it is 6 cm.

Directivity

Antennas can be omnidirectional, sectorial or directive. Omnidirectional antennas radiate the same pattern all around the antenna in a complete 360 degrees pattern. The most popular types of omnidirectional antennas are the Dipole-Type and the Ground Plane. Sectorial antennas radiate primarily in a specific area. The beam can be as wide as 180 degrees, or as narrow as 60 degrees. Directive antennas are antennas in which the beamwidth is much narrower than in sectorial antennas. They have the highest gain and are therefore used for long distance links. Types of directive antennas are the Yagi, the biquad, the horn, the helicoidal, the patch antenna, the Parabolic Dish and many others.

Physical construction

Antennas can be constructed in many different ways, ranging from simple wires to parabolic dishes, up to coffee cans. When considering antennas suitable for 2.4 GHz WLAN use, another classification can be used:

Application

we identify two application categories which are Base Station and Point-to-Point. Each of these suggests different types of antennas for their purpose. Base Stations are used for multipoint access. Two choices are Omni antennas which radiate equally in all directions, or Sectorial antennas, which focus into a small area. In the Point-to-Point case, antennas are used to connect two single locations together. Directive antennas are the primary choice for this application.

CHAPTER-6

SOFTWARE REQUIREMENT

6.1 HFSS (HIGH FREQUENCY STRUCTURE SIMULATOR)

HFSS is a high-performance full-wave Electro Magnetic (EM) field simulator for arbitrary 3D volumetric passive device modeling that takes advantage of the familiar Microsoft Windows graphical user interface. It integrates simulation, visualization, solid modeling, and automation in an easy-to-learn environment where solutions to your 3D EM problems are quickly and accurately obtained. Ansoft HFSS employs the Finite Element Method (FEM), adaptive meshing, and brilliant graphics to give you unparalleled performance and insight to all of your 3D EM problems. Ansoft HFSS can be used to calculate parameters such as SParameters, Resonant Frequency, and Fields. Typical uses include:

- Package Modeling – BGA, QFP, Flip-Chip
- PCB Board Modeling – Power/Ground planes, Mesh Grid Grounds, Backplanes
- Silicon/GaAs - Spiral Inductors, Transformers
- EMC/EMI – Shield Enclosures, Coupling, Near- or Far-Field Radiation
- Antennas/Mobile Communications – Patches, Dipoles, Horns, Conformal Cell Phone Antennas, Quadrafilar Helix, Specific Absorption Rate (SAR), Infinite Arrays, Radar Cross Section (RCS), Frequency Selective Surfaces (FSS)
- Connectors – Coax, SFP/XFP, Backplane, Transitions
- Waveguide – Filters, Resonators, Transitions, Couplers
- Filters – Cavity Filters, Microstrip, Dielectric

HFSS is an interactive simulation system whose basic mesh element is a tetrahedron. This allows you to solve any arbitrary 3D geometry, especially those with complex curves and shapes, in a fraction of the time it would take using other techniques. The name HFSS stands for High Frequency Structure Simulator. Ansoft pioneered the use of the Finite Element Method (FEM) for EM simulation by developing/implementing technologies such as tangential vector finite elements, adaptive meshing, and Adaptive Lanczos-Pade Sweep (ALPS). Today, HFSS continues to lead the industry with innovations such as Modes-to-Nodes and Full-Wave Spice™.

Ansoft HFSS has evolved over a period of years with input from many users and industries. In industry, Ansoft HFSS is the tool of choice for high-productivity research, development, and virtual prototyping.

6.2 SYSTEM REQUIREMENTS

- Microsoft Windows XP (32/64), Windows 2000, or Windows 2003 Server. For upto-date information, refer to the HFSS Release Notes.
- Pentium –based computer
- 128MB RAM minimum
- 8MB Video Card minimum
- Mouse or another pointing device
- CD-ROM drive

6.3 INSTALLING THE ANSOFT HFSS SOFTWARE

For up-to-date information, refer to the HFSS Installation Guide

Starting Ansoft HFSS

1. Click the Microsoft Start button, select Programs, and select the Ansoft, HFSS10 program group. Click HFSS 10.

2. Or double click on the HFSS 10 icon on the Windows Desktop

Fig.6.1 Icon of HFSS

Converting Older HFSS file to HFSS v10

- Because of changes to the HFSS files with the development of HFSS v10, opening a HFSS document from an earlier release may take more time than you are used to experiencing. However, once the file has been opened and saved, subsequent opening time will return to normal.
- Ansoft HFSS v10 provides a way for you to automatically convert your HFSS projects from an earlier version to the HFSS v10 format.

To access HFSS projects in an earlier version.

From HFSS v10,

1. Select the menu item File > Open

2. Open dialog

1. Files of Type: Ansoft Legacy EM Projects (.cls)

2. Browse to the existing project and select the .cls file

3. Click the Open button

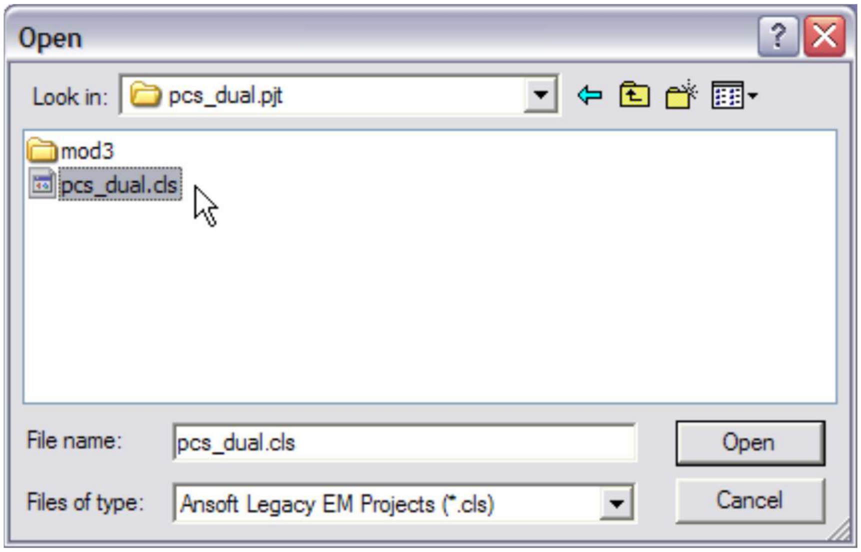

Fig.6.2 Open file

Getting Help

If you have any questions while you are using Ansoft HFSS you can find answers in several ways:

Ansoft HFSS Online Help provides assistance while you are working.

- To get help about a specific, active dialog box, click the Help button in the dialog box or press the F1 key.
- Select the menu item Help> Contents to access the online help system.
- Tooltips are available to provide information about tools on the toolbars or dialog boxes. When you hold the pointer over a tool for a brief time, a tooltip appears to display the name of the tool.
- As you move the pointer over a tool or click a menu item, the Status Bar at the bottom of the Ansoft HFSS window provides a brief description of the function of the tool or menu item.
- The Ansoft HFSS Getting Started guide provides detailed information about using HFSS to create and solve 3D EM projects.

Ansoft Technical Support

- To contact Ansoft technical support staff in your geographical area, please log on to the Ansoft corporate website, www.ansoft.com and select Contact.
- Your Ansoft sales engineer may also be contacted in order to obtain this information.

Visiting the Ansoft Web Site

- If your computer is connected to the Internet, you can visit the Ansoft Web site to learn more about the Ansoft company and products.

- From the Ansoft Desktop
  - Select the menu item Help>Ansoft Corporate Website to access the Online Technical Support (OTS) system.
- From your Internet browser
  - Visit www.ansoft.com

6.4 ANSOFT TERMS

The Ansoft HFSS window has several optional panels:

- A Project Manager which contains a design tree which lists the structure of the project.
- A Message Manager that allows you to view any errors or warnings that occur before you begin a simulation.
- A Property Window that displays and allows you to change model parameters or attributes.
- A Progress Window that displays solution progress.
- A 3D Modeler Window which contains the model and model tree for the active design.

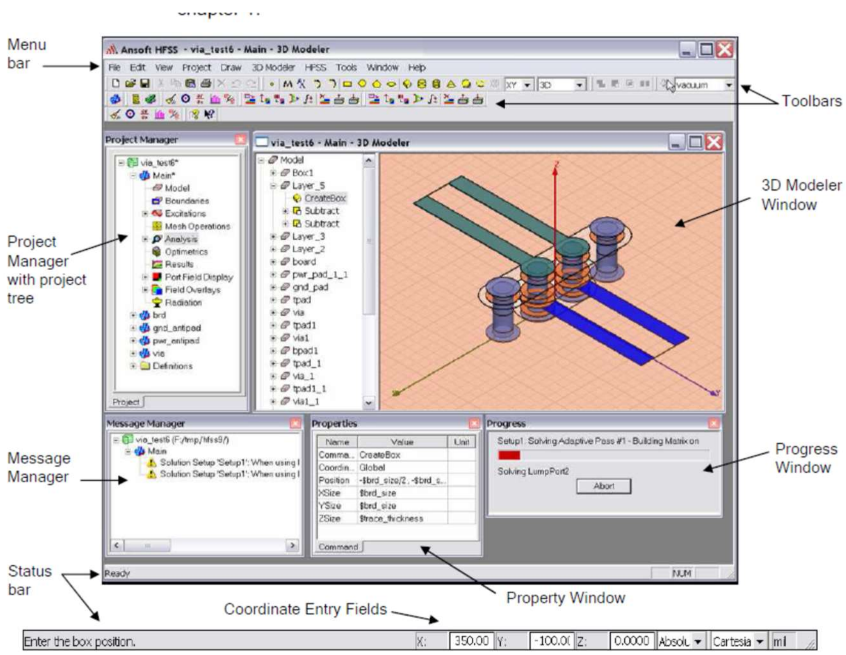

Fig.6.3 Window Model

CHAPTER-7
SIMULATION RESULTS

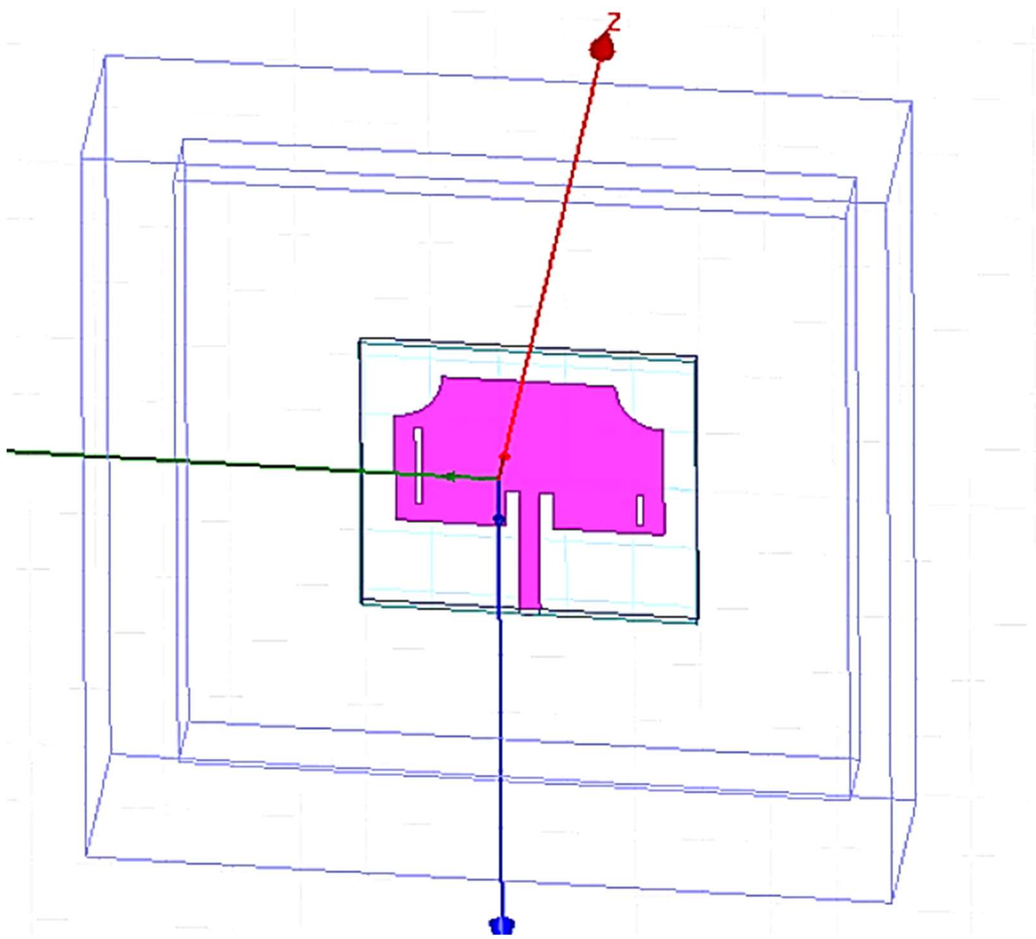

Fig.7.1 Proposed structure.

The above figure shows the radiating element design of proposed antenna. In radiator, the hexagon cuts are created to tuned for the required frequency. The radiator is formed a flexible substrate.

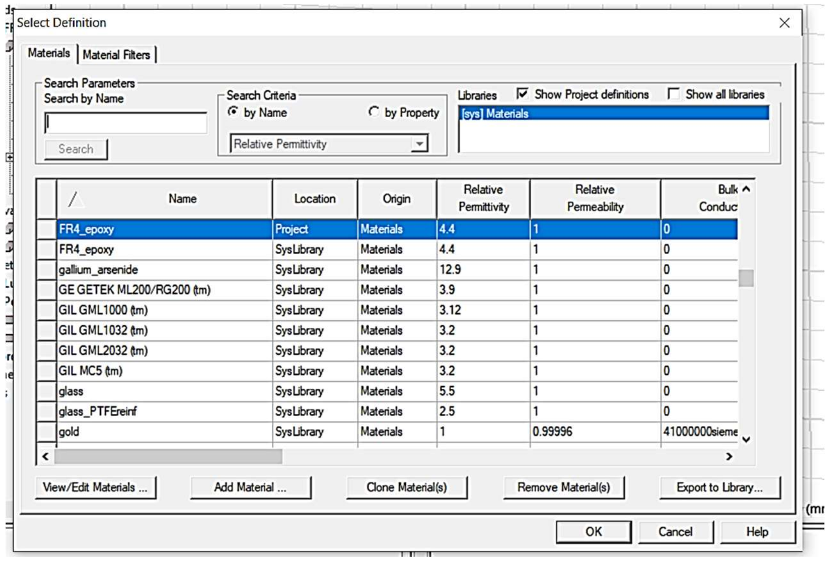

Fig.7.2 Material design

The above figure shows jean substrate design for proposed antenna design. By using film technology the proposed antenna mounted on ultraalarm substrate.

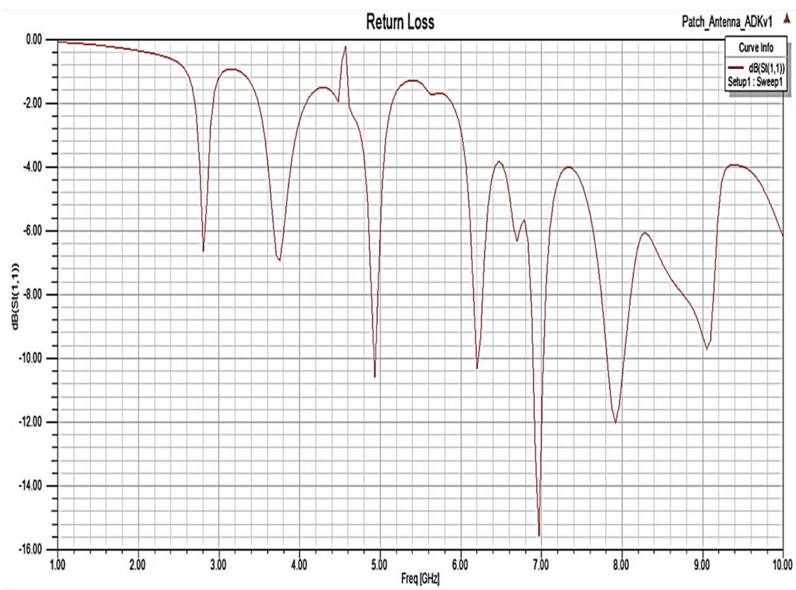

Fig.7.3 Return loss

The above figure shows the return loss analysis of proposed antenna. The proposed antenna achieved a RL of -13 with the tuned frequency. The effect of creating various slots analysed for different cuts in a radiating elements.

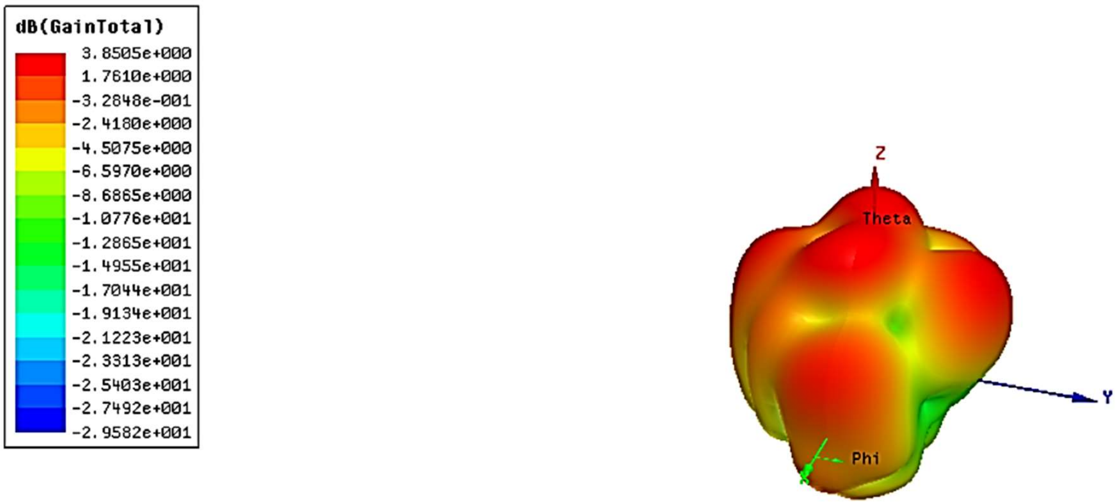

Fig.7.4 3D Gain

Figure shows the gain analysis of proposed antenna. The proposed model achieved a gain value of 5.434 for the tuned frequency. The average values of gain achieved about 5 in the jean substrate.

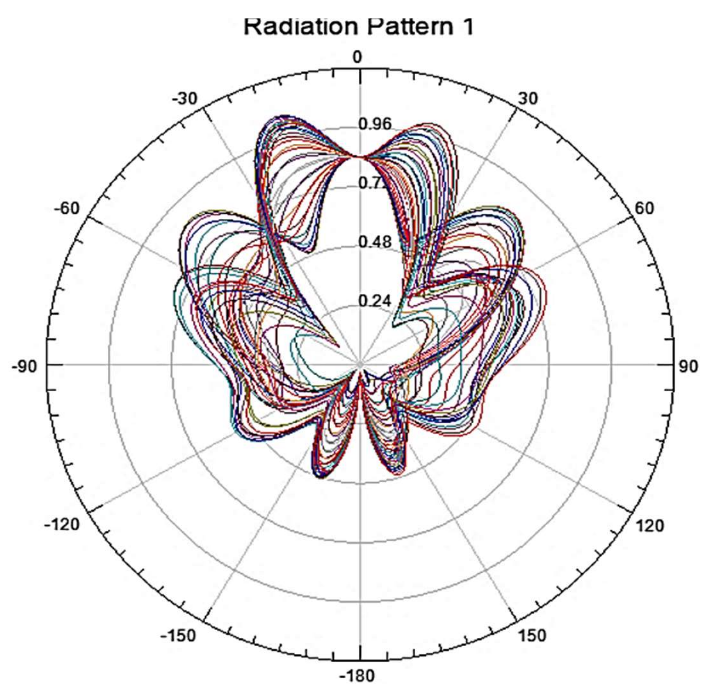

Fig.7.5 Radiation pattern of proposed antenna

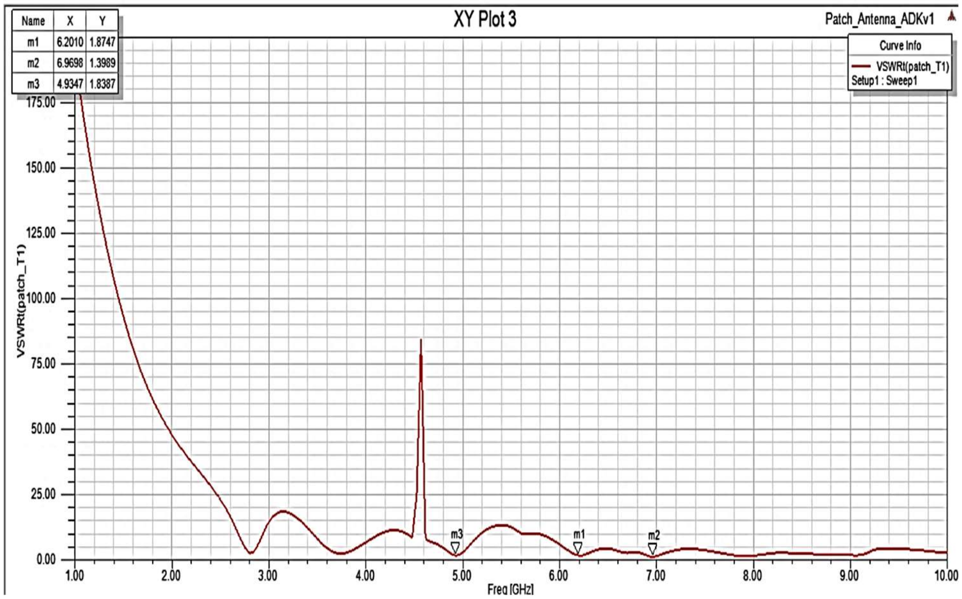

Fig.7.6 VSWR measurement

. No	Parameter	Existing	Proposed
1	RL	-13	-16
2	Gain	3.43	3.8
3	VSWR	1.54	1.62

Fig.7.7 Performance analysis

Table shows the performance comparison of proposed antenna. Compared to other design, the proposed antenna shows higher gain, RL and VSWR results.

CHAPTER 8

CONCLUSION

Multiband patch antennas using microstrip inset feed line suitable for 5G applications is elaborated in the work. The antennas proffered are modeled, designed and analyzed in HFSS software. Gain plot, radiation pattern, rectangular p lot and field overlay are verified for the operation of antennas in frequency band that ranges in the sub 6gigahertz and the millimeter waves. The designed antennas have very low return loss of -10.2 dB, -15 dB and -12.44 dB for 6 GHz,7 GHz, 8 GHz frequencies respectively and the dimensions of the antenna have been optimized to 50×45×0.8 mm3.

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