SUBSTRATE INTEGRATED WAVEGUIDE MICROWAVE ANTENNA AND FILTER DESIGN USING H-FRACTAL UNIT CELL

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AYAD MUSLIM HAMZAH

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy in Electrical Engineering

Faculty of Electrical and Electronic Engineering
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JANUARY 2021

I hereby declare that the work in this project report is my own except for quotations and summaries which have been duly acknowledged

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DR. LUKMAN HANIF BIN MUHAMMAD AUDAH

Beloved father and mother....

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ABSTRACT

Currently, the fifth generation (5G) technology has been assigned for microwave. There are several challenges in developing antennas and filters for 5G devices that need to be addressed such as low efficiency and large size at the lower proposed 5G frequency band (1 GHz -6 GHz). Hence, a compact size device and wideband are the main requirements for the lower 5G bands applications. To allow small package devices for lower 5G band technology, the antennas and filters should be small enough to maintain the integration of massive network and keep a good performance of the state of art devices. Generally, microstrip planar technology is used to implement the antennas and filters. However, due to the size and losses which come from using common microstrip technology that results in a poor performance of the proposed devices. Substrate integrated waveguide with H-shaped fractal unit cell is proposed in this work to overcome these challenges. The proposed antenna operates at 4 GHz and 5.7 GHz frequencies bands which suite the lower 5G applications. The proposed antenna was designed and simulated by using CST MWS formulations. The antenna is fabricated on Roger RO4003C substrate with thickness of 1.52 mm. The measured S_{11} of 10 dB, gain of 5.4 dB, and efficiency of 82 % are achieved at these two bands. The proposed antenna was miniaturized by using H-fractal unit cell. Meanwhile, filter performs centre frequency at 5 GHz with bandwidth of 1.2 GHz and the proposed filter was designed and simulated by using ADS software. The filter is realized on FR-4 substrate with thickness of 1.2 mm with very compact size of $0.12\lambda \times 0.15\lambda$ is achieved with a reduction rate of 23%. The designed filter has an insertion loss of 0.75 mm with similar size of the antenna. However, there are some discrepancies appeared between the measured and simulated radiation pattern due to the losses from the measurement cables and the unwanted signal interferences since the measurement room is partially covered with absorbers. Nevertheless, the designed antenna and filter have a great potential for lower mm-wave and 5G band applications.

ABSTRAK

Pada masa ini, teknologi generasi kelima (5G) telah digunakan untuk kedua-dua gelombang gelombang mikro dan gelombang milimeter. Terdapat beberapa cabaran dalam pembangunan antena dan penapis untuk peranti 5G yang perlu ditangani seperti kecekapan yang rendah dan ukuran dimensi yang besar pada jalur frekuensi 5G yang lebih rendah (1 GHz – 6 GHz). Oleh itu, peranti bersaiz kompak dan jalur frekuensi yang lebar adalah syarat utama untuk aplikasi pada jalur rendah system 5G. Untuk membolehkan pakej peranti kecil digunakan dalam jalur rendah teknologi 5G, antena dan penapis haruslah cukup kecil untuk mengekalkan integrasi rangkaian besar dan mengekalkan prestasi yang baik untuk peranti canggih. Secara amnya, teknologi planar mikro digunakan untuk menghasilkan antena dan penapis. Namun, teknologi microstrip konvensional ini akan mengakibatkan prestasi buruk pada peranti yang dicadangkan disebabkan oleh ukuran dimensi dan kehilangan gelombang yang besar. Pandu gelombang bersepadu substrat dengan sel unit fraktal berbentuk “H” telah dicadangkan dalam tesis ini untuk mengatasi masalah tersebut. Rekabentuk antena dan penapis yang dicadangkan mampu beroperasi pada dua jalur frekuensi iaitu 4 GHz dan 5.5 GHz untuk disesuaikan dengan aplikasi 5G. Simulasi berangka berdasarkan teknik formulasi dalam perisian CST MWS telah dijalankan untuk mengkaji prestasi antena yang dicadangkan. Antena telah dihasilkan menggunakan substrat Roger RO4003C dengan ketebalan 1.52 mm. Kehilangan kembali (s_{11}) yang diukur ialah 10 dB, gandaan sebanyak 5.4 dB, dan kecekapan sebanyak 82% telah dicapai pada dua jalur ini. Antena yang dicadangkan dikecilkan dengan menggunakan sel unit H-fraktal. Sementara itu, penapis yang dihasilkan mempunyai frekuensi pusat pada 5 GHz dengan lebar jalur 1.2 GHz dan direka serta disimulasikan dengan menggunakan perisian ADS. Penapis direalisasikan pada substrat FR-4 dengan ketebalan 1.2 mm dengan ukuran yang sangat padat iaitu $0.12\lambda \times 0.15\lambda$ dengan kadar pengurangan sebanyak 23%. Penapis yang dihasilkan mempunyai kehilangan sisipan 0.75 mm dengan ukuran antena yang serupa. Walau bagaimanapun, terdapat beberapa

perbezaan antara corak radiasi yang diukur dan disimulasikan kerana kerugian dari kabel pengukuran dan gangguan isyarat yang tidak diingini kerana ruang pengukuran sebahagiannya ditutup dengan penyerap. Walaupun begitu, antena dan penapis yang dihasilkan mempunyai potensi besar untuk digunakan dalam pelbagai aplikasi gelombang milimeter dan jalur 5G.

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LIST OF SYMBOLS AND ABBREVIATIONS

$EN - DC$	-	E-UTRAN New Radio Dual Connectivity (EN-DC)
EUTRA	-	Evolved Universal Terrestrial Radio Access
CA	-	Carrier Aggregation
RWG	-	Rectangular Waveguide
PCB	-	Printed Circuit Board
VNA	-	Vector Network Analyser
LHCP	-	Left Hand Circular Polarization
RHCP	-	Right Hand Circular Polarization
LWA	-	Leaky Wave Antenna
TCSRS	-	Triangular Complimentary Split Ring Slot
SSA	-	Semicircle Slot Antenna
ω	-	Angular Velocity
ε0	-	Permittivity of free space
fc	-	Cut-off frequency
Ag	-	Wavelength
dB	-	Decibel
TE	-	Transverse Electric
TM	-	Transverse Magnetic
GHz	-	Gigahertz
SIW	-	Substrate Integrated Waveguide
SRR	-	Split Ring Resonator
CSRR	-	Complementary Split Resonator
BC-CSRR	-	Broadside Coupled
BC-CSRR	-	Broadside Couple Complementary split ring resonator
DFW	-	Dielectric Filled Waveguide
OCSRR	-	Open Complementary Split Ring Resonator

ADS	-	Advance Design System
3D	-	Three Dimension
EM	-	Electromagnetic
AUT	-	Antenna Under Test
VSW	-	Voltage Stand Ratio
RF	-	Radio Frequency

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Societal changes witnessed since the explosion of data services, and the growing appetite for wireless broadband have incentivised the speedy development of the fifth generation of cellular systems (5G), envisioned for year 2020. Currently, the implementation of lower band for fifth generation (5G) in mobile and cellular networks is rapidly spreading worldwide. This accelerating has crucial the researchers to define the requirements need to be applied in the 5G wireless technology for mobile and cellular applications. One of the most important requirements for 5G technology is the expanding the traffic users by increasing the system capacity. This can be done by providing a higher data rates, higher bandwidth, and high efficiency state of art devices [1]. In such case, a new challenge is arising toward the realization of the 5G devices. To meet the requirements that 5G technology should offer, the complexity of the radio frequency (RF) devices has to be increased. The increasing complexity covers the modulation schemes, number of antennas used, carrier aggregation (CA), and E-UTRA New Radio Dual Connectivity (EN-DC) [2]. This results in increasing the bandwidth which leads to high data rates and eventually increases the system capacity. In addition, these trends increase the probability of interference in mobile devices. Moreover, all these trends need to be compact in size to enable device packaging for massive network. In that case, the antennas and filters should be small and highly integrated.

The antennas and filters in 5G technology playing a key role in realizing a high-performance RF device. Antennas and filters need to handle high power capability, high gain, maximize operating frequency range, and occupying less space (compact size) in the lower 5G bands (1GHz-6 GH) [3]. Therefore, advances in antenna and filter technology for 5G system is highly needed to achieving the desired goals.

In engineering point of view, the most critical design point is how to provide a high-performance antenna and filter in term of bandwidth, output power, gain, and compactable size at suggested 5G bands. This motivates the researchers to seek the optimal technology to be implemented with these requirements. Several technologies have been introduced through decades including stripline, microstrip, waveguide, and substrate integrated waveguide (SIW) [4-8]. As well known, the planar technology such as microstrip has gained significant attention among other planar and non-planar technologies, due to its simplicity, low profile, ability of providing high bandwidth, and capability of reducing the size of the antenna and filter. Different types of antennas and filters have been presented with varies technique of implementation.

The most popular type of antenna is the microstrip patch and microstrip slot antenna [9-11]. However, microstrip antennas and filters are generally suffered from low power handling capability and high losses when it integrated as a massive network. Then researchers shifted to non-planer technology such as waveguide structures [12-15]. Despite the very good performance of waveguide structure, the size of the antenna and filter is considered bulky. Due to the depending of inner dimensions of the waveguide size especially at lower frequency (10 GHz and below). Thus, a newly technology is proposed that combines the features of microstrip and waveguide in one planar technology called substrate integrated waveguide (SIW).

Substrate integrated waveguide SIW is a technique which mimics the conventional rectangular waveguide properties using planar technologies, so the SIW is a synthetic metallic RWG of equivalent width filled with dielectric material in planar form [16-18]. Although the SIW structure has similar properties as the conventional rectangular waveguides. The SIW is a periodic guided wave structure; therefore, it may lead to the electromagnetic band gap phenomenon. Also, the SIW structures are subjected to a potential leakage problem due to the periodic gaps.

This type of technology has the ability to be integrated to other PCB circuits and ease the process of integration and fabrication; it is a promising technique for wireless 5G and millimeter-wave technologies. Hence, SIW structures are good candidate for implementation of antennas and filters due to its property of low loss transmission line and compactable size that comprises the properties of microstrip and waveguide technology.

1.2 Problem Statement

With the demanding system requirements for the fifth generation (5G) wireless Communication and the severe spectrum shortage at conventional cellular frequencies, antenna systems operating in the frequency bands have attracted a lot of research interest and have been actively investigated. They represent the key antenna technology for supporting a high data transmission rate, an improved signal and 5G system requires to provide a compact size and high-performance state of art devices. Thus, future (5G) wireless systems have to satisfy main requirements such as the antennas and filters need to be miniaturized with handling their good ability of power handling and higher bandwidth. At lower frequency of proposed 5G bands, the most key point is the size of the antenna and filter that can be highly integrated with RF devices [19]. Therefore, SIW technology is proposed to overcome size reduction which is one of the critical issues in SIW. Furthermore, the miniaturization of antennas capable of providing batter bandwidth and acceptable gain is a challenging task. In antenna design, several SIW antennas have been proposed in order to reduce the size and maintain the performance. SIW antennas at 5G lower bands have unwanted radiation losses comes from the vias holes [20]. In addition, the vias separation distance is depended on waveguide size, which leads to a bulky size for massive RF antenna network at 5G lower bands [21]. Therefore, an alternative is demanded to overcome size issue and radiation loss. Fractal antenna and metamaterial are proposed to be used with SIW antenna design to reduce the overall size and decreases the radiation loss that comes from the vias [22]. However, different shapes and topologies of fractal and metamaterial have been presented with a challenging of implementing without effected the vias radiation and causes more losses. In the case of SIW filters, the current studies focus on size reduction that can be benefit the overall RF transceivers beside the power handling capability. Various SIW filters designs have been introduced with slots line, cavity, and resonators techniques [23-25]. However, these designs result in a big size implementation due to the stagemodes used and using unpanelled vias separation [24]. In this research, the main focus is to use H-shape fractal antenna as a metamaterial structure implemented in the filter and antenna design that reduces the overall size of printed SIW structures while keeping their high performance despite slightly losses.

1.3 Objectives

The main aim of this research is to design and develop a compact low profile antennas and filters using SIW integrated with metamaterial technology at 1-6 GHz. The following are the objectives of the research:

(i) To design a low profile and compact SIW antennas with unit cells acting as resonator at 4 GHz and 5.7 GHz.

(ii) To design and analysis a low profile and a compact of SIW H-fractal shape unit cell bandpass filters with 1^{st}, 3^{rd}, and 5^{th} stage at centre frequency at 5 GHz.

(iii) To propose a new filter design integrated with antenna for 5G technology.

1.4 Scope of Study

This research focuses on designing and developing of a compact and high performance SIW filters and antenna at (1-6GHz).

i) The antennas and filters were designed based on theoretical calculations before simulate and optimize using Computer Simulation Technology (CST) Microwave Studio (MWS). Firstly, a new metamaterial unit cells acting as resonators with small footprints were designed. Then, the SIW transmission lines with fractal slots etched out from the top walls of the printed SIW are designed in the first stage.

ii) Secondly, after analysing the main unit cells, it arranged in a periodic way to design bandpass filters. Thirdly, the unit cell with fractal shape were implemented for SIW antennas with open and short-ended SIW-metamaterial antennas cases. Also, the proposed antennas have single- and double-unit cells to observe influence a number of unit cells on the overall antenna performances.

iii) The antenna and the filter ware fabricated using existing substrate Rogers RO4003C, and FR4 with dielectric constants 3.38, and 4.6 respectively. Finally, the measurement were conducted using VNA network analyser. The gain and radiation pattern measurement were tested with a reference horn antenna at C-band with reference gain of 10 dB. Figure 1.1 shows the scope of this research.

1.5 Significant and contribution of research

In this research, two contributions are achieved as follows:

Miniaturized waveguide slot antennas using negative order resonance are proposed and developed in this thesis. The design of these novel resonant-type antennas is based on the study of a composite right/left-handed (CRLH) substrate integrated waveguide (SIW). Two types of slot antennas, which are open-ended and short-ended, respectively, are proposed and discussed. Four antennas with one or two unit cells are fabricated and measured. Compared with the existing patch antennas and waveguide slot antennas, our antennas show advantages in terms of simplicity, low-profile, high efficiency and miniaturized size with integration with other circuits.

A new family of substrate integrated waveguide metamaterial bandpass filters is proposed which support the backward and forward wave propagations with two adjacent passbands under the cut-off frequency of the structure. Through varying the fractal slots sizes etched over the SIW structures, different frequency transmission responses were realized. Extraction of the metamaterial parameters was achieved via scattering parameters. The equivalent circuit model was analyzed to provide comprehension on the SIW-metamaterial unit cells. The equivalent electrical length of a fractal slot is larger than the conventional slot, making it suitable to design highly miniaturized filters. Three filters using the 3rd iteration H-shaped SIW-metamaterial unit cells were designed and tested using subwavelength resonators. Filter design was used to extract the coupling coefficient and external quality factor to obtain the filters' optimized physical dimensions. The out-of-band rejection can be enhanced by configuring the fractal slots or the SIW. A wide upper out-of-band rejection with attenuation >50 dB with the 5 GHz was realized. The proposed filters offer advantages through low insertion loss, easy fabrication, high selectivity, small size, and low cost. The measured scattering parameters S_{21} and S_{11} were in agreement with the simulated.

1.6 Thesis Organization

Chapter 1 describes the motivation, the background of developing SIW antenna for 5 G application, Problem statement, the research objectives and scope as well as the significant contributions of thesis. The rest of thesis is organized as follows:

Chapter 2 presents a literature on SIW antennas and filters in 5G and lower band technology. SIW transmission lines structures are presented in the beginning, followed by SIW antennas and filter theory. Then, related works on SIW antennas and filters are critically reviewed in this chapter.

Chapter 3 focuses on the methodology used to achieve the proposed designs. The methodology steps are simplified in the form of a flowchart. The design specifications are justified based on related published work and standards requirement as guidance. The design parameters and equations are discussed and the fabrications as well as the measurement procedures are presented.

Chapter 4 presents the design of the SIW antennas and filters steps. Fractal H-shape slot type is chosen and thus the design; simulation and optimization are presented. The antenna and filter are fabricated using RO4003C and FR4 and the performance is discussed.

Chapter 5 concludes the finding of this research. The recommendations for future work on the SIW antennas and filters for 5G technology are listed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the most related work on SIW antenna and filters particularly in lower 5G frequency band. The principle of each component involved is described. The antenna and filter is focusing on the SIW, fractal, and metamaterial technology. The transmission line and SIW principle are presented at the beginning to explain the choice of SIW in implementing the structures at proposed 5G lower bands.

2.2 Substrate Integrated Waveguide

Substrate integrated waveguide SIW is a technique which mimics the conventional rectangular waveguide properties using planar technologies, so the SIW is a synthetic metallic RWG of equivalent width *w*eff filled with dielectric material in planar form [26]. Figure 2.1 (a) shows a typical SIW structure that is manufactured with a linear row of metallic via holes with diameter d, a periodic length s on a low loss material substrate of permittivity εr and the effective SIW width w. Although the SIW structure has similar properties as the conventional rectangular waveguides, it has different features. The SIW is a periodic guided wave structure; therefore, it may lead to the electromagnetic band gap phenomenon. Also, the SIW structures are subjected to a potential leakage problem due to the periodic gaps. Therefore, the wave traveling in SIW structure has different characteristics from those of the conventional rectangular waveguide. TM_{mn} and TE_{mn} modes can be excited on the rectangular waveguide, but only TE_{m0} can be excited in the SIW.

The gaps in the narrow wall of the SIW guide prohibit TM_{mn} mode's current distribution. Thus, TM_{mn} modes cannot be supported as shown in Figure 2.1 (b).

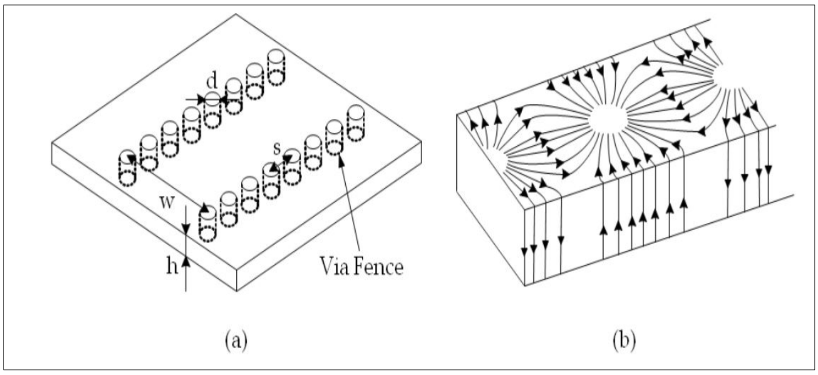

Figure 2.1: (a) Structure of SIW, (b) surface current for TE10 mode [26]

This type of technology has the ability to be integrated to other PCB circuits and ease the process of integration and fabrication; it is a promising technique for wireless 5G and millimeter-wave technologies. Now, a non-planar of conventional rectangular waveguide components has its planar counterpart through the concept of the SIW [26]. This research work will focus mainly on new and novel antennas, dividers, and filters based on the SIW for 5.8 GHz. In applications of greater frequency, the micro strip devices showing inefficiency due to the smaller wavelength of more frequency. Greater tolerances needed while manufacturing micro strip devices. SIW devices favours at greater frequencies but there is complexity in manufacturing process [26]. Among the di-electric filled waveguide, microstrip transitions and it leads to a new concept named Substrate Integrated Waveguide (SIW), the SIW is defined shown in Figure 2.2 with the help of waveguide sidewalls of vias the SIW converted by dielectric waveguide. The signal carried by the metal amount considered as more than in strip line or micro strip determined as an SIW attraction. Lower conductor loss is seen. The considerable demerit is leakage losses and its due to the vias spaced in tight manner.

For C band search, efficient and compact size directional coupler comprised by SIW method is focused. The dielectric filled waveguide (DFW) has been replaced the high frequency by inefficiency exhibited by microstrip devices. DFW converted to SIW by holes and significantly decrease manufacturing cost and dielectric loss presented in traditional waveguides [26].

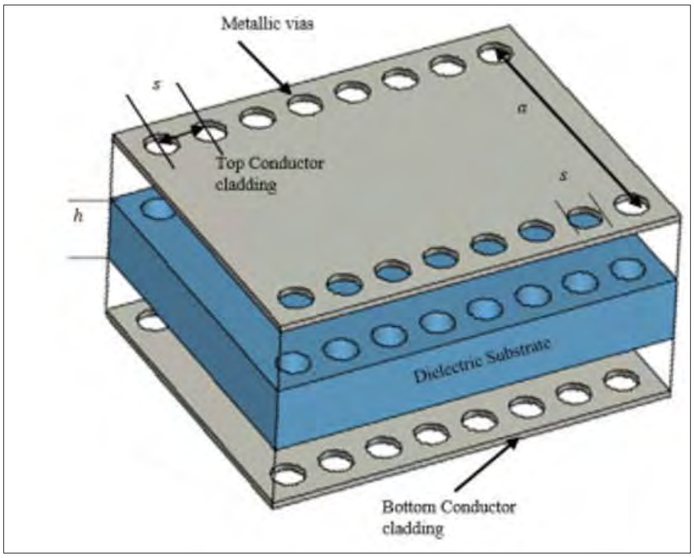

Figure 2.2: SIW configuration [26]

A lot of study is done on transition between microstrip-SIW [27], co-planar waveguide CPW-SIW [28], guided co-planar waveguide GCPW-SIW [29] as shown in Figure 2.3, in order to have benefits of this technology. These transitions can be used to improve impedance matching in SIW based antennas.

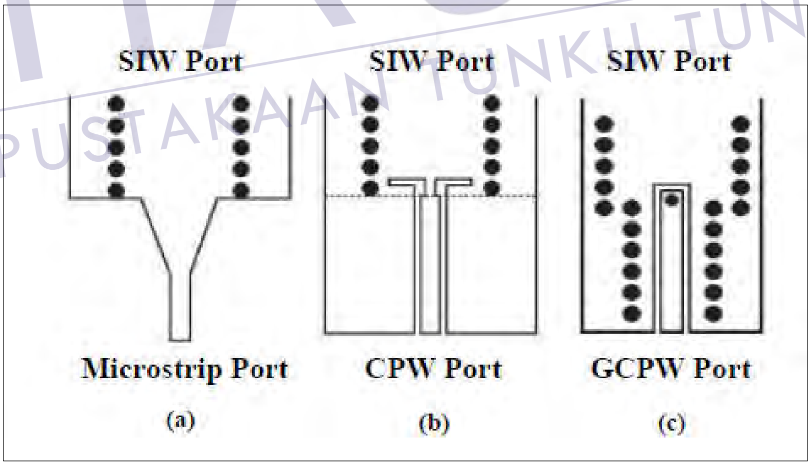

Figure 2.3: Some SIW transitions and structures [27-29]

2.3 The concept of Metamaterial

Metamaterials are artificial material which is recently developed, and it possess negative refractive index, negative permittivity and negative permeability. Compared to readily available materials it explored unusual properties. In Greek, the word Meta defined as beyond, and the materials named as naturally available materials exhibits unusual properties. Meta-materials is not considered as special material and if any metal array of structure can modify the wave transient through its electric and magnetic property. It resulted in refractive index and negative permittivity at a time and the corresponding metallic structure is called as meta-materials.

Veselago [30] firstly presented metamaterials (MTMs), with the assumptions of the ε (electric permittivity) and μ (magnetic permeability) of an effectively homogeneous material could take simultaneously negative values. Because of that, several physical phenomena could change their natural behaviour, such as the reversal of Snell's law, the reversal of Doppler shift, the reversal of Cerenkov effect, among others [30, 31]. The constitutive material parameters ε and μ, are related to the refractive index n as [30]:

$$n = \pm\sqrt{\varepsilon_r \mu_r} \tag{2.1}$$

where ε_r and μ_r are the relative permittivity and permeability related to the free space permittivity. Then, four possible regions appear depending on the sign combinations of (ε, μ); since ε_0 and μ_0 are positive fundamental constants, negative values in $\varepsilon = \varepsilon_0\varepsilon_r$ and $\mu = \mu_0\mu_r$ are due to the sign of the relative parameters εr and μr, respectively. A ε−μ diagram has been shown in Figure 2.4 representing the possible materials arising from the four sign combinations of (ε, μ).

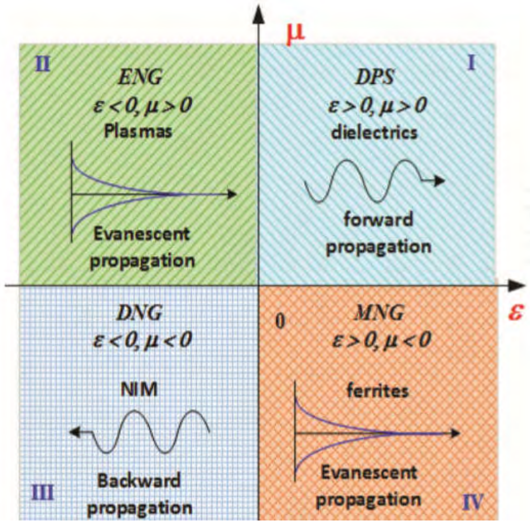

Figure 2.4: ε−μ diagram with four possible materials [30]

Waves can only propagate in materials from regions I and III, where ε and μ parameters are both positive (double positive, DPS, or right-handed medium, RHM) or both negative (double-negative, DNG, or left-handed medium, LHM). Non-propagating evanescent waves are found in regions II and IV, where $\varepsilon < 0$ (epsilon negative, ENG) or $\mu < 0$ (mu negative, MNG). Finally, some other regions of interest might also be considered, such as the epsilon-near-zero (ENZ) where $0 < |\varepsilon| < 1$, and the mu-near-zero (MNZ) where $0 < |\mu| < 1$. Double negative metamaterials (DNG) are characterised by their simultaneous $\varepsilon < 0$ and $\mu < 0$ values. This fact also affects the field equations in Maxwell's formulas. A general definition of the Poynting vector S in a phasor notation is (2.2), where a time dependence e^{+jwt} and a space dependence e^{-jkr} are assumed [31].

$$S = \frac{1}{2} E \times H \tag{2.2}$$

where the electric field E and the magnetic field H are defined by [31]:

$$\beta \times E = \omega\mu H \tag{2.3}$$

$$\beta \times H = -\omega\varepsilon E \tag{2.4}$$

Therefore, for an isotropic and homogeneous medium with $\varepsilon > 0$ and $\mu > 0$, the electric field E , the magnetic field H and the propagation vector β form a right-handed triplet, which is the origin of the right-handed medium (RHM) definition. However, by considering a medium with ε < 0 and μ < 0, the previous equations can be rewritten as [31]:

$$\beta \times E = -\omega|\mu|H \quad (2.5)$$

$$\beta \times H = \omega|\varepsilon|E \quad (2.6)$$

Showing that the $E - H - \beta$ forms a left-handed triplet. This medium is referred to as left-handed medium (LHM), and supports backward waves, because the Poynting vector S is opposite the propagation vector β, that is, the energy and wave fronts travel in opposite directions. This fact is reflected in the RHM and LHM E − H − β triplets Showed in Figure 2.5 [32].

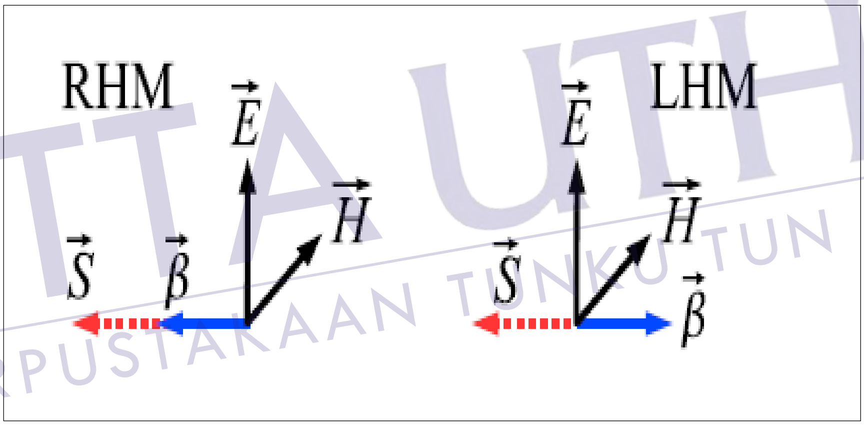

Figure 2.5: The triplets of RHM and LHM medium [32]

Microwave communication system is developing very prosperously, which corresponds to need of low-cost, compact and highly efficient systems. In almost all wireless communication systems, antenna is a necessary component for transmitting or receiving microwave signals along with filters for suppressing unwanted spurious signals. The impedance mismatch between the individually designed antenna and filter causes interference, increases insertion loss and thus affecting the performance of the circuit. Integration of two or more functions together leads to multifunction module miniaturizing the circuit size and leading to improved circuit performance. Since radiating and filtering are the most important functions of the communication system, integrating these functions into a single module will reduce the additional circuit and enhance the overall performance of the circuit. This single module is Filtering Antenna, performing both the functions simultaneously. Filtering Antenna provides shaping of frequency response [32].

Various alphabetic metamaterial structures have been proposed for specific applications; for example, it has been proposed a double "S-shaped" metamaterial in the microwave range. Their metamaterial exhibits a negative refractive index between 15.67 and 17.43 GHz. Few studies have yet been conducted based on their design. It has been proposed a rectangular "U-shaped" metamaterial that exhibits double-negative characteristics at approximately 5, 6 and 11 GHz for different array configurations. It has been demonstrated a "V-Shaped" metamaterial. This structure exhibits double-negative characteristics at only 8.10 GHz. It has been presented a "Z-shaped" metamaterial that is applicable at 4.5 GHz. However, their design has been proven for single-negative (SNG) characteristics with negative permittivity only.

In this thesis, a new H-shaped metamaterial unit cell structure is proposed, and exhibits resonance frequency in the multi-band (C-band) range of the microwave spectra. It also exhibits double-negative properties at those frequencies. The commercially available electromagnetic simulation software package, Computer Simulation Technology (CST) Microwave Studio, was used to obtain the reflection and transmission parameters of the unit cell and to monitor the resonance frequencies. These parameters can be used to determine the effective permeability (μ) and permittivity (ε) for the proposed configurations.

SIW structure keeps the advantages of conventional metallic waveguides, such as high -factor, high selectivity, cutoff frequency characteristic, and high power capacity. It also has the advantages of low profile, light weight, conformability to planar or curved surfaces, and easy integration with planar circuits Their performance improvement methods, including bandwidth enhancement, size reduction, and gain improvement are also discussed based on available literature. Due to this, SIW antennas and array take the advantages of both classical metallic waveguide, which includes high gain, high power capacity, low cross polarization, and high selectivity, and that of planar antennas which comprises low profile, light weight, low fabrication cost, conformability to planar or bent surfaces, and easy integration with planar circuit.

SIW structure is shown in Figure 2.6. In SIW, there are two rows of metallic vias embedded in the dielectric substrate which acts as waveguide by connecting the two parallel metal plates on the top and bottom. The two rows of vias act as the walls of the rectangular waveguide along with the top and bottom metal plates. Nevertheless, though SIW has electrical similarities to rectangular waveguide and provide advantages similar to the rectangular waveguide it is also prone to leakage problem if the design rules are not followed properly. Some design rules and equations have been formulated by researchers in the past for proper design of SIW. It can be used the equations 2.6 and 2.7 in order to define how much vias can be used in the required design.

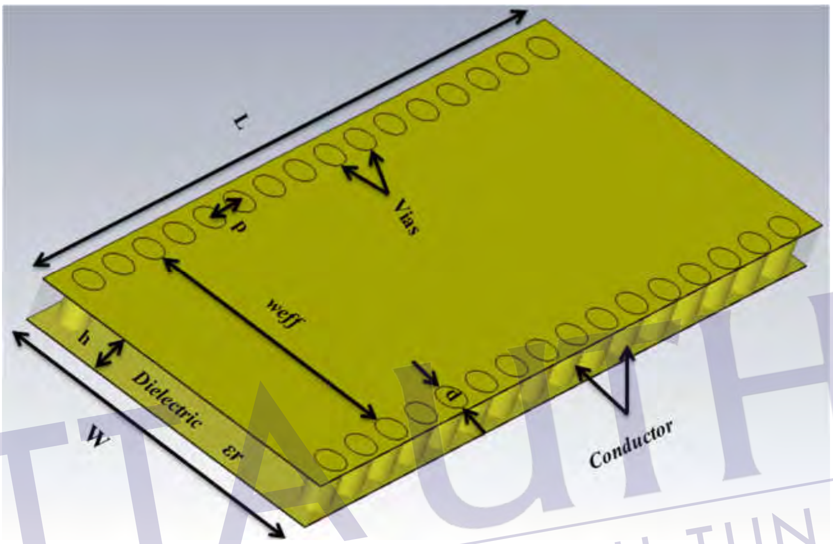

Figure 2.6: SIW structure

The diameter of the via and the space between the vias should be chosen as per Equation (2.7) and Equation (2.8) respectively [121].

$$Dvia < \frac{\lambda g}{5} \tag{2.7}$$

$$p \leq 2Dvia \tag{2.8}$$

where λg is the guided wavelength, $Dvia$ is the vias diameter and p is the space between them. The effective width of the waveguide is given by Equation (2.9) [122].

$$Weff = Wsiw - 1.08\frac{Dvia^2}{p} + 0.1\frac{Dvia^2}{Wsiw} \tag{2.9}$$

where $Weff$ is the effective width, $Wsiw$ is the SIW width which is 11mm, $Dvia$ is the vias diameter which is 1 mm and is the space between them which is 1.5 mm. Cut-off frequency for the SIW in Transverse Electric (TE) mode is given by Equation (2.10).

$$f_{c,mn} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (2.10)$$

where is the cut-off frequency, and are the mode numbers, is the dielectric constant, is the width of the waveguide and it is the height for a given waveguide, the dominant mode is the mode having lowest cut-off frequency. Signals can progress along a waveguide using a number of modes. However, the dominant mode is the one that has the lowest cut-off frequency. For a rectangular waveguide, this is the TE10 mode. The TE means transverse electric and indicates that the electric field is transverse to the direction of propagation. In rectangular waveguide, TE_{10} is the fundamental mode and same is also true for SIW. Figure 2.7 shows the E-field distribution in the SIW. The calculation parameters can be referred Appendix B for calculation steps.

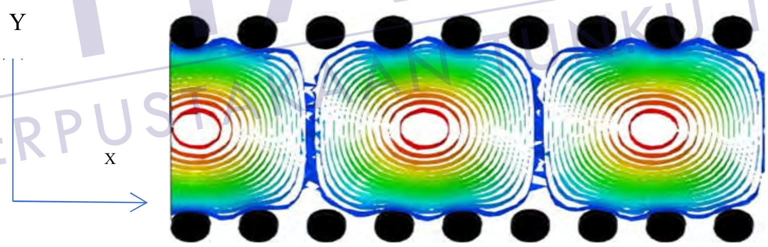

Figure 2.7: E-field distribution in SIW

Table 2.1: Dimensions of substrate integrated waveguide

SIW Physical Characteristics	Numerical Value using for antenna	Numerical value using for filters
Dielectric Constant, ε_r	3.38	4.6
Via Hole Diameter, *d*	0.5 mm	0.5 mm
Via Hole Spacing, *p*	1.5mm	1.5mm
Width, W	9 mm	9 mm
RWG Equivalent Width, *Weff*	8 mm	7.8 mm
Thickness, h	1.52 mm	1.2 mm

.

2.4 Fractal metamaterial SIW Design

Curve configurations are presented in this chapter, followed by the working principles of the proposed SIW-metamaterial unit cells. The extract of the active parameters of the SIW-metamaterial of the unit cells is then shown to demonstrate that the proposed unit cells can operate at the cut-off frequency of the SIW with reverse propagation scenarios for example, double negative DNG) and forward propagation i.e., double positive DPS. Then, the derivation and analysis of the equivalent circuit model.

2.4.1 Fractal Curves

The end of the 19th century has witnessed the emergence of fractal geometry when Piano proposed a continuous curve passing through all points of a specified space [123]. A successive repetition of one specific geometrical form, in an iterative manner, was used to generate fractal curves. In other words, it can be described as a collection of scaled replicas of the first form. The higher orders of fractal curves obtained after each iteration have longer curves than those generated in the preceding iterations to entirely fill the given area where they were generated. The space-filling property of the fractal geometry was exploited to highly miniaturize passive microwave components because, theoretically, traces (lines) with infinite-lengths can be realized on small areas.

Some designs using the fractal geometry have shown that very compact antennas, resonators, and filters can be realized due to its very long microstrip lines being printed on small given substrates. Also, a wide variety of applications such as high impedances surfaces HISs [124], frequency selective surfaces FSSs [125], RF identifications [126], and left-handed metamaterials LHMs [127] utilized the fractal geometry to design multi-band and small structures.

The non-integer dimension is a property of the fractal curves which is between 1 and 2 for planar fractal curves. It can be considered as a measure of how the fractal curves can fill small regions. The ratio in equation 2.11 can be used to calculate the dimensions of the fractal curves,

$$D = \frac{log(k)}{log\ (r)} \tag{2.11}$$

where k is the number of self-similar segments of the fractal curves attained from one segment after each iteration and r is the number of segments obtained from one segment in each iteration.

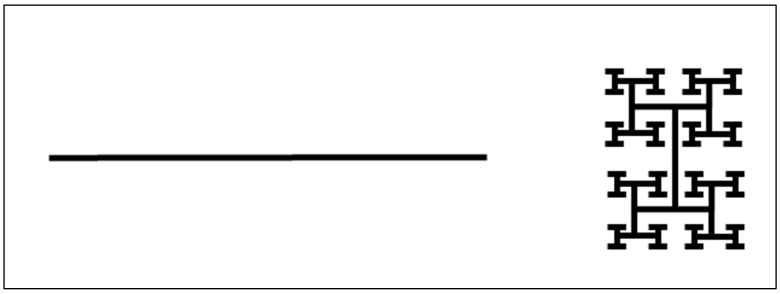

Figure 2.8: A comparison between the conventional straight-line (e.g., transmission-line) and its length-equivalent fractal curve

Figure 2.9 displays a conventional transmission-line (i.e., straight line with a specific width) and its equivalent fractal configuration. Ideally, although the fractal transmission-line can be printed on a small area, both fractal curves and the conventional transmission-line may have the same electrical length. Using fractal geometry allows the use of shorter transmission-lines, but with longer equivalent electrical length. This aids to miniaturize transmission-lines, being a key part to the miniaturization processes of microwave circuits and antennas.

Today, there are a lot of fractal curves which are well-known such as Piano, Koch, Serpiniski, etc. In order to determining which fractal curve is suitable for our design, some criteria should be considered in advance. The miniaturization ratio that a fractal curve can introduce is one of the intentions considered in this research study, so dimensions of the fractal curve is chosen as the most important parameter. The fractal curves which reach dimension 2 are better because of its ability to efficiently fill in small areas, therefore obtaining very compact devices. Several fractal curves have dimensions equal to 2 which is the maximum value, but Figure 3.6 shows some of them such as H-shaped, Piano, and Hilbert fractal curves. In our design, the H-shaped fractal curve was chosen over others for reasons shown later in this research work. Figure 2.9 depicts the process of the H-shaped fractal curve generation. As can be seen, the dimension of H-shaped fractal curve tends to reach 2 with the increase of an iteration order, filling the whole given area.

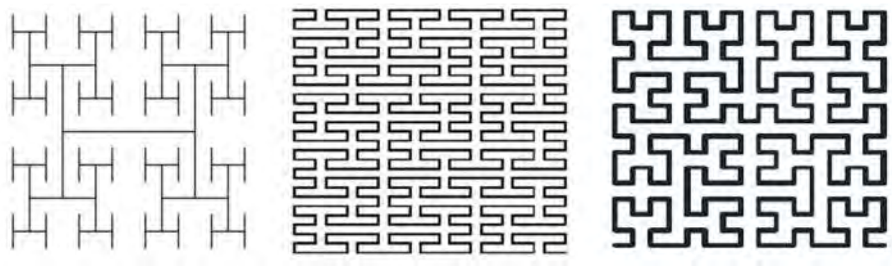

Figure 2.9: Three types of fractal curves (H-shaped, Piano, and Hilbert)

2.5 Related Works on Substrate Integrated Waveguide Antenna

The Substrate Integrated Waveguide Antenna integrated the structure of planar and rectangular waveguide features[33]. For practical applications, the size is higher in some cases. In antenna design the SIW has been introduced and traditional longitudinal waveguide antennas slotted which were same as the slot array antennas and it was same as conventionally slot antennas and conventional structure possess some disadvantages also. In [34], through ground plane and directional radiation pattern the isolation of high-body antenna has been obtained.

The outcome shows the body performance reliability and stability. For multi-band wireless body area network (WBAN) like wearable applications and wearable radar or multi input multi output (MIMO) multi antenna systems the proposed antenna has been considered as better option in this study [35]. To generate multiple beams of Orbital Angular Momentum (OAM) the Half Mode HM-SIW antenna based has been examined. Cavity resonator analysis mode presented in this study and OAM beam generation 1-order has been provided with simple method. In standard process the prototype realized and measured performances seen. This study concludes that OAM antenna structure appropriate to compact size incorporation.

In this article presented in design with single radiating aperture dual circular polarization with reduced beams of side lobe level SLL generated by SIW long slot array antenna parallel plate [36, 37]. Two layers of substrates presented in the discussed antenna. The network of unequal feeding construct by one substrate and long slot array antenna 15 × 15 shared aperture constructed by another substrate. In feeding network 90 degree coupler involved for polarization switching between circular polarization of left hand and right hand. SIW parallel plate prototype has been invented the long slot array antenna. In two planes the fabricated antenna SLL simulation results have been below 18.5 (dB) seen [38, 39]. At 28 GHz band the study presented SIW antenna arrays based circularly polarized Left-hand and right-hand LHCP and RHCP were mainly for applications of millimeter wave. The feeding networks composed with RHCP array of antenna and 8-element LHCP to obtain the better performance of circularly polarized. Performance of radiations gained high and less expensive resulted for proposed circularly polarized antenna based SIW mainly for mm wave.

In [40], a cut-off frequency with backward to forward of continuous scanning of beam, the SIW based (LWA) Leaky Wave Antenna supported the concept. At first transverse slots used followed by extra longitudinal slots which focused on continuous scanning of beam with planar structure. Less dispersive scanning of beam achieved. In [41, 42] in forward direction alone the main beam has been scanned by Leaky Wave Antenna from conventional SIW. Continuously scanning in forward and backward directions the (LWA) from SIW based possessing greater radiations have been proposed in this study. In case of transverse slot, the direction from backward to forward when broadside beam method used, the level of cross-polarization increased. In order to reduce this issue the extra SIW based LWA proposed and it reduced level of cross polarization. Hence continuous beam scanning and reduction in level of cross polarization obtained. In [43], for non-destructive and compact chemical sensor developing, the eighth-mode SIW antenna (EMSIW) with microfluidic channel has been proposed in this study. The S- parameters of EMSIW microfluidic antenna has been measured. From the ethanol concentration and resonant frequency relationship the chemical sensor ethanol of proposed antenna determined in the study.

Leaky wave dispersion which creates general antenna broadband by the compensated lens have been proposed in this study [44]. At K-band the above discussed term defined and in same concept the lens have integrated. The experimental results and full wave simulations have been presented regarding the proposed study. For array antennas exploitation the complementary sources of antenna element composed of wideband linearly polarization has been proposed in this study [45], 22 % of bandwidth of band which was unlicensed covered with reduced loss and high amount of gain resulted in this work.

On single layer printed circuit board the K-band end fire system of SIW with (CP) antenna has been proposed in this research [46]. In the substrate plane dual orthogonal polarizations have been developed by H plane SIW horn antenna. With 23 to 27 GHz frequency the antenna of circularly polarized system have been defined in this study. Using Ferrite LTCC methodology the SIW based antenna arrays monolithic of configuration have been realized in this research [47]. SIW ferrite filling has biased and it leads to tuning. The monolithic incorporation of antennas and phase shifters in SIW has been enabled. This study can leads to huge size executions in future. For 60 GHz applications a cavity backed slot arrays of antenna of SIW has proposed and evaluated in terms of circular polarization, increased gain and broadBand performances [48]. Dual polarization enabled by simplified SIW network. This proposed antenna has been showing better performances in wireless arrangement of millimeter wave applications.

This article explored the novel SIW horn antenna design and broad walls which have detached moderately have been analysed [49]. Between free space and substrate the horn aperture mismatch leads to narrow bandwidth operation issues in SIW horn antenna of conventional method. The distribution of dielectric constants in corresponding direction with various diameters resulted in enhanced radiation operation i.e. occurs end fire radiation pattern stability. Hence the SIW horn antenna shows good performance without any additional extension. Another new technique named (TCSRS) Triangular complimentary split ring slot cavity backed antenna have been proposed based SIW [50]. For 5G wireless communication the proposed antenna at 45 GHz and 28GHz developed and executed. High gain operation has been expected. At these frequencies the arrays antennas have been fabricated with circuit board. For 2x2 arrays of antenna the peak gains measured. In this study [51], the printed circuit board of multilayer made an Air filled SIW with Antenna of antipodal linearly tapered slotted has been discussed and analyzed. For this proposed antenna the air filled SIW emphasize three layers architecture resulted in higher performance and lesser amount of loss. The efficiency in design also achieved. Using corrugated structure of SIW the great amount of gain has been achieved by antenna possessing dual band low profile aperture [52]. The better reflection co-efficient, improvement in profit obtained by SIW of four types and transmission line cavity executed on printed circuit board. Metallic plates decreased. Based on basic slot antenna the antenna gain enhanced.

Using SIW TE20 intrinsic field distribution, the patch antenna array exhibits series and parallel millimeter wave has been presented [53]. The feeding structure of dual slot has been executed. The SIW TE20 has developed patch antenna element in which 10dB bandwidth and 6.48dB profit peak has been simulated. A compressed series and parallel form of various feeding network developed. The performances related to superiority in radiations and it considered as communication high point. Lesser cross polarization also achieved. The applications of circular polarization CP of antenna array and slot antenna of cavity backed composed of low profile fed by dual single have been presented in this study [53, 54]. The cavity backed slot resulted in reduced cost of printed circuit board procedures in standard way with respect to design of antenna based SIW and half mode SIW methods. Based on SIW cavity the novel spoon shaped antenna slot developed for CP radiations. The half mode SIW with semicircle slot antenna (SSA) of cavity backed mainly proposed for size of antenna reduction and bandwidth improvement. SSA design process has been improved. The SSA impedance bandwidth enhanced by dual hybrid modes. Antenna array in sequence rotation proposed for SSA feasibility validation. Finally at 28 GHz the results shows that the arrays of antenna properly designed and results of simulations have acceptable.

In this study, the antenna of cavity backed – planar slotted based SIW of dual band implemented using proposed design method [55]. Through coupling window in cavity general sidewall various sizes of several cavities of SIW proposed. Antenna of higher bandwidth obtained by within the slots shaped with long bow tie the cavities were loaded. The slot dimensions varied and tuned the several hybrid modes generation by slots of long bow tie employment. For planar configuration maintenance, the SIW cavities coupled and employed in orthogonal direction executed slot antenna of dual band two polarised presented. Reasonable bandwidth and gain resulted. The features of better stop band composed of dual band antenna has been proposed in this work [56]. On a SIW cavity the conventional antenna variation namely dual transverse slot engraved. Dual non-radiation modes and dual band operation obtained by two half modes. Radiation nulls created by TE_{110} and TE_{120} even modes. The selection of band edge and profit of non-radiation of the proposed structure enhanced by stop band and two radiation null. Efficiency resulted as lesser pass band of 86% and higher pass band of 75%.

Using shorting the cavity backed slot antenna of SIW based quad and triple resonance has been proposed [57, 58]. Low profile and greater bandwidth achieved in antennas. By circuit model and distribution of electric field the antenna of triple resonance described and wide bandwidth achieved. Extended wide bandwidth obtained by antenna of quad resonance. These two antennas prototype measured and analysed. Bandwidth and peak gain evaluated. The antenna of quad resonance shows higher bandwidth and peak gain than triple resonance. The gap SIW, closed form of expression deduction and modified SIW introduced by communication and concentrated on coupling and fringing in gap fields [59]. This kind of structure corrected the SIW horn antenna on H-plane phase distribution. The antenna gain improved without bandwidth failing. In horn aperture, the printed tapered ladder transitions have been presented for enhancing matching impedance and radiation. The enhanced gain and better matching impedance obtained in horn antenna based planar Ka band have been resulted in this study.

With wide operating bandwidth a greater planar array has been designed and presented in [60], by using printed circuit board of low cost, a SIW antenna array of 4 × 8 developed with W band. Using wide operation bandwidth, the lesser cross polarization, radiation pattern stability and efficiency in high radiation have been attained. For wireless system of millimetre wave this proposed work considered as good applicant. Table 2.2 summarizes the recent SIW antennas works.

Table 2.2: Related works on conventional SIW antennas

Ref.	Technique	Description	Disadvantage
[36]	SIW long slot array antenna parallel plate	From single radiating aperture dual circular polarization with reduced beams of side lobe level SLL generated by SIW long slot array antenna parallel plate.	Size
[38]	SIW antenna arrays based circularly polarized Left-hand and right-hand LHCP and RHCP.	The feeding networks composed with RHCP array of antenna and 8-element LHCP to obtain the better performance of circularly polarized.	Complex structure.
[41]	LWA Leaky Wave Antenna from SIW based possessing greater radiations.	To continuously scanning in forward and backward directions the LWA from SIW based possessing greater radiations have been proposed.	Low gain
[48]	A cavity backed slot arrays of antenna of SIW	For 60 GHz applications a cavity backed slot arrays of antenna of SIW has proposed and evaluated in terms of circular polarization, increased gain and broadBand performance	Size
[49]	Novel SIW horn antenna design	Between free space and substrate the horn aperture mismatch leads to narrow bandwidth operation issues in SIW horn antenna of conventional method. The distribution of dielectric constants in corresponding	Size

Table 2.2 (continued)

Ref.	Technique	Description	Disadvantage
		direction with various diameters resulted in enhanced radiation operation.	
[52]	Corrugated structure of SIW	Using corrugated structure of SIW the great amount of gain has been achieved by antenna possessing dual band low profile aperture.	Complex structure
[54]	Antenna based SIW and half mode SIW methods. Semicircle slotted antenna SSA	The half mode SIW with semicircle slot antenna SSA of cavity backed mainly proposed for size of antenna reduction and bandwidth improvement.	Complex structure
[55]	SIW horn antenna on H-plane phase distribution	The gap SIW, closed form of expression deduction and modified SIW introduced by communication and concentrated on coupling and fringing in gap fields. This kind of structure corrected the SIW horn antenna on H-plane phase distribution.	Size

2.6 Related Works on SIW Based Miniaturized Metamaterial Antenna

The cavity structure inspired by Metamaterial loading. At negative mode the resonator operated at frequency of lower resonance compared with existing dominant mode [61]. To study the cavity operating mechanism the field distributions have been evaluated. The samples of liquid characterized and the permittivity sensor used by cavity. For the conventional SIW structure, the forward and backward wave propagations with dual pass bands at cut-off frequency supported by SIW Meta material band pass filters [62, 63]. Various transmission in frequency responses identified through size of fractal slot variation imprinted over SIW structure. The scattering parameters extracted the Meta material parameters. To design the miniaturized filters the fractal slot electrical length greater than conventional length. Using sub wavelength resonators three filters have been designed by SIW Meta material unit cell of H-shaped 3rd iteration. The external quality factors and coupling co-efficient extracted by design of a filter to achieve filters. The improved rejection in out of band done by SIW or fractal slot reconfiguration. Good agreement seen in scattering parameters. Low cost, selectivity high, insertion loss smaller size and relaxed fabrication attained by this proposed filters.

Based on composite transmission line of left/right handed the antenna CRLH composed of small dual band design process has been proposed [64, 65]. As primary antenna the traditional microstrip patch has been assumed. The compressed size of 20 × 20 antenna at 4.4 GHz and 6.1 GHz operates efficiently. With lesser level of cross-polarization the omnidirectional radiation seen. On antenna of multiband performance and miniaturization, the fractal structure effect with transmission line CRLH ideas have been reviewed. The simulated results shows accuracy and evaluate that for application of wireless communication the suitable applicant was antenna.

The SIW of 0^{th} order Metamaterial has been proposed in this study [66]. The compact size antenna focused with CRLH cell. Related to conventional antenna of micro strip patch the proposed antenna possess reduction in size of 50 percent at 14.4 × 8 mm size of overall radiator the antenna vibrates at 6.1 GHz. Using full wave simulations the 0^{th} order antenna mode has been evaluated. The radiations pattern and matching properties of antenna have been engaged by simulation results. This research explored Antipodal Vivaldi antenna (AVA) of enhanced miniaturized gain composed with triangular metal detectors and steady corrugated edges have been examined [67, 68]. Greater frequencies has been enhanced by AVA radiation aperture of dual surfaces composed with triangular metal detectors. For 5G application of communication devices the AVA array proposed appropriate for incorporation resulted in radiation patterns symmetrically, compressed structure and better directivity.

The complementary split ring resonators (CSRR) and Sierpinski fractal based electrically small antenna SIW have been proposed [69, 70]. The electrically small SIW obtained by fractals and quarter mode SIW. For decreasing the size further the capacitance and inductance presented by ground plane CSRR. The CSRR rotation tuned antenna first mode at resonant frequency. The simulation results shows that during CSRR rotation the resonant frequency differs. The CSRR physical size miniaturize by novel compressed meta-material cells depends on stepped impedance resonator SIR which substituted the conventional CSRR [71]. Three SIW filters used for performance evaluation of proposed system SIR CSRR in terms of decrease in size and designed configurations seen. Below cut-off frequency the forward wave pass band has been disseminated. The arbitrary ratio miniaturization has been obtained by proposed method. The miniaturization verified by designed filters and resulted in good agreement.

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