5G Antenna Design using SIW Technique

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This thesis is dedicated to *my beloved parents*

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Contents

List of Abbreviations and Symbols

Abbreviations

SIW	Substrate Integrated Waveguide
FR	Frequency Range
GCPW	Grounded Coplanar Waveguide
ESIW	Empty Substrate Integrated Waveguide

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Abstract

Owing to exponential growth in mobile communication and the requirement of interconnecting multiple wireless devices, high data rates, low latency and large bandwidth are the basic requirements. To serve this purpose, new communication standard i.e. 5G is in its development phase. In next phase of 5G, millimeter waves are used for communication due to their advantages such as higher capacity, large bandwidths, high density of devices, extreme base stations, ultra-reliable device-to-device and machine-to-machine communications.

However,due to shorter wavelengths in millimeter wave region, radiated RF energy face high attenuation rates. To overcome this problem, high gain and narrow beam antennas are required for seamless communication. For narrow beamwidth, array configurations of individual radiating elements with dedicated feed or an array of multiple slots are reported in the literature. Multiple technologies are used in published designs such as Leaky Wave Antennas, Planar Antennas, SIW Slot Antennas etc. Among these antennas, SIW technology due to its simpler structure and easy integration possibility with planar circuits, is used in the thesis to design a directive antenna at 28 GHz band.

In this thesis, the antenna is based on a single-layer SIW slot array fed by microstrip to SIW feed transition. The designed prototype has a footprint of $21 \times 28\text{mm}^2$ on a 0.254 mm thick substrate with a unidirectional beam having a gain of 14 dBi and a narrow beam in both E and H planes. The antenna exhibits -10dB impedance bandwidth of 3 GHz (27.3-30.3 GHz).

Chapter 1

Introduction

The rapid expansion and innovation of wireless communication networks has raised the demand of high-quality, high-capacity networks for wireless users and applications. Wireless communication, like wired communication (optical fibre), aims to deliver high-quality, dependable communication, and each new generation of services marks a significant stride (or jump) in that direction. This evolutionary adventure began in 1979 with 1G and is now ongoing with 5G.

1.1 Generations

1.1.1 1G - First Generation

This was the first mobile phone technology generation. In the late 1970s, the first commercial cellular network was created, with fully implemented standards being established throughout the 1980s. These are analogue telecommunications standards that were launched in the 1980s and lasted until 2G digital telecommunications supplanted them. 1G had a maximum speed of 2.4 Kbps.

1.1.2 2G - Second Generation

When cell phones transitioned from 1G to 2G, it was the first big update. With General Packet Radio Service (GPRS), the maximum speed is 50 Kbps, or 1 Mbps with Enhanced Data Rates for GSM Evolution (EDGE). Prior to the big transition from 2G to 3G wireless networks, the lesser-known 2.5G and 2.75G standards served as a bridge.

1.1.3 3G - Third Generation

The main network architecture of the 3G standard is UMTS, which stands for Universal Mobile Telecommunications System. For a "real" 3G network, the UN's International Telecommunications Union IMT-2000 standard calls for fixed speeds of 2Mbps and mobile rates of 384kbps. HSPA+ has a potential maximum speed of 21.6 Mbps.

1.1.4 4G - Fourth Generation

Its purpose is to provide high speed , high quality and high capacity to users while improving security and lower the cost of voice and data services, multimedia and internet over IP.The two important 4G standards are WiMAX and LTE (Long Term Evolution) that is a series of upgrades to existing UMTS technology and will be rolled out on Telstra's existing 1800MHz frequency band. The max speed of a 4G network when the device is moving is 100 Mbps or 1 Gbps for low mobility communication like when stationary or walking, latency reduced from around 300ms to less than 100ms, and significantly lower congestion.

1.1.5 5G - Fifth Generation

5G promises far faster data speeds, increased connection density, and significantly lower latency among other benefits. Device-to-device communication, reduced battery usage, and greater overall wireless coverage are major 5G ambitions. The maximum speed of 5G is expected to be 35.46 Gbps, which is 35 times faster than 4G. Massive MIMO, Millimeter Wave Mobile Communications, and other key technologies to keep an eye on. Massive MIMO, milimetre wave, tiny cells, and Li-Fi are just a few of the emerging technologies that might be employed to deliver 10Gb/s to a user with previously unheard-of low latency, and link at least 100 billion devices. Comparison among these different technologies is given in Table 1.1.

1.2 5G Communication

Radio frequencies (also known as spectrum) are used in wireless communications systems to transmit data across long distances. 5G is similar to 4G, however it uses higher bands

Features	1G	2G	3G	4G	5G
Development	1970-84	1980-99	1990-2002	2000-10	10-15
Technology	Amps	GSM	WCDMA	LTE	MIMO, mmWaves
Frequency	30 kHz	1.8 GHz	1.6-2 GHz	2-8 GHz	3-30 GHz
Bandwidth	2kbps	64kbps	2Mbps	1Gbps	1Gbps-higher

Table 1.1: Communication Technologies Comparison

of radio frequencies that are less crowded. This enables it to transport more data at a much quicker rate. Millimeter waves are the higher frequency bands (mmwaves). While higher bands are quicker in carrying data, sending across long distances might be problematic. Physical things, such as trees and buildings, may readily obstruct them. 5G will use numerous input and output antennas to improve signals and capacity throughout the wireless network to overcome this difficulty.

Shannon Hartley theorem has been proved helpful in comprehending the sustainability for faster data speed as shown below:

$$C = M \times \; Blog2(1 + S/N) \tag{1.2.1}$$

In the above equation, C represents channel capacity in bit/second whereas M, B represents number of channels and bandwidth of each channel. It is self-evident, based on the theory, that in order to increase channel capacity, changes in the system M, B, and S/N must be made. To increase channel capacity, 5G, which is an evolution of 4G. It uses various well-known and long-established methods in its architecture.

1.3 5G Antennas

5G NR objectives requires new antenna designs that use active antenna arrays to provide better coverage, reduce interference, and increase data-carrying capacity. To operate in its full range of assigned frequencies, 5G NR uses a scalable framework that functions at frequencies between 450 megahertz (MHz) and 6GHz (Frequency Range 1 [FR1]) and between 24.25 and 52.6GHz (Frequency Range 2 [FR2]). A 1 GHz signal, which is in FR1, has a wavelength of about 30 centimeters (cm). A 28 GHz signal in FR2 has a wavelength of 1.07mm. The same antenna may not work for these two signals. 5G devices operating in both FR1 and FR2 bands may require at least two sets of antennas. This is manageable in large equipment and base stations that have room for multiple antenna arrays. It becomes a significant design challenge for small devices and cell phones.

For designing antenna for 5G communication, following parameters are taken into account:

Parameter	Value	Ref
Gain	5-10 dBi	[13]
Pattern	fan / Pencil beam	[1]
Beamwidth	$10\text{deg} - 30\,\text{deg}(SinglePlane)$	[11]
Size	16×16 To 48×48 mm^2	[6]

Table 1.2: Antenna Requirements

1.4 Antenna Structures

There are three main antenna types that have been reported in literature over the past few years.

1.4.1 Planar Antennas

A planar antenna puts both the active and parasitic elements on one plane, making them two dimensional. Planar antennas include microstrip antennas and printed circuit board antennas. The antenna “patches” may be square, triangular, or circular. These antennas were widely used because low-cost ultra-wideband antenna, especially when they’re mass produced via printed circuit board technology. These antennas are used for arrays because of large aperture. Directional beam control is achieved by varying the phase of each element. Also, Planar antennas have a low profile. They can support linear and circular polarization based on the design used.

There are several disadvantages in using this antenna. The low profile of planar makes them popular in arrays. However, the elements and feed lines influence each other. This

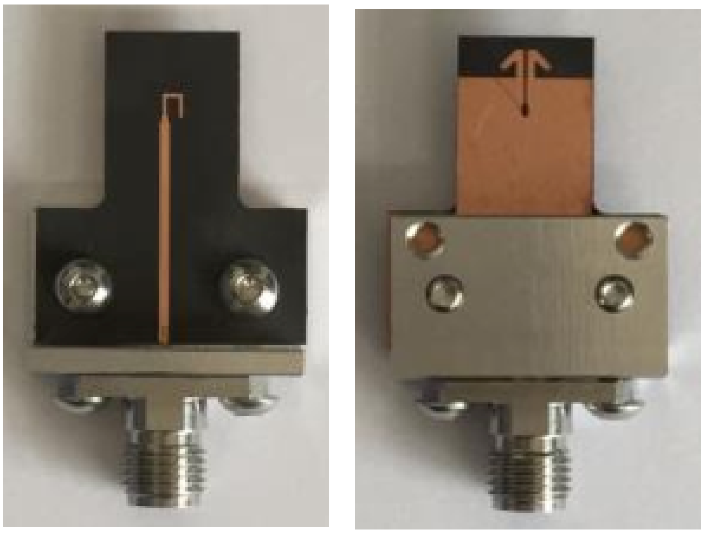


Figure 1.1: Printed Planar Dipole Antenna[1]

means that planar arrays need to be designed to account for mutual coupling between elements and internal reflections. Yet arrays are needed for improving efficiency. Many planar antennas have a narrow bandwidth in mm Wave bands. This makes efficiency of microstrip antennas low as they have low radiation efficiency and low gain. This can be improved by loading notches and putting a shorting pin in the radiating patch. Gaps between the patches of the planar antenna also improve the gain. This is why we see quad patch antennas with four mid-sized patches instead of an antenna with a single, very large "patch."

1.4.2 Single Layer SIW Antenna

Substrate integrated waveguide (SIW) is a technology enabling the design and manufacture of miniaturized waveguides. SIW technology mimics a dielectric waveguide that is implemented in a planar form due to the use of metallized vias, which form a waveguide in the employed substrate. In contrast with microstrip technology, SIW can be used to design radio-frequency devices operating at millimeter-wave frequencies (mmWave).

SIW antennas are of special interest due to the ease of integrating them as radiating elements in a complete system [14]. Due to the low profile of SIW technology, a broad variety of SIW antennas have been conceived with both single and multiple layers. For instance, various researchers [15] have employed several SIW layers to create an antenna with a progressive aperture, where the substrate is drilled to improve the bandwidth and the gain. In [2], a 60 GHz antenna array is presented where multiple SIW layers were fabricated on low-temperature co-fired ceramic (LTCC). In this case, the radiating element is an aperture backed by a cavity. many other antennas have also been designed with layers of different types.

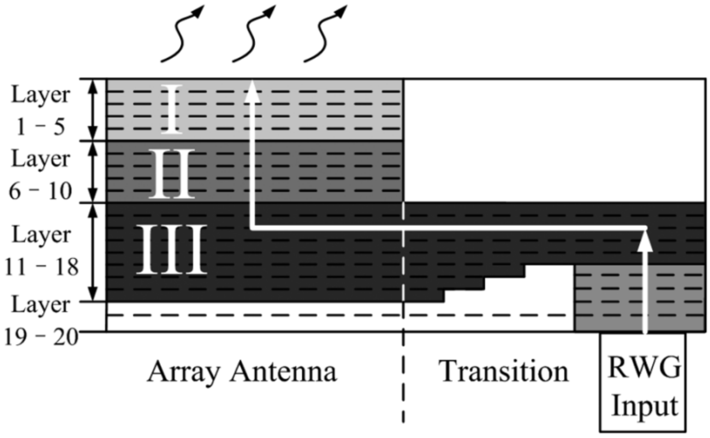


Figure 1.2: Side View of Array[2]

1.4.3 Multi-Layered Antenna

The major problem of microstrip antenna is its narrow bandwidth. To achieve broader bandwidth performance the multi-layer microstrip patch antenna structure can be used. Microstrip antenna consists of a metal conducting patch on the top side and, can be printed on a thin grounded dielectric surface called substrate. In the simplest cases, a Single radiating element can be energized via the coaxial line, microstrip line, or via electro-magnetic coupling.

An example antenna made in multi layer technology can be constructed as follows. The radiating Element is a rectangular patch etched on the underside of the upper layer of the laminate and Stimulated through the slot cut in the shield covering the upper side of the lower layer of the Laminate. The slot can be powered by asymmetrical strip line or concentric lines. This type of antennas has the following characteristics: parameters of the laminate used to build the antenna and the power line can be chosen optimally, it is possible to achieve very low levels of unwanted radiation, the need of precise composing of the package, difficult theoretical analysis, and large possibilities of adjustment of the impedance .

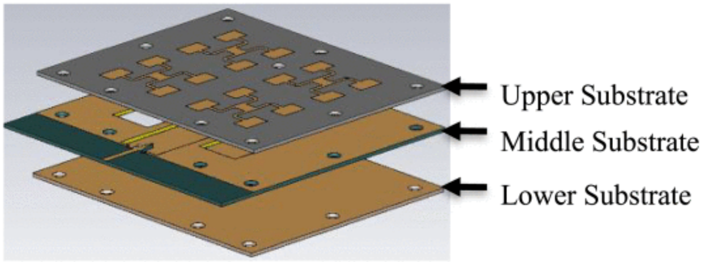


Figure 1.3: Multi-Layer Array[3]

It can be concluded that, for both classic and multi-layer antennas, the presence of the dielectric has an impact on the reduction of the dimensions of the radiating element in comparison to the option without the dielectric. One of the major disadvantages of classic strip antennas is their relatively low energy efficiency. This is mostly due to losses in the dielectric. However, in multi-layer antenna, the radiated electromagnetic wave in a large part is formed not in the dielectric but in the free space. So we can expect smaller losses.

1.4.4 Challenges Faced in 5G Antenna Design

5G NR objectives requires new antenna designs that use active antenna arrays to provide better coverage, reduce interference, and increase data-carrying capacity. To operate in its full range of assigned frequencies, 5G NR uses a scalable framework that functions at frequencies between 450 megahertz (MHz) and 6GHz (FR1) and between 24.25 and 52.6GHz (FR2). The challenge for antenna designers is physics. A 1GHz signal, which is in FR1, has a wavelength of about 30 centimeters (cm). A 28GHz signal in FR2 has a wavelength of 1.07mm. The same antenna will not work for these two signals, so 5G devices operating in both FR1 and FR2 bands will require at least two sets of antennas. This is manageable in large equipment and base stations that have room for multiple antenna arrays. It becomes a significant design challenge for small devices and cell phones.

1.5 Motivation

Multiple frequency bands in FR-2 (24.25 -52.6 GHz) have been selected for use in super data layer (eMBB) of 5G networks. These frequency bands will be used for addressing specific cases requiring very high data rates. Assigned bandwidth for these bands will be of 800 MHz. These high frequencies (above 6 GHz) will also play an important role for 5G in meeting the ITU-R IMT-2020 standard. Coordinated efforts are being made by different regions and countries for standardization of bands. 24.25–29.5 GHz and the 37-43.5 GHz bands are the most promising bands for 5G deployments and are being utilized by different regions for early deployment of 5G networks. Examples of frequency bands in FR-2, utilized by different countries/ regions is tabulated below:

Prominent 5G Bands for Mobile Communication		
Region	Bands(GHz)	Bandwidth(GHz)
Europe	25.25- 27.50	2.25
USA	27.50 - 28.35 37.00 - 38.60	0.85 .6
China	24.75 - 27.50 37.00 - 42.50	2.75 5.5
Japan	27.50 - 29.50	2

Table 1.3: mm-Wave Bands in Different Regions World Wide

1.6 Problem Statement

In FR2 i.e. mmWave band of 5G systems an antenna is required having small foot print with low cost and easy fabrication . Due to high atmospheric attenuation rate at above 20 GHz frequencies, the antenna is required to have high gain in addition to uni directional broadside beam with low side lobe levels for reliable communication in desired band. Furthermore, closely placed but different frequency bands are being utilised in different regions worldwide. This requires a wide band antenna to cover all frequency bands regardless of operating region.

Chapter 2

Literature Review

In this chapter, state of the art published antennas are discussed. Antennas are divided in to Planar antennas, Single layer SIW and multilayered SIW antennas. Further, feeding mechanism of the antennas is given due importance in analysis and comparison of the antennas. Antenna dimensions, substrate thickness, impedance bandwidth, Gain and fabrication complexity levels are also discussed in this chapter. Literature is analyzed in this chapter on the basis of antenna categories .i.e. Planar, Single Layer SIW and Multi layer SIW antennas.

2.1 Planar Antennas

In [1] a broad band dipole is designed and arranged in array configuration with 8 elements in x-plane. Array is fed by integrated balun, which consists of a folded microstrip line and a rectangular slot. Dipole elements in the antenna are tilted at angle of 45°to make its size compact. A stub is inserted in between adjacent dipoles to keep mutual coupling levels below -20 dB. Antenna is simulated to observe its scanning performance in E-plane by feeding different phases of input at all 8-elements. Substrate thickness of 0.254mm is used in fabrication while overall dimensions of the antenna are 48Ö48mm^2. Achieved –10 dB S11 bandwithd is 36.2% at 28 GHz with gain of 12 dBi and radiation efficiency of 93% (simulated) as shown in Fig 2.1. While HPBW of the antenna is 13.7°in E-plane and 155°in H-plane.

In [4] a novel method for reducing mutual coupling is discussed while presenting a broadband antipodal Vivaldi antenna for use in mm-Wave band of 5G communications.

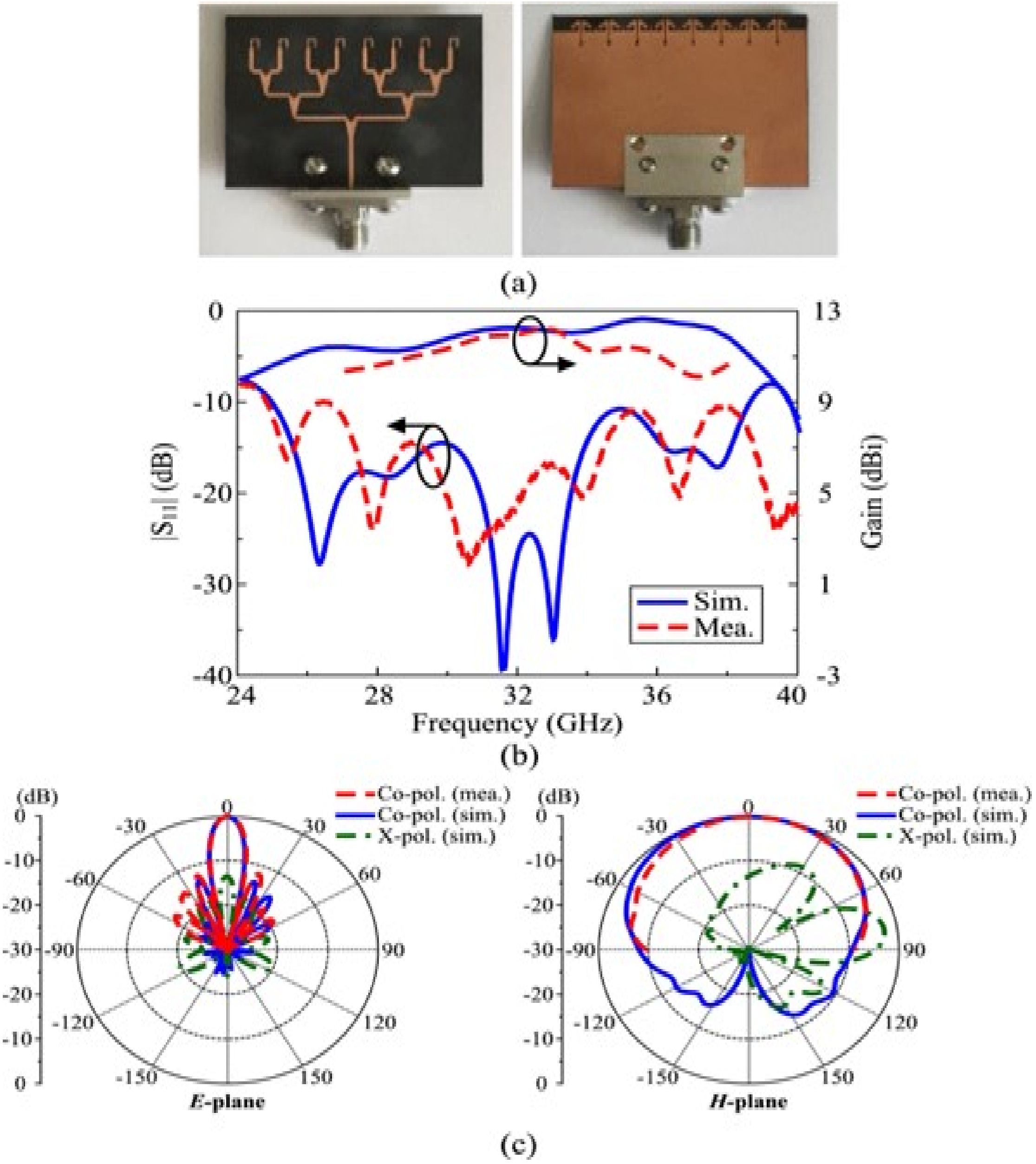


Figure 2.1: Fabricated Antenna with Simulated and Measured Parameters [1]

Antenna is based on 8 element linear array of radiating elements which are fed by 1 to 8 power divider. Notch structures are added to the ground plane to reduce mutual coupling of the radiating elements. The antenna exhibit narrow beamwidth in E-plane however a very wide beam is observed in H-plane. Moreover, antenna has footprint of 28Ö60mm^2 on 0.787 mm thick substrate. Impedance bandwidth of 4% at 26 GHz is achieved with peak gain of 11.32 dBi.

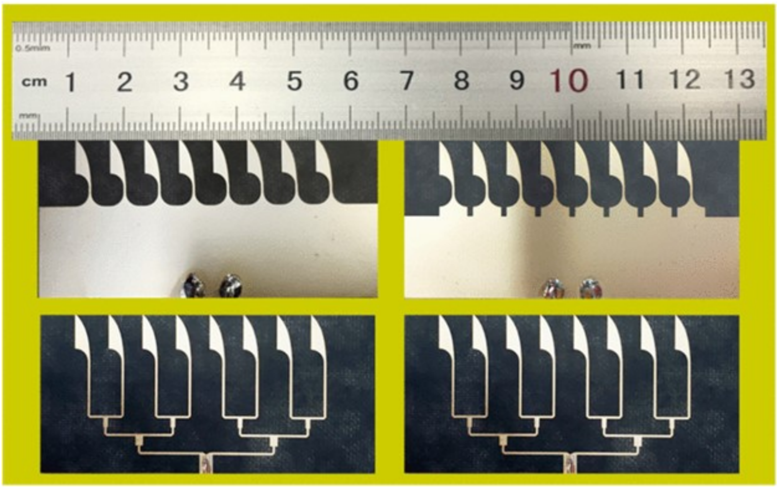


Figure 2.2: Fabricated Antenna With (Right) and Without (left) Coupling Reduction Notches [4]

2.2 Single Layer SIW Antennas

In [5] a low cost wide band simple antenna is proposed at 33 GHz and is based on single layer of SIW cavity. Simple rectangular slots are etched on top copper layer as radiating structures. The antenna is fed by simple coaxial probe inserted inside the antenna for excitation of higher order modes inside the cavity. The excited higher order modes are TE 130, TE 310 and TE 330. 1.58 mm thick Rogers 5880 substrate is used for fabrication. Overall dimensions of the antenna are $16 \times 16mm^2$. Achieved –10 dB S11 bandwithd is 26% at 30 GHz with gain of 13.8 dBi and radiation efficiency of 92%.

In [6] dual mode SIW cavity backed triangular complementary split ring slot antenna with wide band proposed. Antenna is designed to work on 2 bands i.e 28 GHz and 45 GHz. Cavity for the antenna is designed to resonate in TE 102 and TE 201 modes. Complementary Ring slots are etched on top copper layer as radiating elements. Separate antennas are fabricated for both bands in 1×2 and 2×1 configuration. Antenna is fed by specially designed SIW to GCPW transition. At 28 GHz antenna is fabricated on 0.508 mm thick single layer substrate with dimensions of $22 \times 20mm^2$ as shown below. Achieved –10 dB S11 bandwithd is 16.6% at 28 GHz with gain of 13.5 dBi and radiation efficiency of 95%. At 45 GHz antenna is fabricated on 0.508 mm thick single layer substrate with dimensions of $18 \times 10mm^2$. Achieved –10 dB S11 bandwithd is 22.2% at 45 GHz with gain of 14.4 dBi and radiation efficiency of 85%.

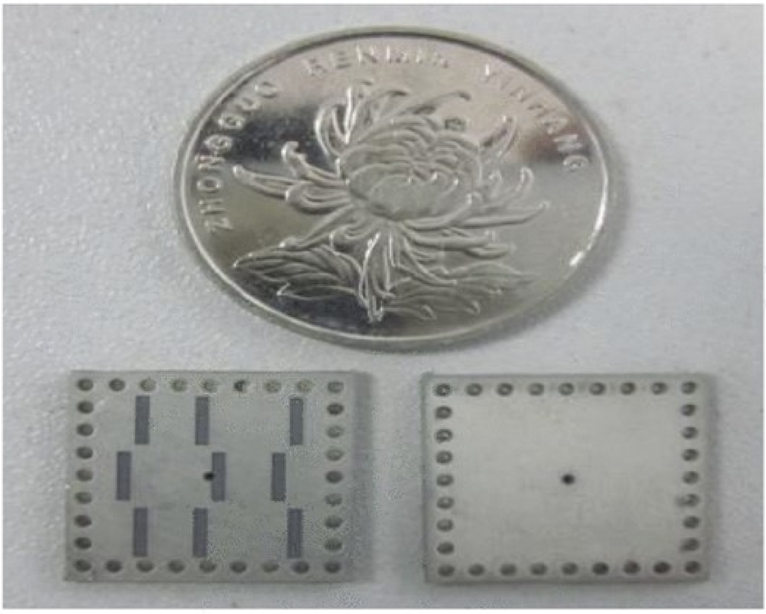


Figure 2.3: Antenna Prototype [5]

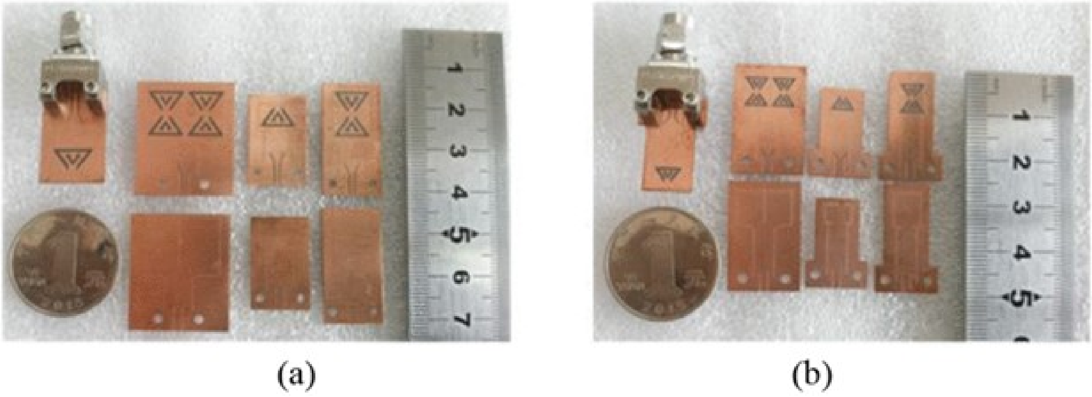


Figure 2.4: Antenna Prototype (a) at 28GHz (b) at 45 GHz [6]

A printed log periodic dipole array with bow-tie parasitic cell is presented in [7] . Several bow-tie patches are is used for gain enhancement for 5G mm-Wave application of the antenna. Substrate Integrated Waveguide is used as feed to the antenna and SIW is fed by coaxial probe. Prototype is fabricated on 0.508 mm thick substrate and antenna dimensions are $10 \times 17.7mm^2$. 22.22% impedance bandwidth is achieved at 45 GHz with peak gain of 12.5 dBi as shown in Fig. 2.5. A total of 4 antennas are proposed in this work having patches and bow-ties as parasitic cells for gain enhancement. Bow-tie directors on both sides of the antenna give best results in terms of gain enhancement.

A low profile and low cost antenna base on multi layer SIW technology is proposed in

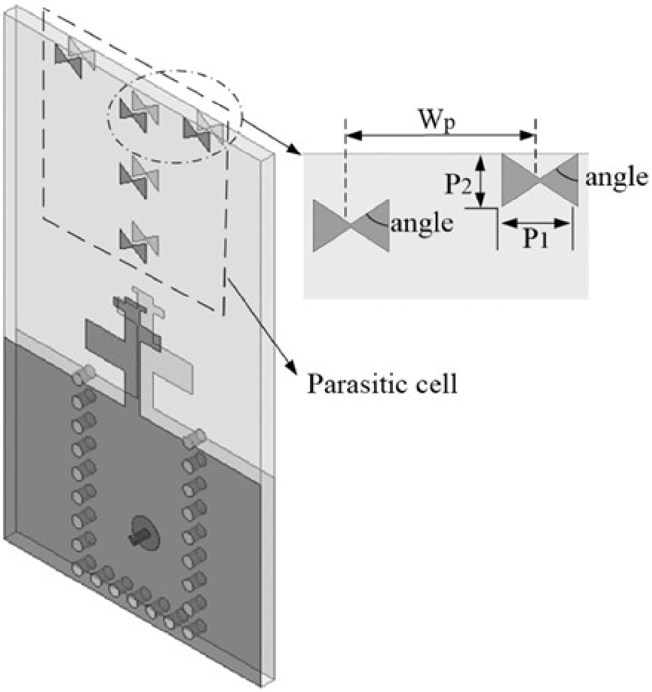


Figure 2.5: Proposed Antenna with parasitic cells highlighted[7]

this paper [8]. Antenna is based on tilted radiating slots on top layer, which is backed by SIW cavity resonating at higher order mode; TE 440. Initially lateral slots are etched on lower SIW based layer for radiation. Same number of dipoles as of slots on lower cavity are placed on top layer at an angle of 45°.

Each dipole is placed exactly above radiating slot of the lower cavity. Top and bottom layers are separated by an air gap of 1 mm. The upper dipole layer is called linear to CP converter. In order to achieve complementary circular polarization, top layer dipoles are to be rotated at an angle of 90°. SIW cavity is fed by a coaxial probe and thickness of each substrate layer is 0.508 mm. Planar dimensions of the antenna are $23 \times 23mm^2$ and impedance bandwidth of 5.3% at 28 GHz with 16 dBi gain and 96% radiation efficiency is achieved.

Traditional Dumbbell shaped slot antenna based on SIW cavity is modified in [9] and presented. Additional resonant points are introduced in the design to obtain higher gain for application in mmWave frequency bands. SIW cavity is resonated at higher order modes and energy is radiated through modified dumbbell shaped slot. TE 102, TE 301 and TE 302 modes are excited in the cavity to achieve wider bandwidth of the antenna. Different shaped slot antennas are designed in the paper to evolve best

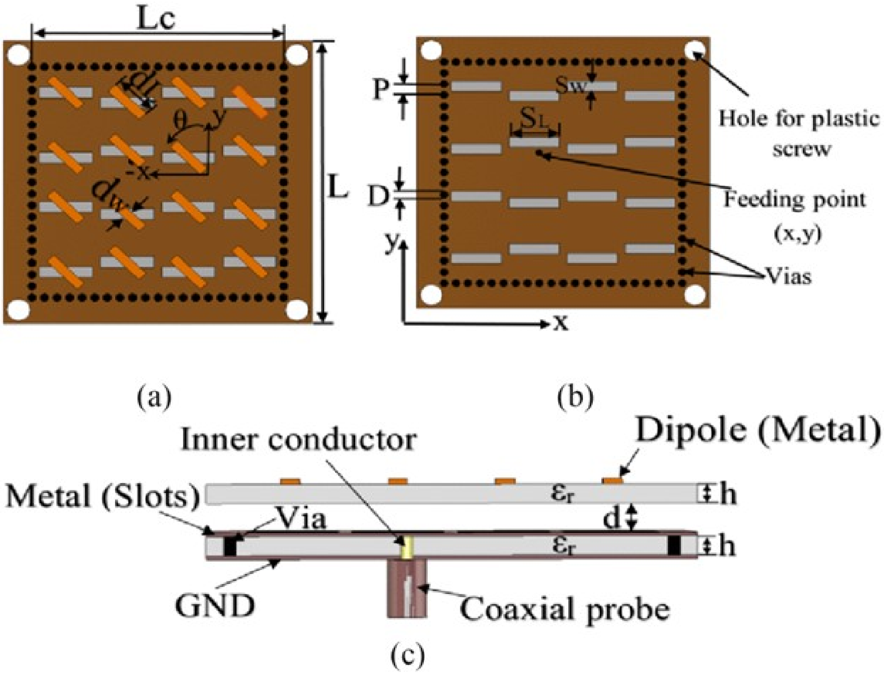


Figure 2.6: Exploded and assembled view of proposed antenna[8]

modification in the dumbbell. Antenna is based on 0.787 mm thick substrate with planar footprint of $20 \times 25mm^2$. Feeding mechanism used is GCPW to SIW transition. Impedance bandwidth achieved is 26.7% at 23 GHz with gain of 9.5 dBi and narrow beam in E-plane. However, beamwidth is much wider in H-plane.

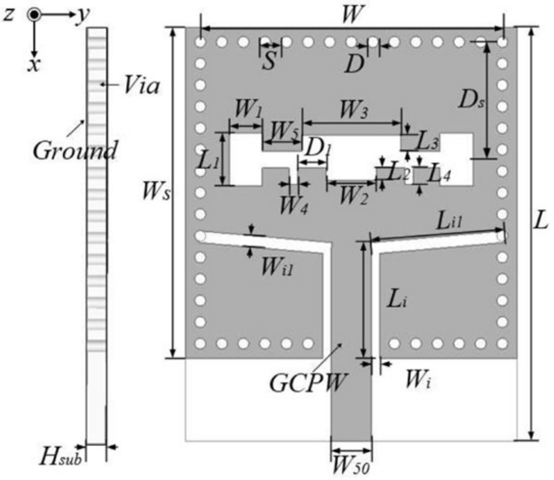


Figure 2.7: Antenna Design and Dimensions[9]

Liner slots are etched on top copper layer of an Empty Substrate Waveguide in [10]. Narrow radiation pattern is achieved in one plane while wide beamwidth in other plane. Difference in beamwidths is mainly due to linear configuration of the radiating slots.

Antenna is fed by microstrip to ESIW transition. Peak gain achieved at 28GHz is 11.6 dBi with impedance bandwidth of 10.4%. Results are however based only on simulations are no fabricated prototype is reported in the publication.

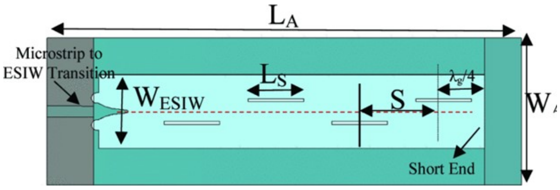


Figure 2.8: Antenna design and dimensions[10]

2.3 Multilayer SIW Antennas

In [11], a dual mmWave band antenna based on multi layer SIW technology is studied. SIWs are miniaturized by using only one quarter of the cavity and four of the QMSIWs are tightly coupled for resonance at two frequencies. An array of these designed cavities is placed linearly to achieve high gain of the antenna. Feed network of the antenna is realized on separate layer which is placed below the cavity layer. Each coupled QMSIW group is fed by bowtie slot placed on lower substrate. Slots are fed by two stage 1 to 4 power dividing network. Substrate thickness of top layer is 0.508 mm while for bottom layer is 0.1 mm. Substrates used are Rogers Duroid 5880 and RO 4450F respectively. Impedance bandwidth in 28 and 38 GHz bands are 13 5.8% with gain of 10.1 10.2 dBi respectively. Radiation efficiency of the antenna is 76 71% for two reported bands. Due to linear array configuration narrow HPBW is achieved only in E-plane of the antenna.

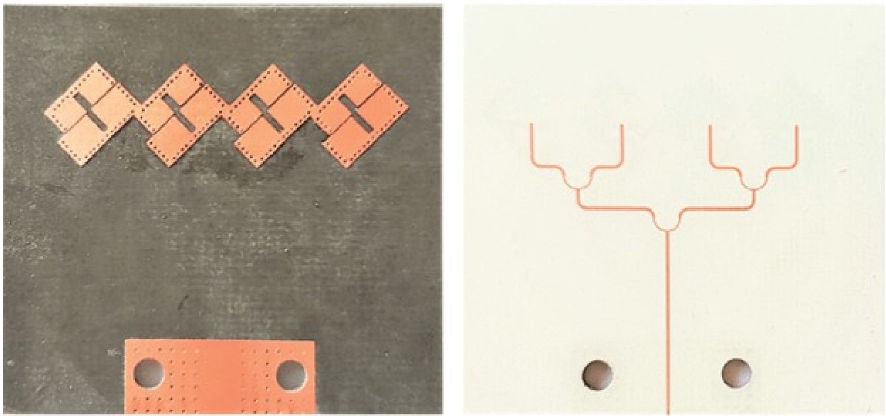
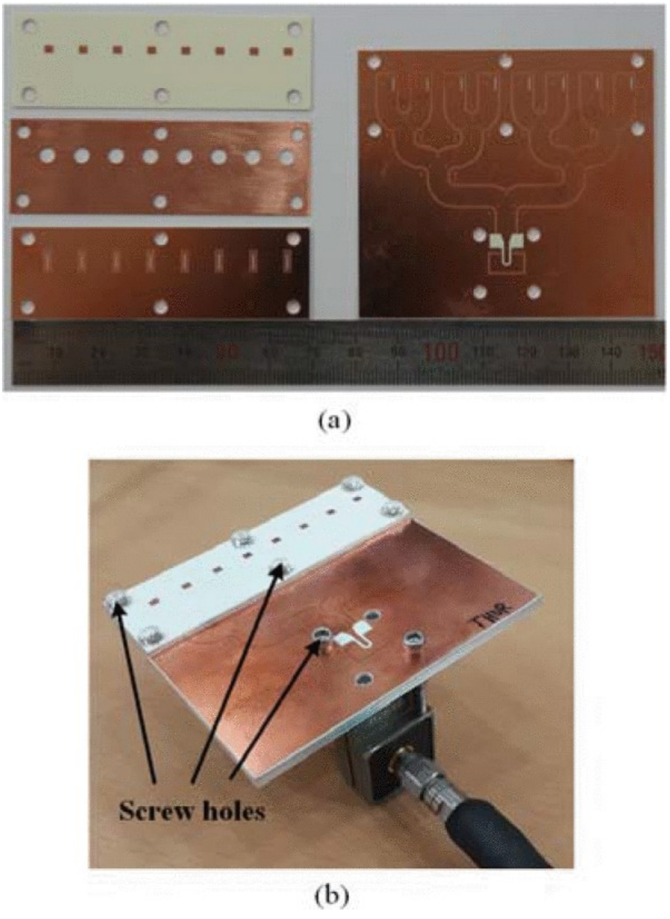


Figure 2.9: Fabricated array of antenna[11]

A multilayer Empty Substrate Integrated Waveguide antenna is proposed in [3] . Substrate is etched in H shape in the middle layer of the antenna while radiating 16 radiating patches in 2D array and sub-array configuration are placed on top upper substrate layer moreover, four coupling slots are etched on ground plane of top substrate layer. Bottom substrate layer is used as ground plane. Lateral walls of the antenna are laminated with PEC to create standing waves inside the cavity. ESIW is fed by microstrip to ESIW transition. Substrate thickness used in all layers is 0.508 mm of Rogers Duriod 5880. 12.4% of impedance bandwidth at 28 GHz and peak gain of 18 dBi with radiation efficiency of 91% are achieved in the antenna. Planar dimensions of the antenna are $42.5 \times 43.3mm^2$.



(a)

(b)

Figure 2.10: Fabricated Antenna (a) Exploded view of four layers (b) Assembled antenna[12]

In [12] a multi layer SIW based antenna is proposed with 8 radiating elements which are fed un-equally by SIW divider network based on Taylor distribution. Waveguide to SIW transition is use to feed the divider network in the antenna. Radiating patches are placed on top layer which are fed by etched slots on middle SIW layer. Total 4 layers are used in fabrication of the antenna; 3 layers of substrate and a copper plate beneath the radiating patch. Substrates 1, 2, and 3 are made of Rogers 4350B laminates with a thickness of 0.508 mm.The thickness of the copper plate is 0.5 mm and total height of the antenna array is 2.199 mm. Overall size of the antenna is $39 \times 39mm^2$. Achieved –10 dB S11 bandwithd is 8.1% at 28 GHz with gain of 14 dBi and radiation efficiency of 60%. It is important to note that HPBW of the antenna is 10°in E-plane however, in H-plane it is 80°.

Ref	Geometry & Feed	Bandwidth (GHz)	Gain (dBi)	HPBW (E)	HPBW (H)	η
[1]	• 48×48 mm^2 • h=0.254 mm • single layer 8 element dipole array • T-Junction Power Dividers	25-38 (13GHz) 36.2 % @ 31.5 GHz	12.5	13.7	155	93%
[6]	• 30×30 mm^2 • h=0.508 mm • single layer 2×2 slot array • GCPW	27-29 & 40-50 2 & 10 GHz 7.14 & 22 % @ 28 & 45 GHz	13.5 14.4	30	35	95% 85%
[5]	• 16×16 mm^2 • h=1.58 mm • 3×3 slot array single layer SIW Cavity • Coaxial Probe	28-36.6 (8.6 GHz) 26 % @ 30 GHz	13.8	-	-	92%
[7]	• 10×17.7 mm^2 • h=0.58 mm • Single element antenna • Coaxial Probe fed SIW	40-50 (10 GHz) 22.2 % @ 45 GHz	12.5	-	-	-
[8]	• 23×23 mm^2 • h=0.508 mm • Dual layer SIW cavity fed Patch array • Coaxial Probe	26.95-28.25 (1.3GHz) 5.3 % @ 28 GHz	16	30	8	96%

Ref	Geometry & Feed	Bandwidth (GHz)	Gain (dBi)	HPBW (E)	HPBW (H)	η
[9]	• 20×25 mm^2 • h=0.787 • single layer cavity backed slot • GCPW	18.2-23.8 (5.6 GHz) 26.7 % @ 23 GHz	9.5	Narrow	Wide	-
[10]	• 43.5×14.3 mm^2 • h=0.508 mm • 1×4 array of ESIW • Microstrip to ESIW	26.5-29.4 ((2.9 GHz) 10.4 % @ 28 GHz	11.6	16.7	142.3	94%
[3]	• 42.5×43.3 mm^2 • h=1.16 • Dual layer 4×4 ESIW fed patch array • Microstrip to ESIW	26.5-29.4 (2.9 GHz) 10.4 % @ 28 GHz	18.2	16.6	18.7	91%
[12]	• 39×39 mm^2 • 3 layer Cavity backed patch array • 8-way SIW	27.2-29.5 (2.3 GHz) 8.1 % @ 28 GHz	13.97	10	80	60%

Table 2.1: Summary Table of Literature Review

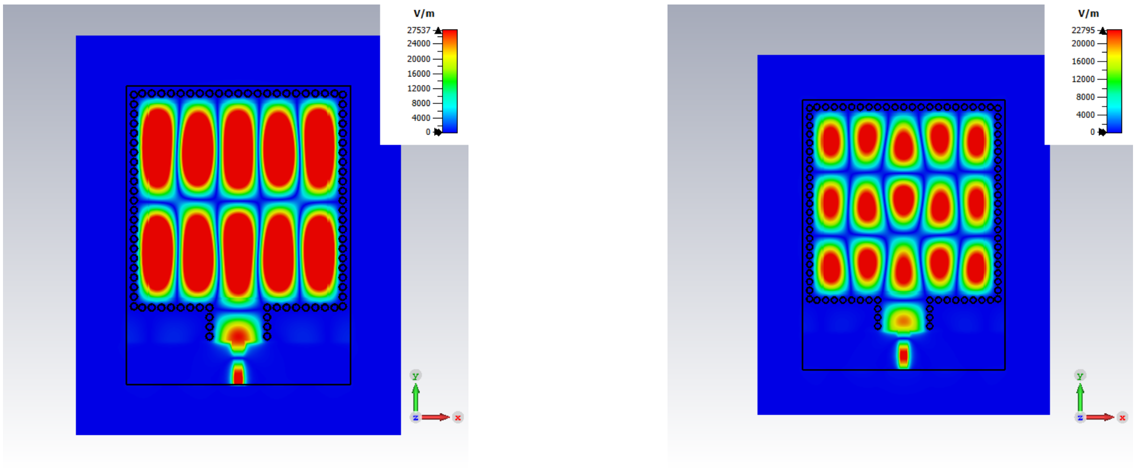
Chapter 3

Antenna Design

This chapter consists of complete antenna design based on Substrate Integrated Waveguide (SIW) fed by simple microstrip to SIW tapered transition and can be easily integrated with planar mmWave RF circuits. Design evolution procedure, separately for antenna and feed are discussed in this chapter. Simulations results followed by measured results of fabricated antenna are briefed and illustrated with the help of diagrams and tables for complete understanding of the antenna. Discussed results include antenna impedance Bandwidth, Gain, Radiation Efficiency and Beam widths of the antenna.

3.1 Design Evolution

Owing to superior properties of Substrate Integrated Waveguides (SIW) such as Low profile Low loss, High Q factor, easy fabrication, self-sufficient electromagnetic shielding and easy integration with planar circuits including active and passive components etc. It was decided to design antenna for 5G FR-2 28GHz band. Deign evolution included design of SIW cavity with array of Slots having patches inside the slot. Microstrip to SIW transition was also studied and designed for antenna testing and its integration with Microwave circuits.



(a)

(b)

Figure 3.1: TE Modes of Resonant Cavity (a) at 28.5 GHz (b) at 30.8 GHz

3.1.1 SIW Cavity Design:

Initially, design of SIW cavity for excitation of higher order modes was studied and implemented using following equations mentioned in[16]:

$$f_c(TE_{10}) = \frac{c}{2\sqrt{\epsilon_r}}.(asiw - \frac{d^2}{0.95p}) \tag{3.1.1}$$

In order to ensure minimum leakages from the cavity side wall .i.e. made by cylindrical vias, optimum diameter d and spacing p between them are calculated by using following equations:

$$d \leq \frac{\lambda_g}{5} \tag{3.1.2}$$

$$p \leq 2d \tag{3.1.3}$$

Keeping above mentioned equations in view and to achieve a wide band frequency response a cavity with two resonances around desired frequencies i.e. 28 GHz and 30 GHz was designed. Modes resonated inside the cavity are TE 502 at 28.5 GHz and TE 503. Resonated modes are shown in Fig 3.1. S11 response of designed cavity is shown in Fig 3.2, where multiple resonance frequencies are shown. Frequencies with highest resonance are considered for the design of the antenna as discussed earlier where higher order modes are shown.

Thickness of substrate plays an important role in resonance frequency ad it was learnt that thinner the substrate lower will be the bandwidth. However, an optimum cavity

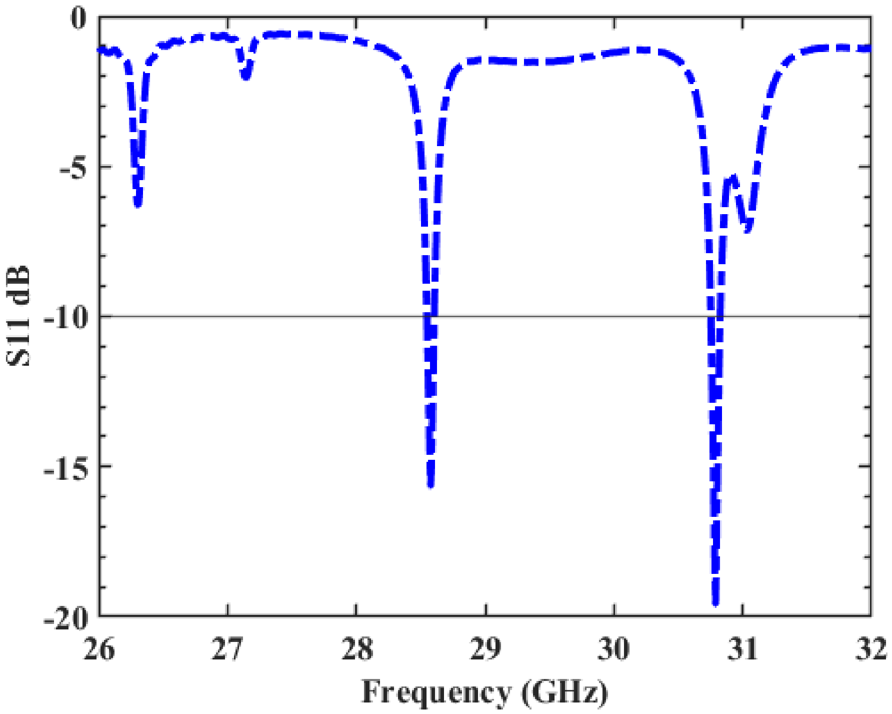


Figure 3.2: Cavity Resonance Frequencies

design was achieved with multiple resonance frequencies especially at the band of interest i.e 28 GHz to 30 GHz. Minimum Substrate thickness achieved with desired resonance bands is 0.254 mm of Rogers 5880 substrate.

3.1.2 Slots Design and Configuration

Slots on top the cavity were designed to radiate the energy in such a way that radiated energy from each slot will have constructive interference in far field to achieve a directed beam in both E and H planes. Initially only diamond shaped slots were designed for radiation of EM energy. Slots were than filled with tapered patches to create dipoles having radiating X and Y component of the E-Field. However, X-Component being out of phase in each slot were cancelled out ad only radiating Y-Component of the E field. Multiple configurations for slots are designed i.e 1×1, 2×2, 3×1, 3×2, 3×3 and 4×4 were simulated. 3×3 was simulated with multiple S11 resonances and unidirectional directed beam. Following figures show S11 response of all configurations.

Fig 3.3 and 3.4 show S11 response of 1×1 and 2×2 slot response. Maximum power in these cases is reflected back at the port due disturbance in mode formation inside the

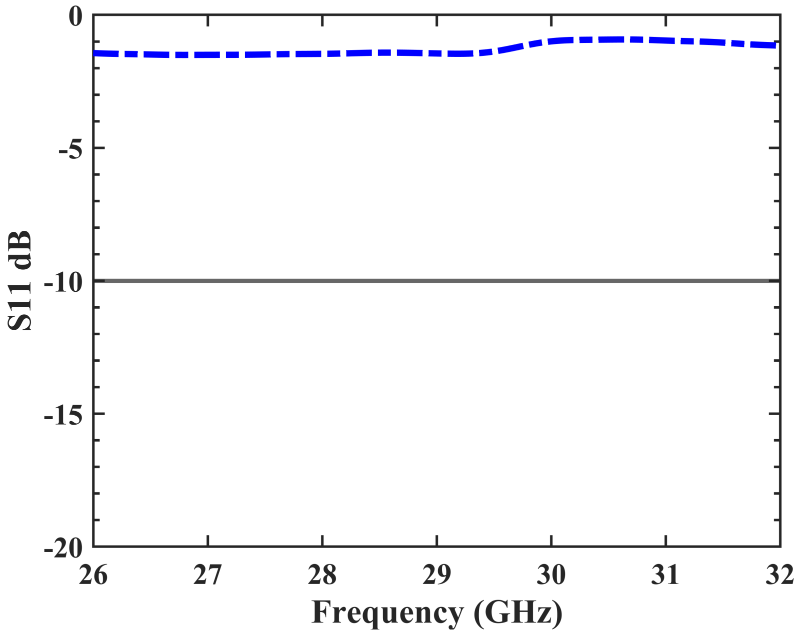


Figure 3.3: S11 Response of 1×1 Slot Configuration

cavity as cavity size is decreased and does not correspond to multiple of half wavelength of the operating frequencies.

In Fig 3.5 width of the cavity is kept same as of 1x1 cavity, however by increasing length of the cavity to incorporate higher modes in y plane resonance is achieved at frequency lower than 27 GHz. Beamwidth on the other hand achieved using this configuration is narrow in E-plane but very wide in H-plane. 3×2 and 4×4 slot configurations also show s11 response pf the antenna which is not desirable in targeted band. Whereas, desired results are only obtained using array configuration of 3×3 slots.

Final design and configuration of slots is shown in Fig 3.9 and Fig 3.10. Design parameters are also given in Table 3.1.

3.1.3 Field Analysis

Analysis of slots was undertaken to understand the radiation mechanism through E field distribution and Surface current distribution. CST Microwave Studio ® is used for design and simulations. E field analysis shows that slots are working as folded dipoles. Each slot behaves as pair of folded dipole stacked in y-plane of the antenna. Further analysis shows that dipoles are radiating EM energy with Y component of the field as Co

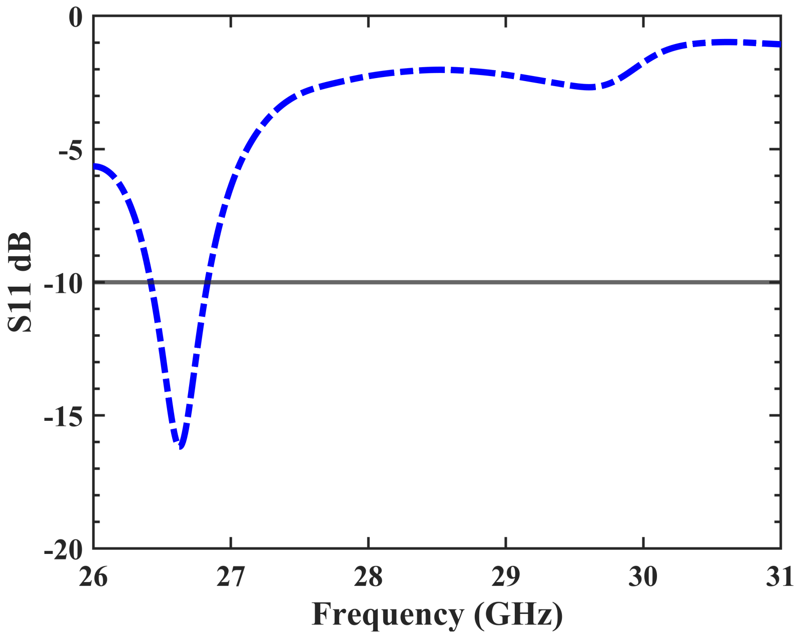


Figure 3.4: S11 Response of 2×2 Slot Configuration

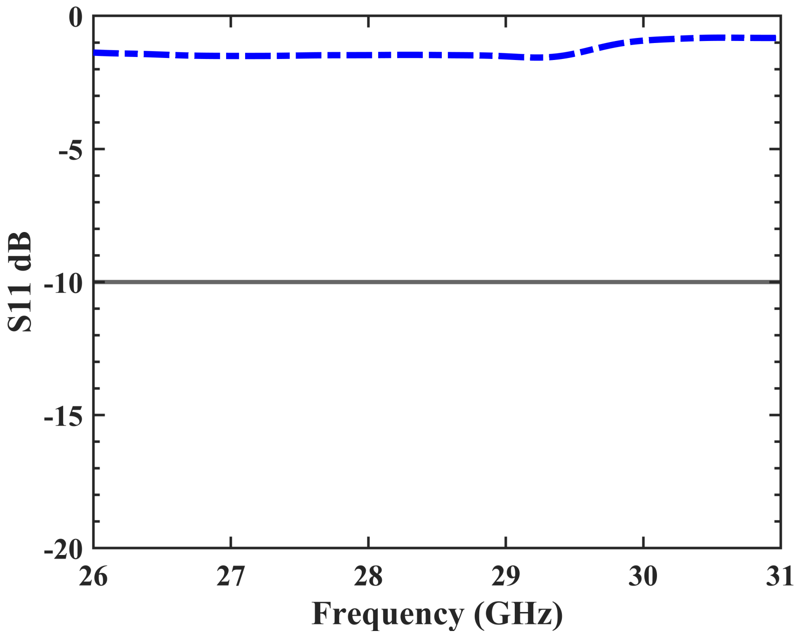


Figure 3.5: S11 Response of 3×1 Slot Configuration

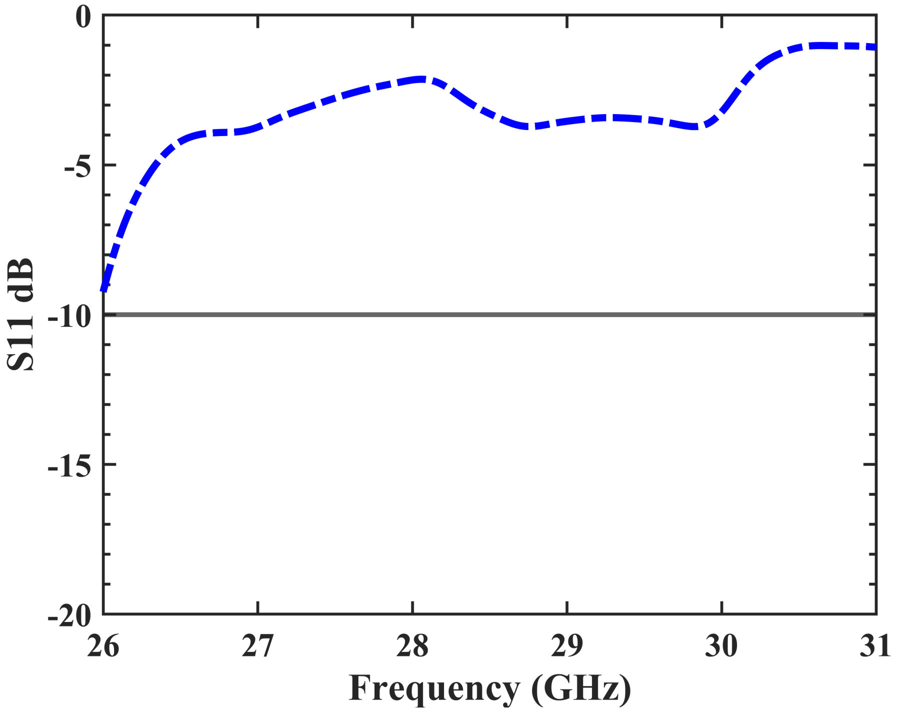


Figure 3.6: S11 Response of 3×2 Slot Configuration

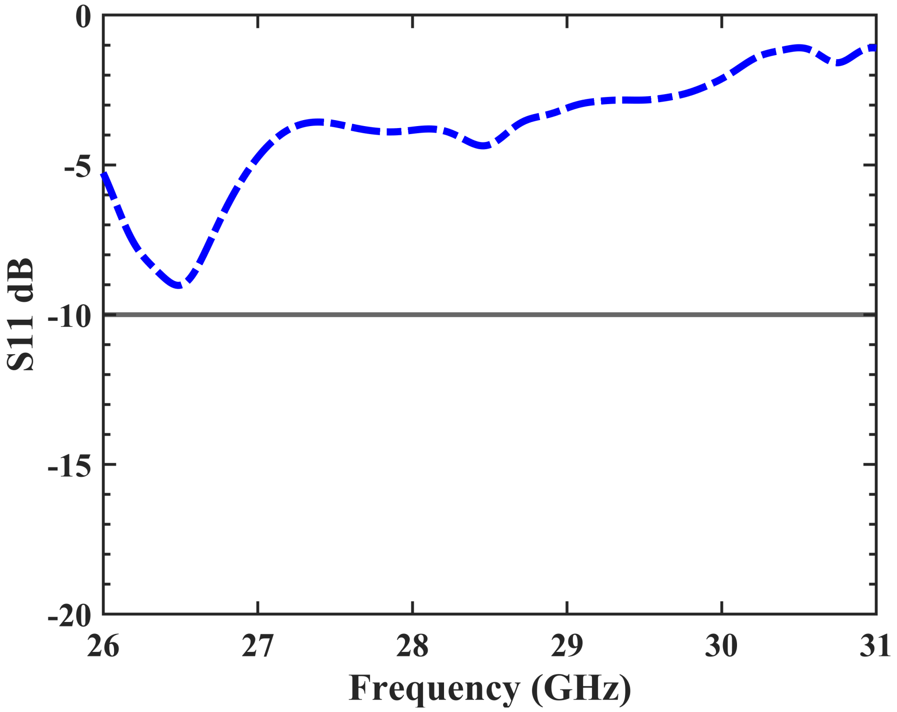


Figure 3.7: S11 Response of 4×4 Slot Configuration

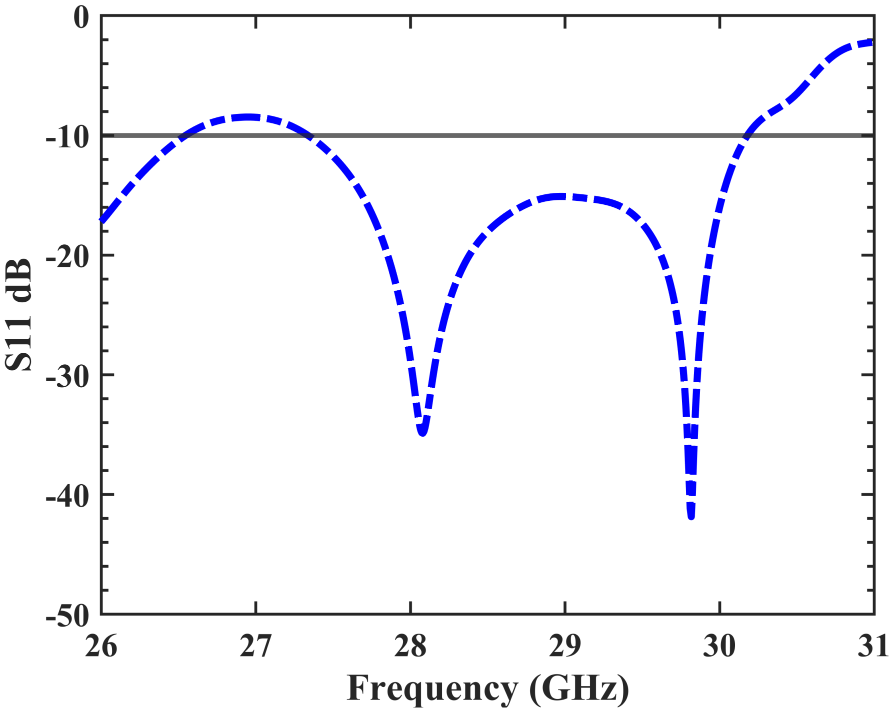


Figure 3.8: S11 Response of 3×3 Slot Configuration

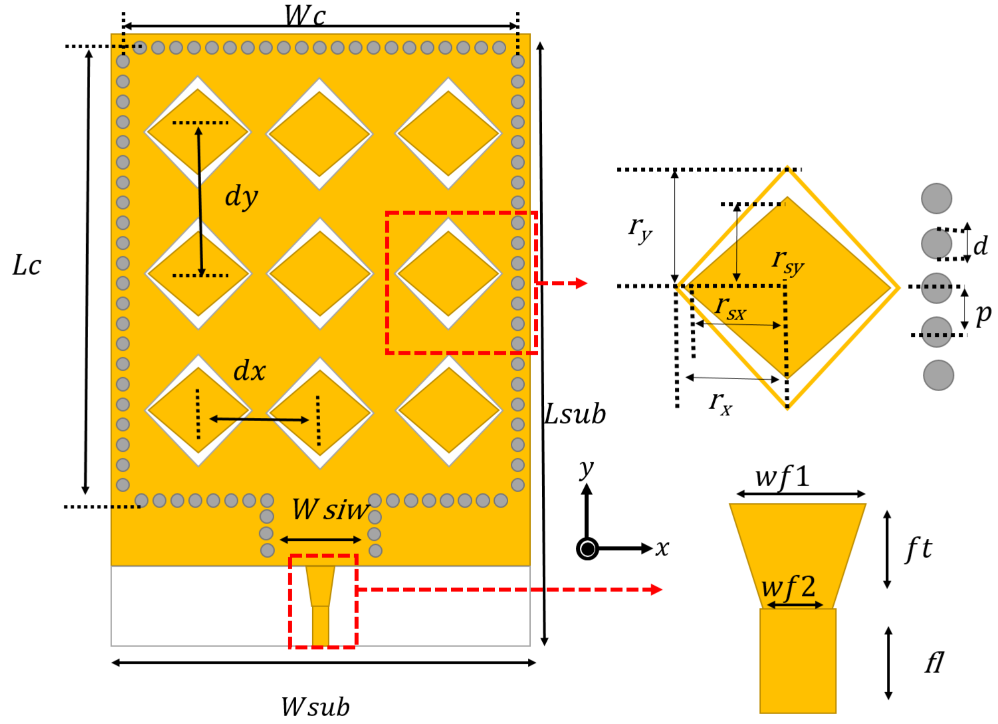


Figure 3.9: Antenna Design Top View

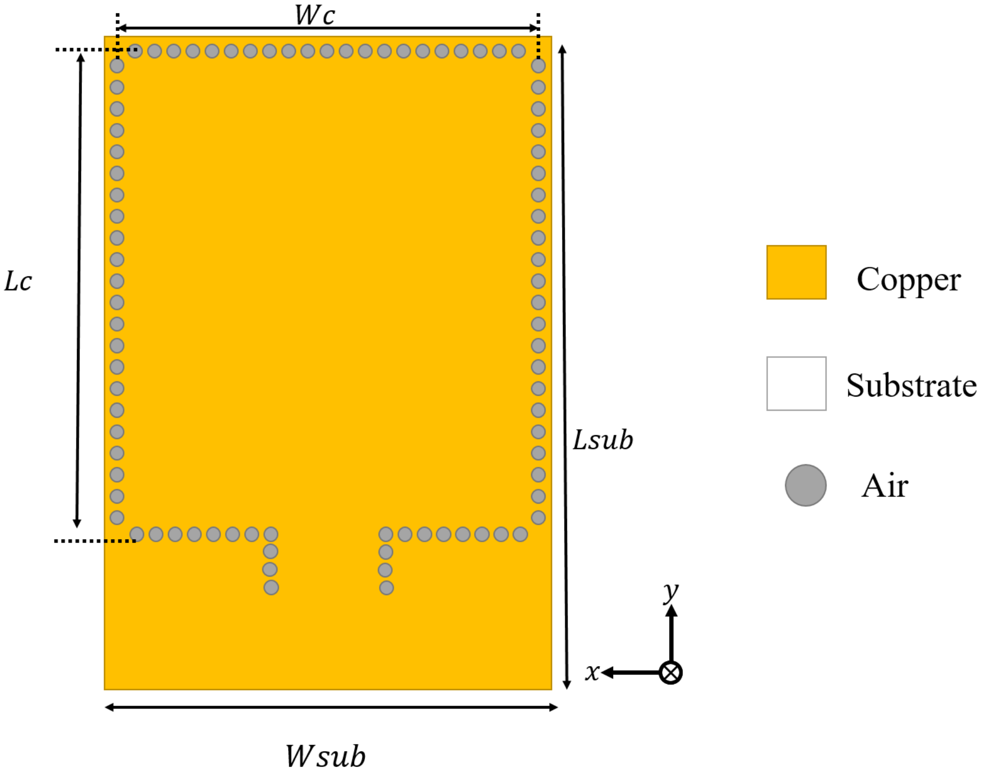


Figure 3.10: Antenna Design Bottom View

Parameter	W sub	L sub	W_c	L_c	r_x	r_{sx}
Value	21	28	19.53	20.03	2.7	2.3
Parameter	r_y	r_{sy}	dx	dy	lsiw	wf1
Value	2.824	2.14	5.7	6.313	2.5	1.25
Parameter	p	ft	fl	srad	wf2	Wsiw
Value	0.9	2	2	0.35	0.787	5.4

Table 3.1: Final Design Parameters of Antenna

pole and X component as Cross pole. Fig 3.11 and 3.12 shows the configuration of both field components. Y component of the field is radiated by both dipoles of each slot in phase while X component is radiated by opposite complementary arms of the dipoles at one given phase. Other side of complementary arms of dipole radiate the x component 180 degrees out of phase. Thus x component of the radiated field is cancelled out and only y component is radiated.

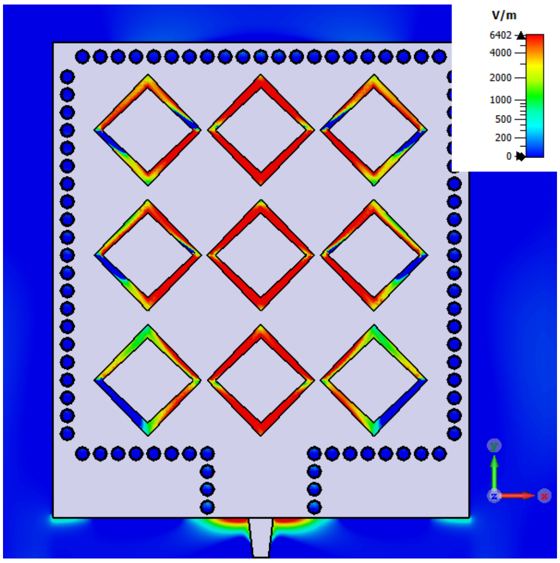


Figure 3.11: Y Component of the Radiated Field @ 28 GHz

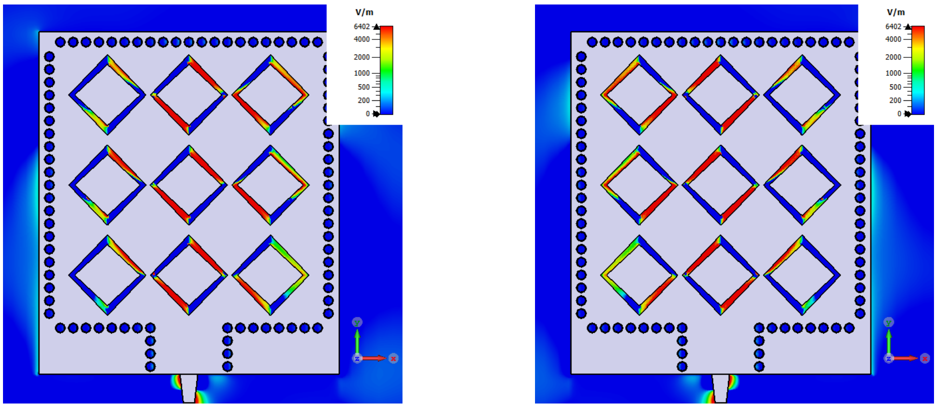


Figure 3.12: X Component of the Radiated Field at 45 and 225 Degree Phase @ 28 GHz

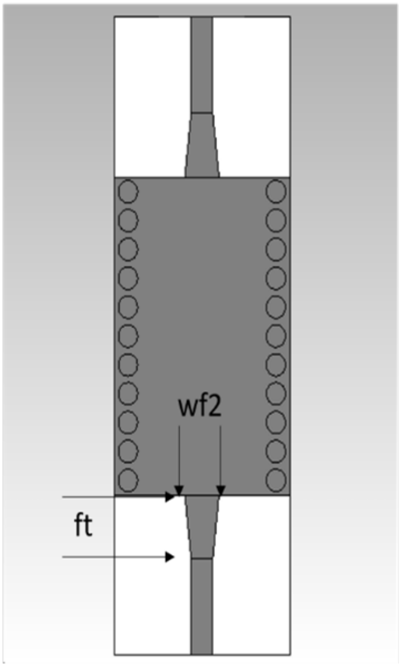


Figure 3.13: Microstrip to SIW Feed Design

3.2 Microstrip to SIW Design

To integrate the antenna with planar circuits a connecting transition is required. Multiple transitions from literature were studied. Published transitions include Microstrip to SIW and GCPW to SIW transition as reported in [Substrate Integrated Waveguide Antennas] and [17].

Keeping the published literature in view a transition is designed with microstrip line connected to a tapered microstrip which finally connects to the SIW having TE10 propagation mode at 28 GHz. Design of the transition is shown in Fig 3.13 along with S11 response in Fig 3.14. Wide frequency band for transition is considered that antenna complete frequency range is covered and if antenna bandwidth is enhanced in future works the transition can easily withstand the wider bandwidth. It is important to mention that taper length in the feed plays an important role in bandwidth performance and it is always to be chosen in multiples of quarters of the wavelength to minimize return loss. Design parameters of feed are given Table 3.1.

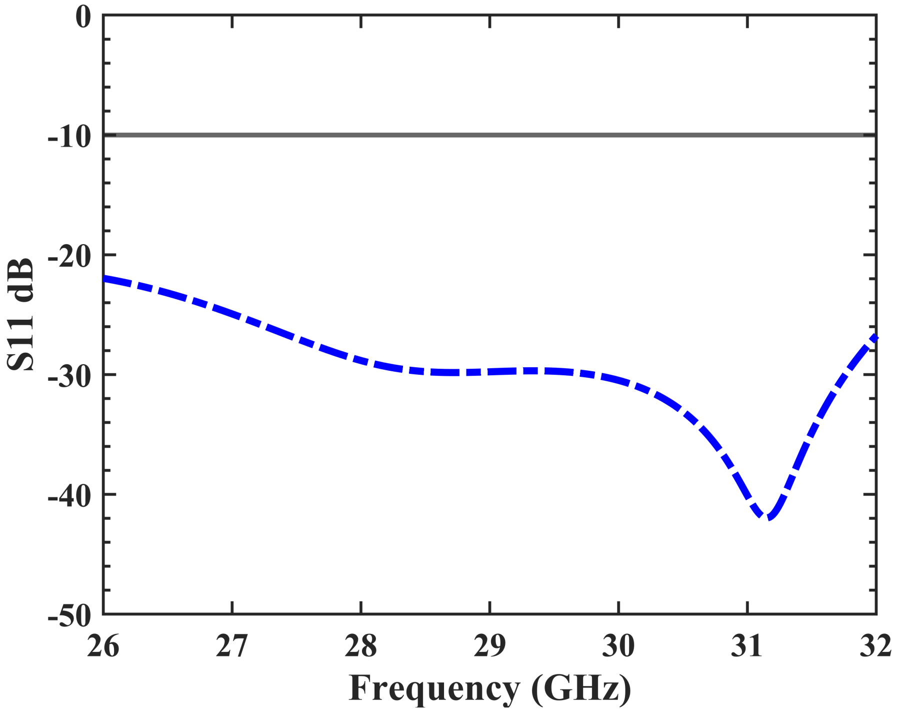


Figure 3.14: Simulated S Parameters of Microstrip to SIW Feed Design

3.3 Fabrication and Measurements

This section includes the fabrication and measurement of the antenna prototype. Measured results of the antenna are plotted in comparison with the results simulated. Measured results are in close agreement with simulated results. Fig 3.15 shows the image of actual fabricated prototype.

Simulated and measured S parameters response of the antenna are shown in Fig. 3.16. Measured results are in close agreement to the simulated results. Frequency shift in the measured results can be observed which is mainly due to tolerances errors of fabrication and measurement setup.

Frequency bandwidth of 3 GHz i.e. 27.3 – 30.3 GHz; similar to simulated antenna is achieved with fabricated prototype. Thus confirming the simulated antenna design.

Similarly radiation patterns of the antenna were also measured and compared with the simulated results. Comparison of simulated and measured radiation patterns is shown in Fig 3.17. Comparison is carried out at 28 GHz, 29 GHz and 30 GHz in both E and H plane of the antenna. Measured results are showing that beam patterns of the antenna

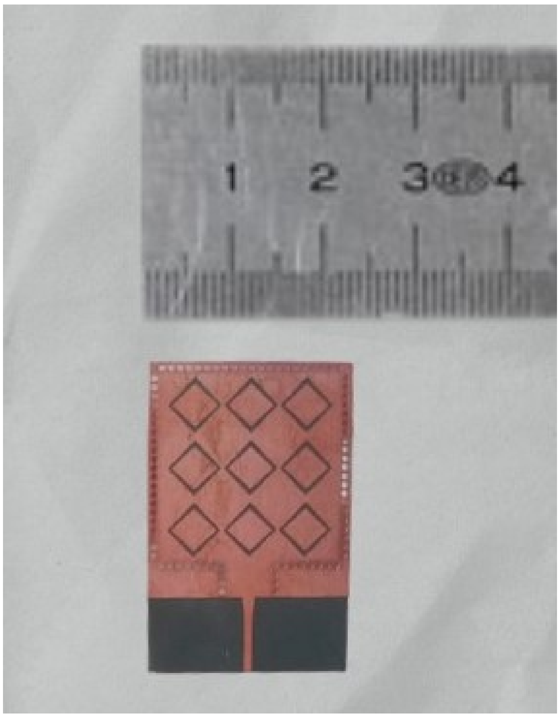


Figure 3.15: Fabricated Prototype

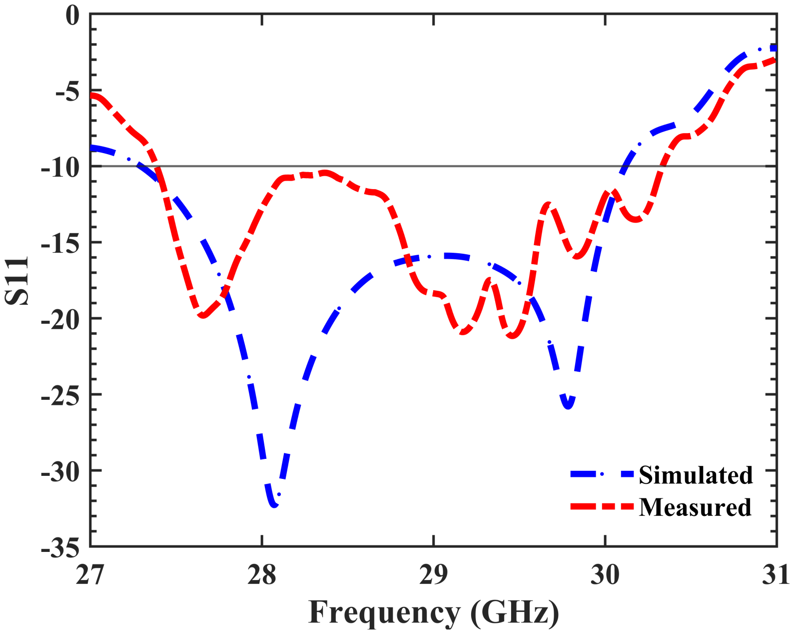
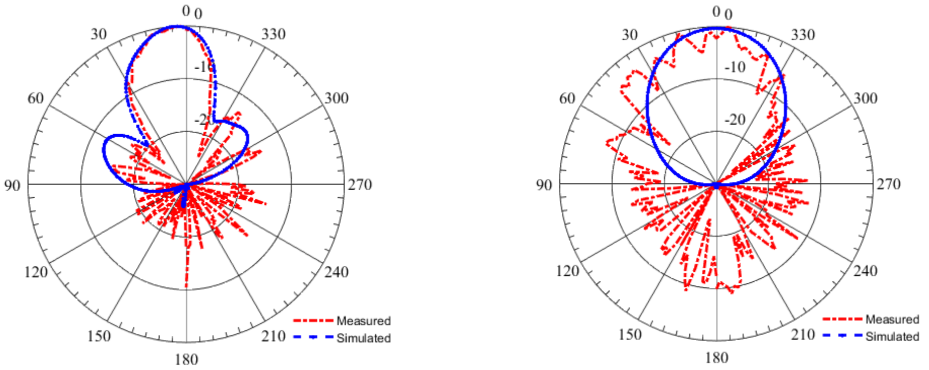


Figure 3.16: Simulated and Measured S Parameters of Antenna

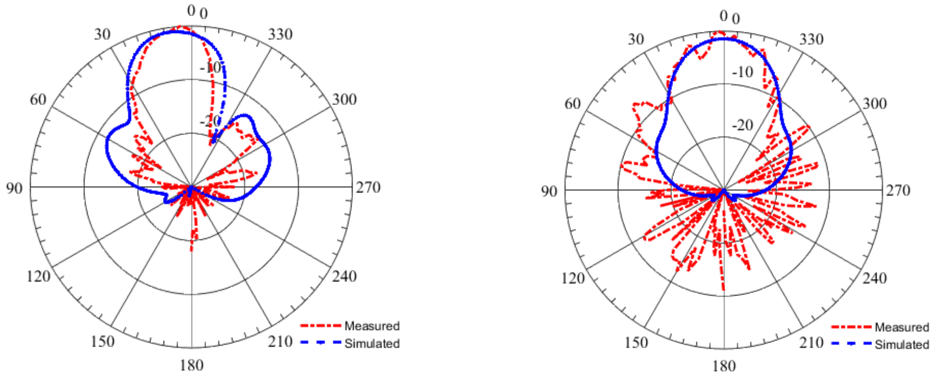
are in considerable agreement with the simulated results.

Fig 3.18 shows the simulated and measured broadband gain of the antenna in entire frequency band. In entire operating band gain of antenna is above 11 dBi with highest gain of 14.dbi at 30 GHz. Gain performance of fabricated prototype clearly agrees with the simulated gain in CST Studio.



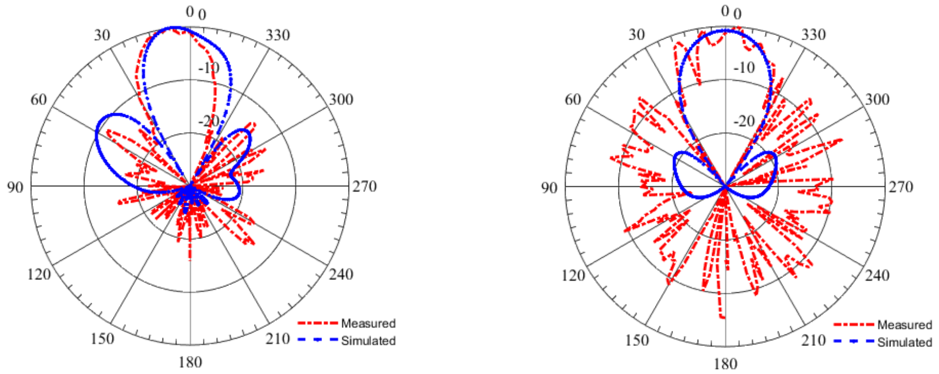
(a) E Plane

(b) H Plane



(c) E Plane

(d) H Plane



(e) E Plane

(f) H Plane

Figure 3.17: Simulated and Measured Radiation Patterns 1. 28 GHz 2. 29 GHz 3. 30 GHz

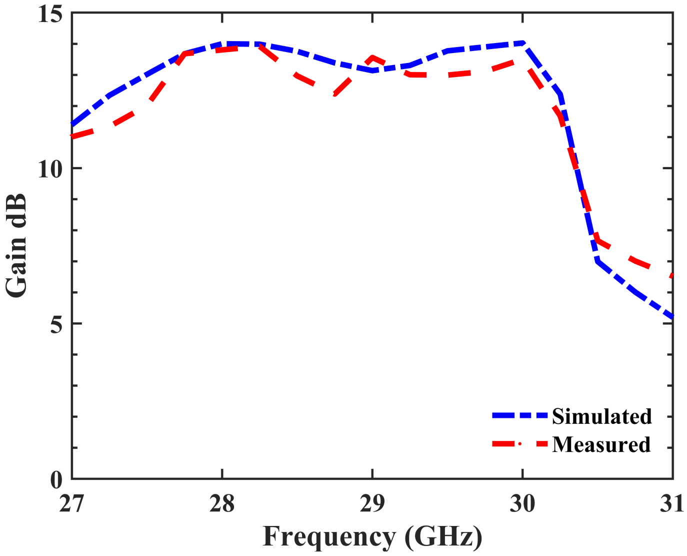


Figure 3.18: Simulated and Measured Gain Performance of the Antenna

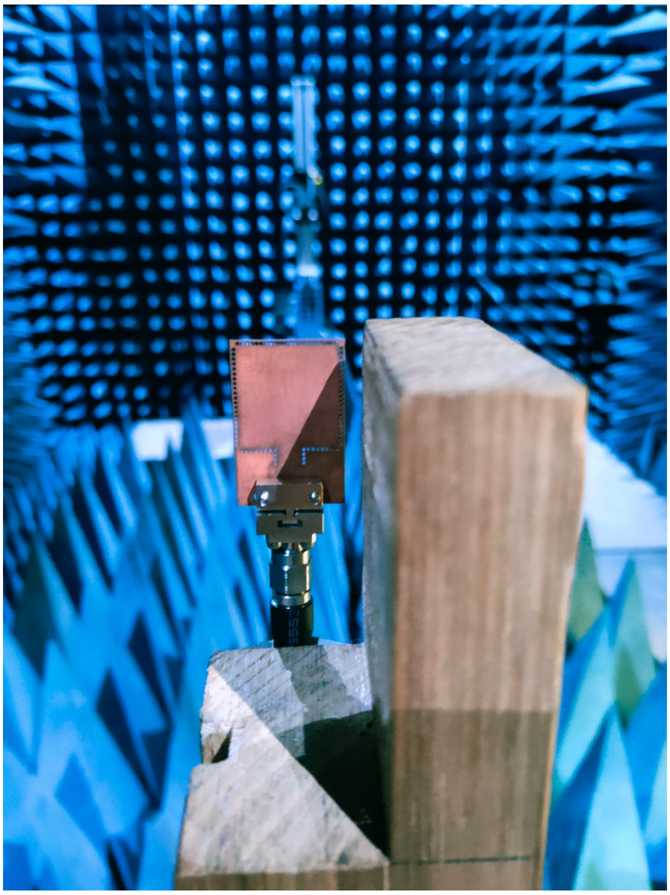


Figure 3.19: Antenna Measurements in Anechoic Chamber

Chapter 4

Conclusion

With very high demand of internet traffic and fast connectivity deployment of future generations of communications standards are knocking at the doors. Sub 6 GHz bands of 5 G are being launched and are in testing phases around the globe. In parallel mmWave band networks are in research phases and will be launched soon. One of the major component in mm Wave band communications is antenna at base stations as well as on individual device or end user side. Owing to higher attenuation rates due to smaller wavelengths at these bands require a high gain antenna with directed beam. Moreover, on end user device node the antenna also needs to be compact and requires easy integration with the existing circuitry of the devices.

Keeping above merits in view, an antenna based on SIW technology has been designed while keeping the principle of compact size, simplicity of fabrication and low cost. Targeted gain performance of the antenna is achieved while keeping unidirectional radiation pattern. Simple feed based on microstrip to SIW is also designed for testing of the antenna. Fabricated prototype has shown excellent gain and impedance matching performance of the antenna and is in agreement with the simulated results.

Overall size of the antenna is $21 \times 28mm^2$ including 2 mm length of microstrip feed. Unidirectional beam patterns are achieved with peak gain of 14 dBi and gain variation from 11 dBi to 14 dBi in entire operating band i.e. 27.3 GHz to 30.3 GHz. In future performance of the antenna can be enhanced by making linearly polarized antenna into dual polarized or in best case circularly polarized.

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