CERTIFICATE

It is certified that the work contained in the thesis titled ***"Some Investigations on SIW Cavity-Backed Slot Antennas For 5G Applications"*** by ***"Amit Kumar"*** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

27/6/22

Supervisor

Dr. Amit Kumar Singh
Associate Professor,
Department of Electronics Engineering,
Indian Institute of Technology (BHU) Varanasi,
Uttar Pradesh, INDIA 221005.

DECLARATION BY THE CANDIDATE

I, ***Amit Kumar***, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of ***Dr. Amit Kumar Singh*** from ***July 2017*** to ***June 2022*** at ***Department of Electronics Engineering***, Indian Institute of Technology (BHU) Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc.* reported in journals, books, magazines, reports, dissertations, theses, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 27/6/22

Place: Varanasi

Amit

(Amit Kumar)

CERTIFICATE BY THE SUPERVISOR

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

27/6/22

(Dr. Amit Kumar Singh)
Associate Professor
Department of Electronics Engineering,
Indian Institute of Technology (BHU) Varanasi

सहआचार्य/Associate Professor
इलेक्ट्रॉनिकी अभियांत्रिकी विभाग
Department of Electronics Engineering
भारतीय प्रौद्योगिकी संस्थान
Indian Institute of Technology
(काशी हिन्दू विश्वविद्यालय)
(Banaras Hindu University)
वाराणसी/Varanasi-221005

27.06.2022.

Signature of Head of Department

आचार्य व विभागाध्यक्ष/PROFESSOR & HEAD
इलेक्ट्रानिकी अभियांत्रिकी विभाग/Department of Electronics Engineering
भारतीय प्रौद्योगिकी संस्थान (का.हि.वि.)/Indian Institute of Technology (BHU)
वाराणसी/Varanasi-221005 (INDIA)

27/6/22

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Some Investigations on SIW Cavity-Backed Slot Antennas for 5G Applications

Name of the Student: Amit Kumar

Copyright Transfer

The undersigned hereby assigns to the Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the *Doctor of Philosophy.*

Date:

Place: Varanasi **(Amit Kumar)**

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Dedicated to my Family

and

beloved Daughters

ACKNOWLEDGEMENT

Foremost, I would like to express my sincerest regards and love to my father, Sri Ram Pal Singh, and mother, Smt. Sarvesh, for their constant support and love throughout my life. I will always be in debt no matter what I do, and I will always be your reflection.

Besides my parents, I would like to thank my supervisor, Dr. Amit Kumar Singh, for his invaluable support and assistance. I feel immense pleasure in expressing my profound sense of gratitude and sincere regard for his constant feedback and expertise during all these years. I am eternally grateful to have had the opportunity to work on my thesis under his supervision.

I wish to extend my sincere gratitude towards my research performance evaluation committee (RPEC) members, Dr. M. Thottappan, Department of Electronics Engineering and Dr. S. K. Singh, Department of Computer Science and Engineering, for their encouragement and insightful comments. I would like to convey my sincere gratitude to Dr. V. N. Mishra, Head of Department of Electronics Engineering, IIT (BHU) for providing effective management, necessary facilities and valuable suggestions for success of this work. I would also like to thank all the faculty members for their kind cooperation and encouragement during this journey.

I would like to express my special thanks to Dr. Sarthak Singhal, Dr. Sudhir Bhaskar, Dr. Ashutosh Mishra, and Dr. Munish Kumar for their fruitful suggestions and valuable assistance from simulation to measurement.

I am very much thankful to research scholars of the microwave research laboratory for providing a stimulating and friendly environment. My thanks go to, Mr. Amit Kumar Singh, Mr. Azharuddin, Mr. Deepak Ram. Also, my thanks to my juniors Mr. Dharmedra Kumar(D.K), Mr. Ankit Verma, Mr. Bipin Maurya for all the "non-research" discussions over tea, which temporarily took off the Ph.D. pressure.

I am indebted to my colleagues and friends, Mr. Sumit Yadav, Mr. Nisheet Upadhay, Mr. Ashish Kumar Singh, Mr. Lavesh Xaxa, and Mr. Diptiranjan Samanta for their constant encouragement and support.

Finally, I heartily express sincere thanks to my big family for their unconditional love, extreme patience and constant support over the years. They provide me strength and confidence to attain this task. I express my sincere appreciation to my sisters, Sarita Singh and Shama for their continuous support and encouragement. They are the source of strength for me and remain an invaluable asset to me.

Above all I would like to thank my better half, Seema for her eternal support and understanding of my goals and aspirations. Her infallible love and support have always been my strength. Her patience and sacrifice will remain my inspiration throughout my life. Thank you for being my muse, editor, proofreader, and sounding board. But most of all, thank you for being my best friend. I owe you everything.

Above all, I thank **Lord Vishwanath** for providing me strength and courage in completing the work.

(Amit Kumar)

Contents

List of Figures

List of Tables

List of Symbols

Symbol	Description
E	Electric Field Intensity
H	Magnetic Field Intensity
k	Wave Number
λ	Wavelength
c	Speed of Light in Free Space
α	Attenuation Constant
α_c	Attenuation constant due to conductor losses
α_d	Attenuation constant due to dielectric losses
α_{rad}	Attenuation constant due to radiation losses or leakage factor
β	Propagation Constant
ϵ_0	Permittivity in vacuum
ϵ_r	Permittivity of the Dielectric
$tan\delta$	Loss Tangent of the Dielectric
σ	Electrical Conductivity

Abbreviations

Abbreviation	Description
ADS	Advanced Design System
ARBW	Axial-Ratio Bandwidth
AXS	Asymmetric Cross-Slot
CBSA	Cavity Backed Slot Antenna
CBWSA	Cavity Backed Wideband Slot Antenna
CCL	Channel Capacity Loss
CP	Circularly Polarized
CPW	Coplanar Waveguide
CSRR	Complementary Split Ring Resonator
DB-DCP	Dual-Band Dual-Circularly Polarised
DG	Diversity Gain
DGS	Defected Ground Plane
DRA	Dielectric Resonator Antenna
ECC	Envelope Correlation Coefficient
eMBB	Enhanced Mobile Broadband
FCC	Federal Communications Commission
FEM	Finite Element Method
FR	Frequency Ratio
FTBR	Front-to-back Ratio
GCPW	Grounded Coplanar Waveguide
HFSS	High Frequency Structural Simulator
IBW	Impedance Bandwidth
IMT	International Mobile Telecommunications
IoT	Internet of Things
ITU-R	International Telecommunication Union Radiocommunication
LHCP	Left Handed Circularly Polarized
LP	Linearly Polarized

Abbreviation	**Description**
LTCC	Low Temperature Co-fired Ceramic
LTE	Long Term Evolution
MEG	Mean Effective Gain
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
mMTC	Massive Machine-Type Communications
MSPA	Mircrostrip Patch Antenna
NLR	Non Linear Replication
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PTH	Plated Through Hole
Q	Quality Factor
RF	Radio Frequency
RHCP	Right Handed Circularly Polarized
SDA	Self Diplexing Antenna
SIW	Substrate Integrated Waveguide
SIW-CBA	Substrate Integrated Waveguide-based Cavity-Backed Antenna
SLL	Side Lobe Level
SMA	Sub-miniature Version A
SoS	System-on-Substrate
SRR	Split Ring Resonator
STA	self Triplexing Antenna
TE	Transverse Electric
TM	Transverse Magnetic
TEM	Transverse Electromagnetic
uRLLC	Ultra-Reliable Low-Latency Communications
UWB	Ultra Wideband
VNA	Vector Network Analyzer
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WRC	World Radiocommunication Conferences

Preface

Waveguides are used to transfer electromagnetic energy from one point to another with negligible losses. However, such structures are rigid and not always desirable and require high-precision manufacturing devices. Hence, the concept of substrate integrated waveguide (SIW) has been introduced, which has emerged as one of the most versatile and promising candidates in providing multiband/wideband antenna structures along with high gain. They possess advantages for both cavity-backed (high gain/directivity levels and unidirectional radiation patterns) and planar antennas (easy fabrication and low profile). In this work, planar antennas are designed using substrate integrated waveguide (SIW) technology to have low losses, high quality factors, and low fabrication costs. In our work, the concept of SIW technology have been utilised in the design of (i. wideband antennas, ii. self-multiplexed antennas, and iii. multiple-input-multiple-output (MIMO) antennas), which are discussed as below.

An interesting problem with the SIW cavity-backed slot antenna is improving the bandwidth performance of the antenna. Due to the high-quality factor cavity backing, the operation of the SIW cavity-backed slot antenna is affected by its inherent narrow bandwidth. To overcome this problem, a study of a wideband (SIW) cavity-based slot antenna is presented in this thesis. The proposed antenna consists of a U-shaped slot etched in the ground plane, which helps in achieving the wideband behaviour ranging from 26.20–30.30 GHz. A detailed analysis of the SIW cavity and the prediction of various modes propagating inside it using accurate design equations are also discussed.

Parametric studies on various parameters to improve the performance in terms of wide impedance bandwidth, gain, and efficiency levels are also discussed in detail. A good matching characteristic along with a good level of gain, radiation efficiency levels, and stable radiation patterns makes the proposed antenna a suitable candidate for 5G applications, such as (27.50–28.28 GHz in Japan, 26.50–29.50 GHz in Korea, and 27.50–28.35 GHz in the USA).

Various wireless applications, such as mobile handheld devices and RF frontend systems, require multiple transceivers to operate in different frequency bands. However, the antenna needs to be followed by a higher-order filter or diplexer network to differentiate between transmit and receive channels, which increases the complexity of the system. A useful solution to this problem is to design self-diplexing antenna systems due to their simple and compact size, with no requirement for a decoupling network, better isolation between the excitation ports, and ease of integration with the RF front-end components. Here, to fulfil the above requirement, a SIW-based circularly polarized (CP) self-diplexing antenna is designed. The proposed antenna makes use of an elliptical slot in the metallic ground plane, which is excited with the help of two separate microstrip feedlines, placed face-to-face with each other. This arrangement produces two different frequencies, centred around 21.70 GHz and 27.10 GHz, when separately excited by port-1 and port-2, respectively. The CP operation in both frequency bands can be achieved by rotating the elliptical slot, which gives 3 dB axial-ratio bandwidth (ARBW) of 3.01% and 6.62% in the lower and upper-frequency bands, respectively. The attractive features such as low profile and low weight make the proposed SIW antenna suitable for satellite and millimeter-wave 5G applications. An extension of the self-dipelxed antenna is also implemented by realising a self-triplexing antenna (STA). A SIW based self-triplexing antenna with a non-linear replicated hybrid slot (NLR-HS) is proposed. To the author's best knowledge, the concept of NLR is the first of its kind in the literature used for obtaining self-triplexed operation. Initially, the SIW cavity is loaded by a hexagonal slot merged with two rectangular transverse slots that together produce two distinct resonances around 5.23 and 7.50 GHz. The variation in resonant frequencies of both the lower and upper frequency bands can be modelled by applying NLR to the hexagonal slot. To achieve the self-triplexing operation, a coaxial probe-fed parasitic hexagonal patch is placed concentrically inside the hexagonal slot. The third resonance is centred around 10.82 GHz, which can be modelled with the help of the gap between the hexagonal slot and the parasitic patch. Easy independent tuning of all the three frequency bands is allowed using scaling of the hexagonal slot in x- and y-directions and spacing (or gap) between the hexagonal parasitic patch and the hexagonal slot. Hence, the flexible operation of the proposed STA can be easily utilized for different frequency bands in C-, and X- band. To validate the proposed idea, the design is fabricated and experimentally tested. The antenna is good for LTE/LTE Advanced, WLAN, Wi-Fi, and a weather monitoring satellite.

Wireless applications such as 5G cellular communications need large bandwidth and high data rates for streaming video content. For this, dual polarised antennas are being utilised in wireless systems to decrease the influence of fading caused by multipath propagation. For this, a simple cavity-backed SIW based 2×1 MIMO antenna with an asymmetric cross-slot (AXS) to obtain dual-band dual-circularly polarized (DB-DCP) operation is presented. Initially, the SIW cavity consisting of metallic vias on all four sides is implemented. This cavity is divided into two smaller SIW cavities using a row of metallic vias and excited using the coaxial feed for MIMO configuration. The partitioning using metallic vias offers a compact size for diversity performance and provides good isolation between the excitation ports without using any decoupling structure. To achieve CP in both operating frequency bands, the arms of the AXS were tuned sufficiently to realize 3 dB ARBW from 22.62-26.33 GHz and 29.20-30.12 GHz within the IBW, ranging from 22.60-26.36 GHz (Band-I) and 29.04-30.42 GHz (Band-II), respectively. The diversity performance of the proposed antenna is also studied and calculated using S-parameters and far-field analysis. The proposed antenna can feasibly support satellite and 5G cellular communications.

The research work investigated in this thesis provides a detailed study of several design methodologies to enhance the performance of high frequency microwave antenna systems in terms of compactness, bandwidth, and gain. To get a better insight into the proposed designs, the behaviour of the cavity modes propagating inside the SIW cavity is presented. All the antenna designs have been fabricated, and the measured results are experimentally verified with the simulated ones. An equivalent circuit modelling of all the proposed designs, along with surface current distributions at various resonating frequencies, is also performed. A detailed comparative study of the proposed designs with the current state-of- the- art in the literature in terms of physical and electrical size, isolation, gain, efficiency, FTBR, and complexity is summarised in the thesis.

Finally, the major contributions of the entire investigation are summarized. In addition, it also provides recommendations for future work.