Design and Testing of a Dual-Band SIW Antenna loaded with CRLH-TL unit cell for WiMAX Application

A DISSERTATION

submitted in partial fulfillment of the requirement

for the award of the degree of

MASTER OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

(With Specialization in RF and Microwave Engineering)

submitted by

RAHUL PACHPOLE

(17533016)

Department of Electronics and Computer Engineering

Indian Institute of Technology Roorkee

Roorkee – 247667, India

June 2019

CANDIDATE'S DECLARATION

I hereby declare that the dissertation topic **"Design and Testing of a Dual-Band SIW Antenna loaded with CRLH-TL unit cell for WiMAX Application"**, have done by me under the guidance of **Dr. A. Patnaik**, in the partial fulfillment of the requirement for the award of the degree of Master of Technology in RF and Microwave Engineering, Electronics and Communication Engineering Department, Indian Institute of Technology, Roorkee is my original work. The results submitted in this dissertation report have not been submitted for the award of any other Degree or Diploma.

Date: June, 2019

Place: IIT Roorkee

RAHUL PACHPOLE

Enrollment No. 17533016

RF and Microwave Engineering

Department of ECE, IIT Roorkee

CERTIFICATE

This is to certify that the statement made by the candidate is correct to the best of my knowledge and belief. This is to certify that this dissertation topic**, "Design and Testing of a Dual-Band SIW Antenna loaded with CRLH-TL unit cell for WiMAX Application"** is an original record of candidate's own work accomplished by him under my guidance and supervision. He has not submitted it for the award of any other degree.

Date: June, 2019

Place: IIT Roorkee

Dr. A. PATNAIK

Associate Professor

Department of ECE, IIT Roorkee

ACKNOWLEDGEMENT

At this moment, I acknowledge that I am eternally grateful to the God Almighty for being the beacon of hope during my project.

I am ineffable in expressing my deep sense of gratitude to my project guide Dr. A. Patnaik, Associate Professor, Electronics and Communications Engineering, whose vision is the guiding light of this work. His empathetic approach, wise counsel and an abundant supply of fresh hope have gone a long way in shaping this project.

I am also thankful to Mr. Anil Kumar Nayak and other staff and administration of ECE department for providing me with adequate support and facilities.

I thankfully acknowledge everyone whose papers and articles I have read and everyone with whom I have had technical discussions.

I am also forever beholden to my parents and friends for their unfathomable love, boundless affection, personal sacrifices, incessant inspiration and constant prayers, which supported me to stay at rough tracks.

Rahul Pachpole

CONTENTS

ABSTRACT

In this report, a CRLH-TL Unit Cell Loaded Dual-Band SIW Antenna for WiMAX applications is proposed. The antenna has a radiating patch composed of composite right/left hand transmission line (CRLH-TL) unit cells which are excited by two $\lambda_g/4$ resonators with a shorted pin, for impedance matching, in between to supress the harmonics. The proposed antenna resonates at dual band having frequencies at 3.65 and 4.2 GHz. The measured reflection coefficient is less than -10 dB. The radiation efficiency over the band are 71 and 60 % and gain obtained are 2.7 and 5.8 dBi, respectively. Though there is wide application of CRLH, which have been discussed in the coming chapters, yet they have drawbacks regarding gain and efficiency. The simulations are done by one full wave packages i.e. ANSYS HFSS that associated with finite element method (FEM). The simulated and measured results have been found good agreements with each other.

Second part of this report is an extended portion of the work done in above part. Basically, Substrate Integrated Waveguide (SIW) technology has been used in the same design of proposed antenna with minor changes in dimensions with improved performance in terms of peak realized gain, radiation efficiency, FTBR, reduced cross-polarization level for WiMAX-applications has been proposed in this proposed work. Same CRLH patch with its mirror image on the opposite side has been used in differential and common mode. The measured results show that the SIW based improvised antenna have reflection coefficient less than -10 dB. The simulated maximum gains are 3.2 and 7.1 dBi, respectively. The antenna has achieved a simulated radiation efficiency of 55 and 87 %at two different frequencies. The simulation and measured results are matched and are much higher compared to values reported in the literature for CRLH based antennas.

List of figures

List of tables

As a starting point in the integration of microwave components and circuits, microstrip planar antennas are widely used in the design of passive circuits due to their compact size, integrability and also the capability of mass production [1]. As the dimensions of these wireless devices are getting a smaller low profile and lightweight antennas are playing a more critical role in the field of communication. Single band antennas may be used for day to day usable devices, but modern communication requires more advanced antennas that can operate on multiple bands of frequencies [2] – [3] that can reduce the constraints for applications that require stringent design specifications. Moreover, such high-density merged antennas, manufactured with a cost-effective fabrication technique, should be capable of offering widespread mm-wave applications. For such characteristics, antennas have been designed using composite right/left-handed transmission line (CRLH-TL) [4] – [6].

In the last decade, there has been keen interest in the progress of microwave-based components and circuits based on CRLH-TL [7]. The main advantage of CRLH-TL over normal transmission line is that, it has an additional series interdigital capacitor (IDC) (for series resonance) and shunt shorted inductor (SSI) (for shunt resonance) in periodic repetition, realized by microstrip line and coplanar waveguide [8], which provides lower loss and wider bandwidth [9]. Both the series and shunt resonances decide the transition frequency, which separates the right-hand region and left-hand region [4], [8]. Since these are easy to fabricate by using standard printed circuit board (PCB) technology, hence simplified design of many multi frequency antennas [10] – [13], broadband antennas [14] and zeroth order resonant antennas [15]- [18] have been studied earlier. Regardless of providing multiband frequency operation, low losses, and broad bandwidth still it fails to overcome some problems.

One of the major drawbacks of the antenna is being low radiation efficiency and low gain when the antenna operates in zeroth order resonance mode. There are two reasons behind above drawbacks first, small radiator size and second, inherent loss by the structure [17]. In order to overcome the above constraints substrate integrated waveguides (SIW) technology have been a promising candidate to implement along with CRLH-TL.

The SIWs are integrated waveguide-like structures, which is made-up by using two rows of metallic vias or cylinders rooted in a dielectric substrate that electrically connect two parallel metal plates. The distance between the two rows of periodic boundaries determines the cut off frequency with the contemplation of dielectric-filling effects. SIW structures show characteristics like traditional rectangular waveguides, including the field design and scattering characteristics. Moreover, it retains most of the advantages of conventional metallic waveguides, that is high quality-factor and high power-handling capability. But the most noteworthy benefit of SIW technology is the possibility to integrate all the components on the same substrate, including passive and active components. The productive amendment of mm-wave wireless systems requires a platform for implementing all these components with high performance, low-cost and unfailing technology and SIW proves it to be worthy.

First introduced as post-wall waveguide [18], it has been then combined with CRLH-TL for traveling wave antennas [20], [21], minimizing the size of antenna on SIW resonator with CRLH-TL [7], a study of leaky wave patch antenna using SIW type CRLH-TL [22], etc. Due to this, it gives high radiation efficiency and more gain than those of CRLH zeroth-order resonant antennas [18]. We will further discuss the implications of SIW in coming chapters.

1.1 Fundamentals of CRLH-TL

A right-handed TL can be characterized by a ladder network designed by the replication of a unit cell with a series inductor having per unit length inductance L_R and a shunt capacitor with a per unit length capacitance, C_R. The dual of the right-handed TL is designed by the duplication of the unit cell with a series capacitor with per unit length capacitance of C_L and a shunt inductor with a per unit length inductance of L_L.

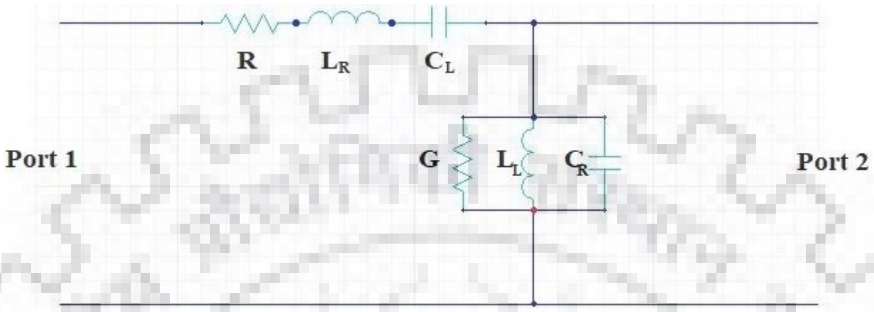


Fig 1.1 The basic composite right-hand/left-hand unit cell

As mentioned in [4], pure left-handed TL cannot exist in authenticity due to the parasitic lead inductances and stray capacitances. The amalgamation of a right-handed TL and a left-handed TL leads to the formation of a CRLH TL structure. Its unit cell is composed of the constitutive lumped parameters C_L, L_R, C_R and L_L as shown in Fig1.1. The physical length of the unit cell should be much less than the operating wavelength λ_g. The reiteration of the CRLH unit cell constitutes a CRLH transmission line.

A CRLH transmission line unit cell, as shown in Fig 1.1, is categorized by following emittances,

$$Z = R + j\left(\omega L_R - \frac{1}{\omega C_L}\right)\ \Omega \tag{1.1}$$

$$Y = G + j\left(\omega C_R - \frac{1}{\omega L_L}\right)\ \Omega^{-1} \tag{1.2}$$

Where ω represents the resonance frequency for the unit cell for both right-hand mode (ω_R) and left-hand mode (ω_L), following are the expressions for them,

$$\omega_R = 1/\sqrt{L_R C_R} \text{ rad/s} \tag{1.3}$$

$$\omega_L = 1/\sqrt{L_L C_L} \text{ rad/s} \tag{1.4}$$

1.2 Concept of SIW

In microwave engineering, microstrip is been widely used in the design of all kinds of passive circuits due to its compact size, ease of integration, and eagerness for bulk production. The fundamental concept is to produce a nonplanar structure with a dielectric substrate and make it in planar form, which is completely compatible with other planar structures, this can be achieved by creating artificial waveguide structure. But with frequency increasing, as an open structure, a microstrip circuit shows undesirable radiation. Such radiation not only presents additional losses in the circuit, but it also harms the nearby components. For example, if the feeding network of an antenna array is realized using a microstrip-type of the circuit, the undesired radiation from the feeding network may seriously affect the radiation performance of the antenna. On the other hand, the previous rectangular waveguide circuit has the least radiation loss because of the closed structure due to which all the electromagnetic energy gets bounded within the waveguide, but it is bulky as compared to its microstrip matching part. With the increase in frequency, the dimensions of the waveguide decreases, but at the cost of integrating many waveguide circuits, which are still not an easy task to perform.

In the last decade, a new type of technology line called substrate integrated waveguide (SIW) has been studied extensively. It is a low-cost recognition of the old waveguide circuits for microwave and millimetre-wave applications. Quite naturally, SIW inherits certain advantages of conventional waveguide such as high-quality factor and high-power handling capability with self-consistent electrical and mechanical shielding. The most attractive feature of this SIW technology is that a full-scale integration can be expected, involving passive and active circuits as well as antennas on the same substrate by embedding into a printed circuit board (PCB). The wave propagation characteristics and the design equations for SIW have been studied in [23]- [25], still full a full wave analysis is required to study SIW circuits. For analysis, the finite element method and finite-difference time-domain method can be used, but they require the geometry discretization of the whole circuit which may require large memory and is time-consuming. Method of moments (MOM) can be used to discretizes the geometry discontinuities [26]. But all the methods above assume circumference current to be uniform which is invalid since current density inside the circuit is much stronger than that of the outside. Thus, the discretization of the metal posts is unavoidable and that increases the system matrix size.

In order to overcome discretization problem, many alternatives have been presented in the literature like cylindrical Eigen function was applied [27]- [30] with circular cylindrical elements, another method was efficient hybrid method [31], [32] to study a 2D substrate integrated waveguide circuit. There is no geometry discretization for the cylinders, and thus boundary conditions on the complete surface of a cylinder are imposed inherently.

1.3 Mathematical analysis of SIW

The analysis method presented in this section focuses on SIW circuits, and it follows a classical procedure of solving an electromagnetic equation. First, the electromagnetic field expressions in the substrate are obtained [19], then the boundary conditions are imposed at the ports and the boundary of each metallic post. After that, a linear system that consists of a set of linear equations are derived from the boundary conditions. Finally, the circuit characteristics, such as the S parameters, can be obtained by solving the linear system. Fig 1.2 illustrates SIW and its equivalent rectangular waveguide (RW) based on which equations has been derived [19].

$$a = l\bar{a} \tag{1.5}$$

$$\bar{a} = \xi_1 + \frac{\xi_2}{\frac{2p}{d} + \frac{\xi_1 + \xi_2 + \xi_3}{\xi_3 - \xi_1}} \tag{1.6}$$

$$\xi_1 = 1.0198 + \frac{0.3465}{\frac{a}{p} - 1.0684} \tag{1.7}$$

$$\xi_2 = -0.1183 - \frac{1.2729}{\frac{a}{p} - 1.2010} \tag{1.8}$$

$$\xi_3 = 1.0082 - \frac{0.9163}{\frac{a}{p} + 0.2152} \tag{1.9}$$

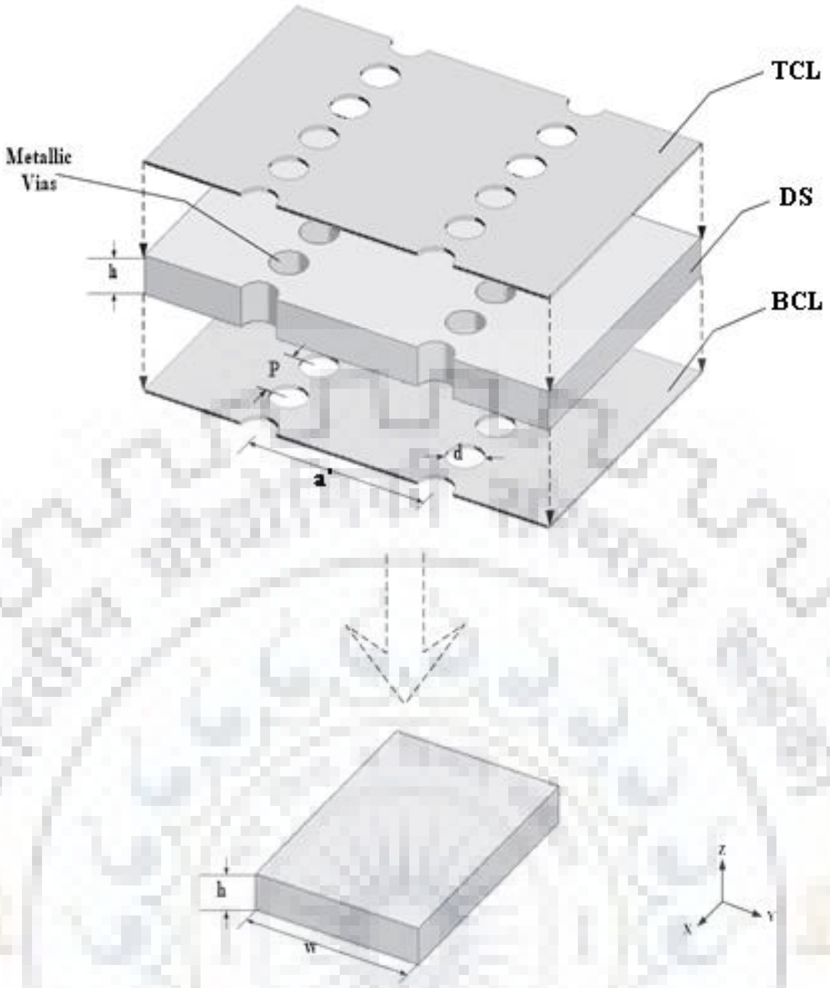


Fig. 1.2 SIW and equivalent of RW [19]

where, TCL is top copper layer, DS is dielectric substrate and BCL is bottom copper layer. Based on the parameters of the above equation a, h, p, d, f can be calculated and used accordingly. In Fig 1.3, the classical RW schematic is presented.

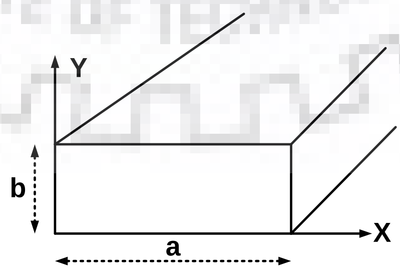


Fig 1.3 Schematic of a classical RW

Based on RW dominant TE_{10}, the E_y and H_z components are found to be as follows.

$$E_y = \frac{j\omega\mu}{\pi a} A\cos(\pi x/a)\exp(-j\beta z) \tag{1.10}$$

$$H_z = A\sin(\pi x/a)\exp(-j\beta z) \tag{1.11}$$

$$\frac{j\omega\mu W}{4}\ln(\frac{W}{4R}) = \frac{jw\mu_o}{(\pi/a)}\ln(W/4R) \tag{1.12}$$

Then longitudinal impedance (parallel to the wall) of a waveguide in yz- plane positioned along the x axis (in range x < -a/2 and x > a/2) is given as

$$\eta_s = \frac{E_y}{H_z} = \frac{jw\mu_o}{(\pi/a)}\cot(\pi x/a) \tag{1.13}$$

Let the width of the SIW be a' , and the width of the equivalent RW be a. The surface impedance of the SIW wall is dependent on the incident angle theta of the plane wave gets bounce inside the waveguide similarly the surface impedance of the imaginary wall in the RW in (1.13) is also dependent on the incident angle theta of the plane wave bouncing inside the waveguide but in a different manner. We may now equate the surface reactance from (1.13) with that of the wall of the cylinders in (1.12) then the following equation is obtained.

$$\frac{j\omega\mu W}{4}\ln(\frac{W}{4R}) = \frac{jw\mu_o}{(\pi/a)}\cot(\pi a'/2a) \tag{1.14}$$

From the above equation, we can calculate equivalent width a' SIW as follows

$$a' = \frac{2a}{\pi}\cot^{-1}(\frac{\pi W}{4a}\ln\frac{W}{4R}) \tag{1.15}$$

where a' is the width of the SIW, W is the distance between two adjacent cylinders, R is the radius of the cylinder and the width of the equivalent RW in Equation (1.14) implies that when cylinder radius R is less than one-fourth of the cylinder separation W, the width a of the equivalent RW is bigger than the width a' of the SIW and vice versa. The equivalence means that the propagation constant γ of the SIW (of width a') is nearly the same as that of the RW (of width a) to which a standard formula is available in [33]. One empirical equation to calculate a_{effe} is given by

$$a_{effe} = a - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{a} \tag{1.16}$$

where $d / p < 1/3$ and $d / a < 1/5$. SIW can be demonstrated by rectangular waveguide with equivalent width and maintains radiation loss at a negligible level when its geometrical parameters meet the following conditions: -

- The metalized hole diameter should be $d < \lambda_g/5$
- The spacing between hole should be $p < 2d$
- The physical width of SIW should be $a' = a_d + \frac{d^2}{0.95p}$

With the continuous progression in the technology, the value for footprint on a circuit board is increasing gradually. The importance of the on-board space is driving the antenna engineers and researchers to focus on the compact antenna designs. In [34]- [36] antennas designed were more compact than earlier half wavelength antennas because of infinite wavelength operation. In last decade, the CRLH-TL has been permitted to expand the shape from 1-D to 2-D [37] or 3-D transmission line [38], which have led to several applications such as tuneable leaky wave antenna with fundamental backward wave [39] and broadband line couplers with tight coupling [40]. Since CRLH-TL supports multiband operation antennas, it's unit cells have taken over conventional monopole, and dipole antennas for the same and have been reported in [41]- [46]. In [41]- [43], metallic vias were used for the realization of shunt inductance of the CRLH unit cell. These cells were demonstrated for patch antenna [47]- [49], slot antenna [50], and dipole antenna [51] so that they can operate in zeroth order mode.

Though antennas studied above based on CRLH-TL provided alternate ways for avoiding many problems regarding antenna size and frequency of operation, but their operation on zeroth order mode often suffer from two major problems which are low radiation efficiency and low gain. According to [17], the reason behind this drawback is two factors which are small radiator size and the inherent loss caused by the artificially engineered structures. In [52] CRLH unit cells were used to achieve multiband operation with symmetrical loading for dual-band operation and asymmetrical loading for triple band operation, but gain they achieved were very less at one case even negative value of -0.99dB. In [53] via free unit cells were designed for simplifying the fabrication process, thereby decreasing the overall price of the antenna but at the cost of its efficiency.

In order to confront such challenges of gain and efficiency, SIW comes to play a major role in the designing part of the antenna. Some of the designs of SIW antennas with interdigital capacitor etched on the top surface has been reported in [54]- [56]. In [54] it's been found that when SIW gets combined with an interdigital capacitor (IDC) on antenna surface, it shows a CRLH characteristic which demonstrates the reduced size, high gain and high radiation efficiency. A slot antenna in [57], with the same concept as used in [54], has been implemented and got improved efficiency of 80%. In [47] a SIW type CRLH-TL with IDC instead of metal patches were also verified in C band application. In [58], size reduction techniques using SIW have been implemented along with CRLH-TL and thereby achieving high efficiency.

After studying all the above papers, it is clear that there are still some issues like gain and efficiency which need to be worked on so in this report, an effort has been made first to improve performance parameters of microstrip patch antenna by using CRLH transmission line for multiband frequency operation and size reduction. In the second part using SIW technique to improve the lagging parameters present in the CRLH-TL in order to design more efficient and compact antenna.

3.1 Antenna Design

The design and dimensions of the proposed CRLH-TL based antenna are shown in Fig 3.1, 3.2, and 3.3. The antenna is composed of the rectangular patch along with two $\lambda_g/4$ resonators connected in the feeding line section, as shown in Fig 3.1. A shorting pin of the radius r_p has been inserted at the end of the feed, which has been located at the centre of two $\lambda_g/4$ resonators. The dimension of the patch is $L_{xx} \times W_{yy}$, and those of resonator is $L_{gs} \times w_g$. The radiating patch is excited by those resonators in the feeding line placed at a distance of g_s from patch itself. The antenna has been designed on a single layer Roger RO4232 (tm) substrate with a dielectric constant (ε_r) of 3.2, loss tangent ($\tan\delta$) having value 0.0018 and thickness (h) of 1.524 mm as shown in Fig 3.2.

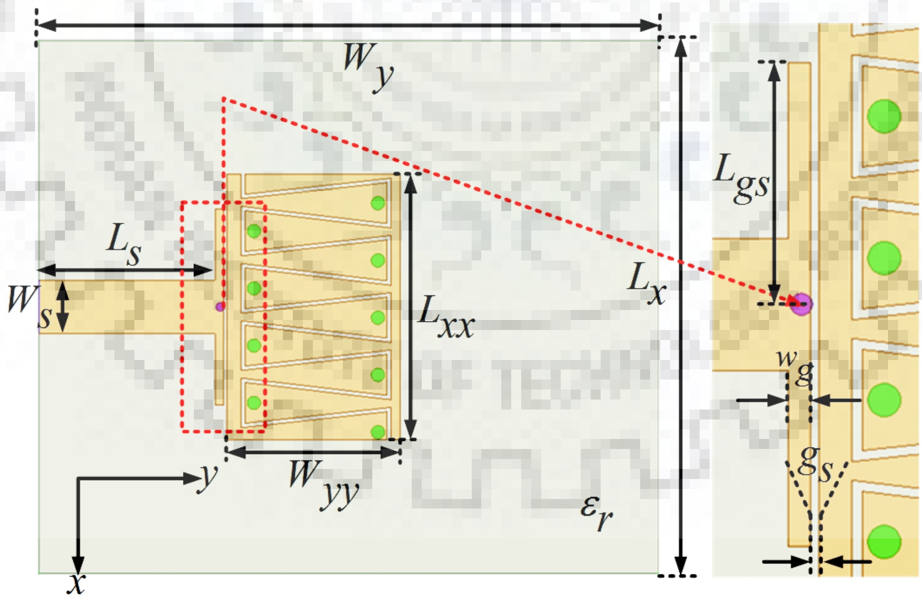


Fig 3.1 Top view of antenna

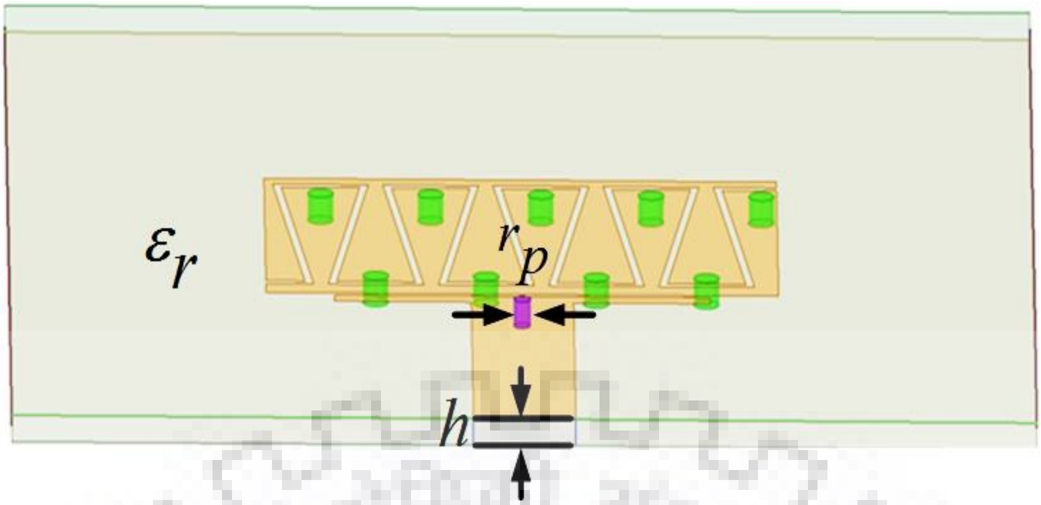


Fig 3.2 Schematic View

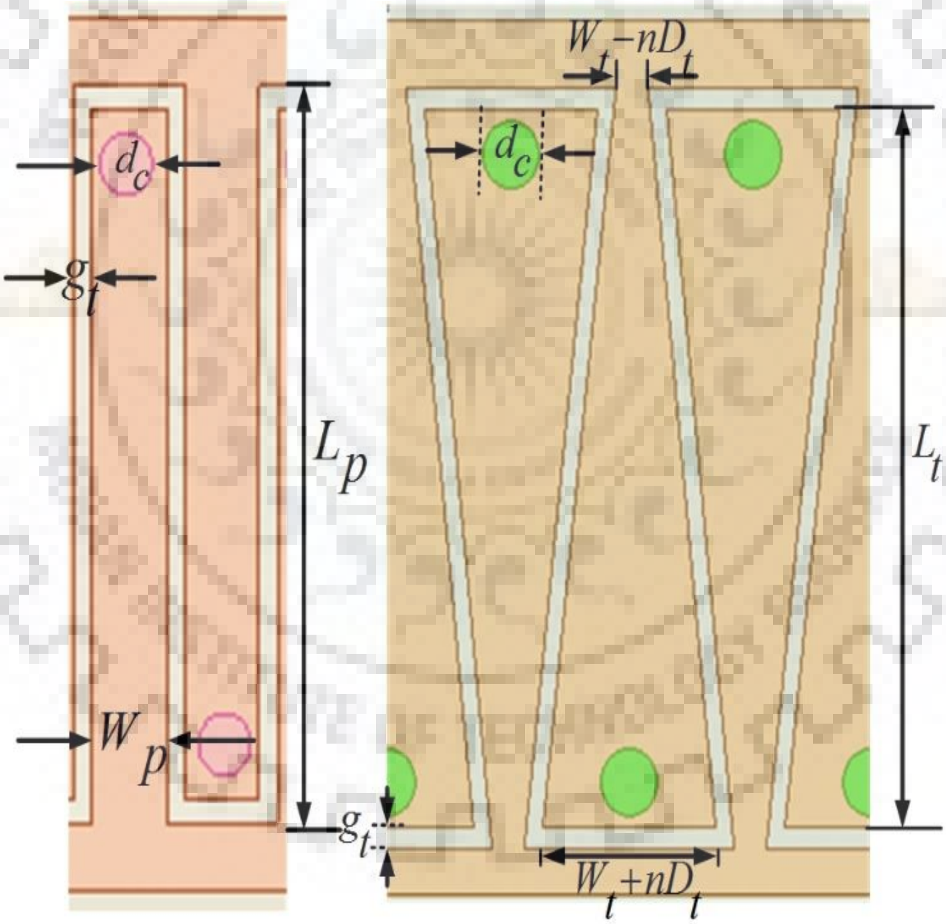


Fig 3.3 Representation of a unit cell

The antenna consists of a basic unit cell, which is an inter-digital capacitor (IDC) CRLH-TL unit cell [59]. As shown in Fig 3.3, the fingers of the IDC and the gap between them contribute to series inductance and capacitance per unit length, which is varied according to the requirement of operating frequency. The vias of the unit cell along with the thickness of substrate control the parallel inductance and capacitance [60]. All of this component can be fabricated easily on the top layer of a substrate having dimensions ($L_x \times W_y$). The dimensions of other parameters are presented in Table 2.1. All the simulations are carried out using the electromagnetic software ANSYS' HFSS version 17.1.

TABLE 2.1 DIFFERENT DESIGN DIMENSIONS OF THE PROPOSED ANTENNA

Parameters	**Size (mm)**	**Parameters**	**Size (mm)**
L_X	60	g_s	0.4
W_y	70	d_c	1.5
L_{XX}	30	r_p	1
W_{yy}	19.5	W_t	0.85
W_S	6	h	1.52
L_S	20	P	4.6
L_{gs}	12.33	g_t	0.5
W_{gs}	1	L_t	16.5

The $\lambda_g/4$ resonators are employed here so that they can act as coplanar distributed resonators when placed at a certain gap (g_s) from the main patch, as shown in Fig 3.1. The gap, along with the shorting pin plays an important role in achieving better impedance matching performance and reducing fake radiation due to harmonic resonance from the patch radiator. The reason behind this suppression can be in explained in two ways. First, the patch antenna is fed capacitive through these resonators, which mean power can be supplied at different frequencies only when both patch and resonators are resonating. Secondly, all even order modes cannot be excited with $\lambda_g/4$ resonators because of shorting pin shared between them at the centre. The dual band achieved is due to variation in lumped parameters at a particular resonant frequency.

The circuit diagram of the IDC based CRLH-TL unit cell is shown in Fig 3.4 below.

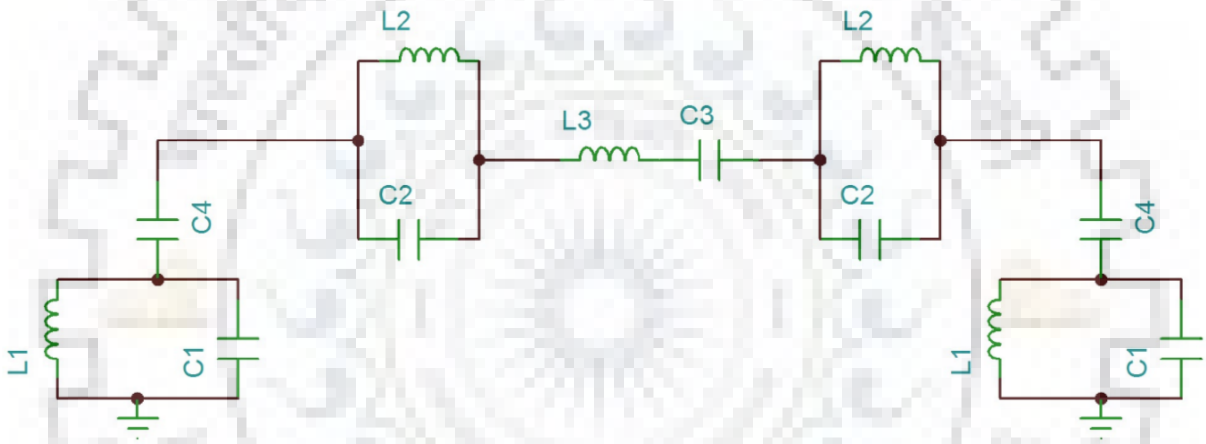


Fig 3.4 CRLH-TL unit cell

The above circuit diagram is a representation of improvised unit cell shown in Fig 3.2; it consists of a π network (L_1, C_1 and L_3, C_3) of a basic CRLH unit cell and additional two parallel LC tank circuits. This LC tank circuit consists of L_2 and C_2, which represents the rectangular slots present in the unit cell. C_4 is the capacitive coupling between the ground shortened stubs and IDC structure and can be varied by altering its diameter (d_c). In order to estimate the values of inductors and capacitors, the circuit was simulated in Advance Design System (ADS) software by calculating their S_{11}, which is shown in the next section. By tuning the lumped element values, to get the desired result in the S-parameters, their values have been found and shown in Table 2.2. The simulated S11 plot has been shown in Fig 3.5 with little frequency shift.

Table 2.2 EXTRACTED LUMPED PARAMETERS FOR CRLH UNIT CELL

L1(nH)	C1(pF)	L2(nH)	C2(pF)	L3(nH)	C3(pF)	C4(pF)
1.0	0.4	0.158	5.0	1.45	5.6	0.9

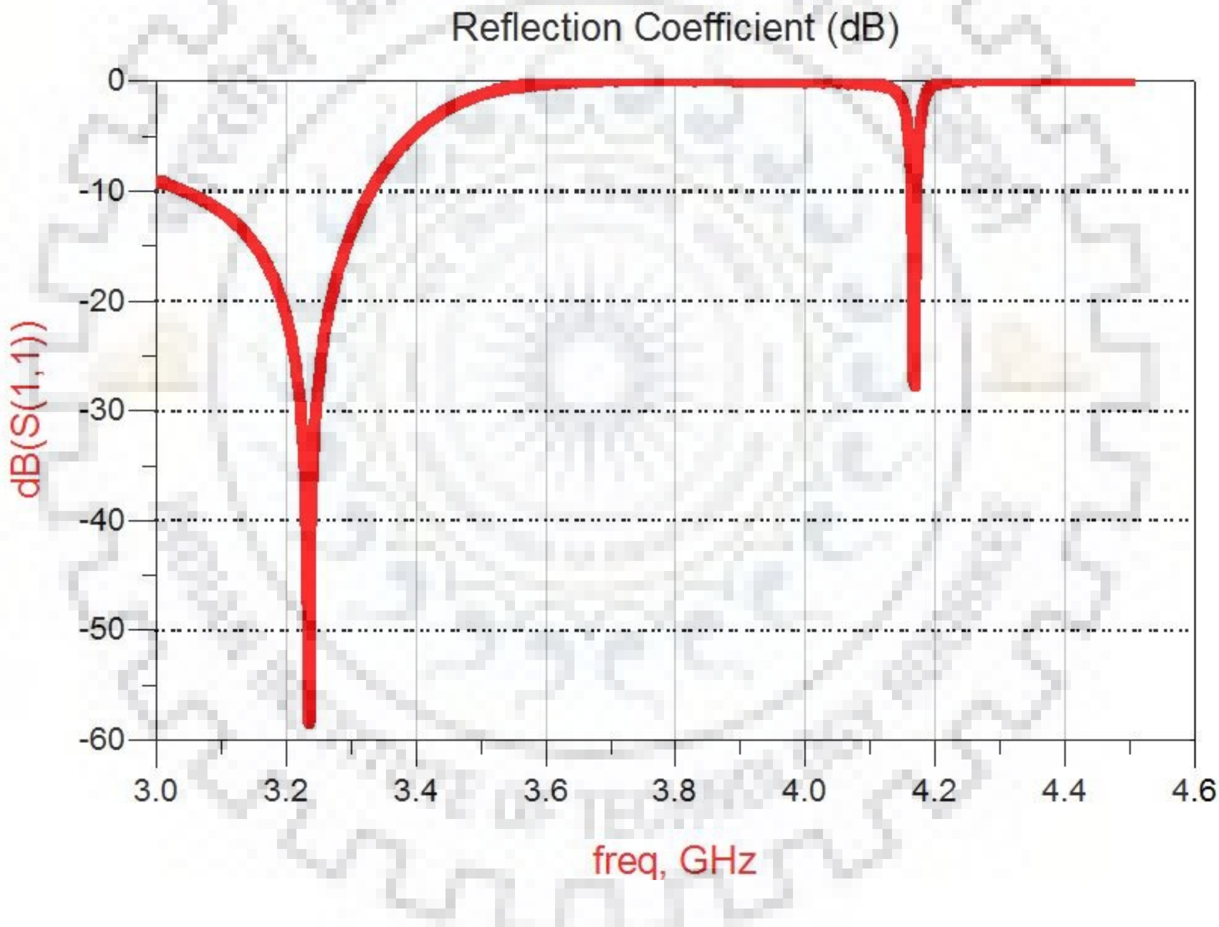
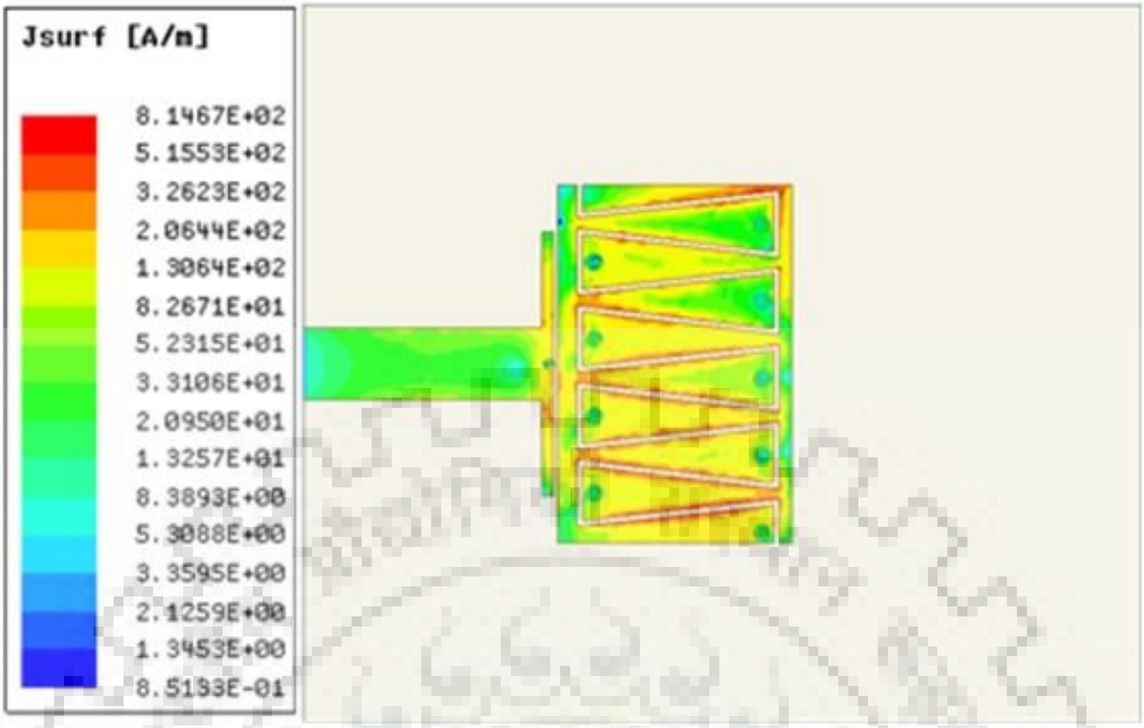
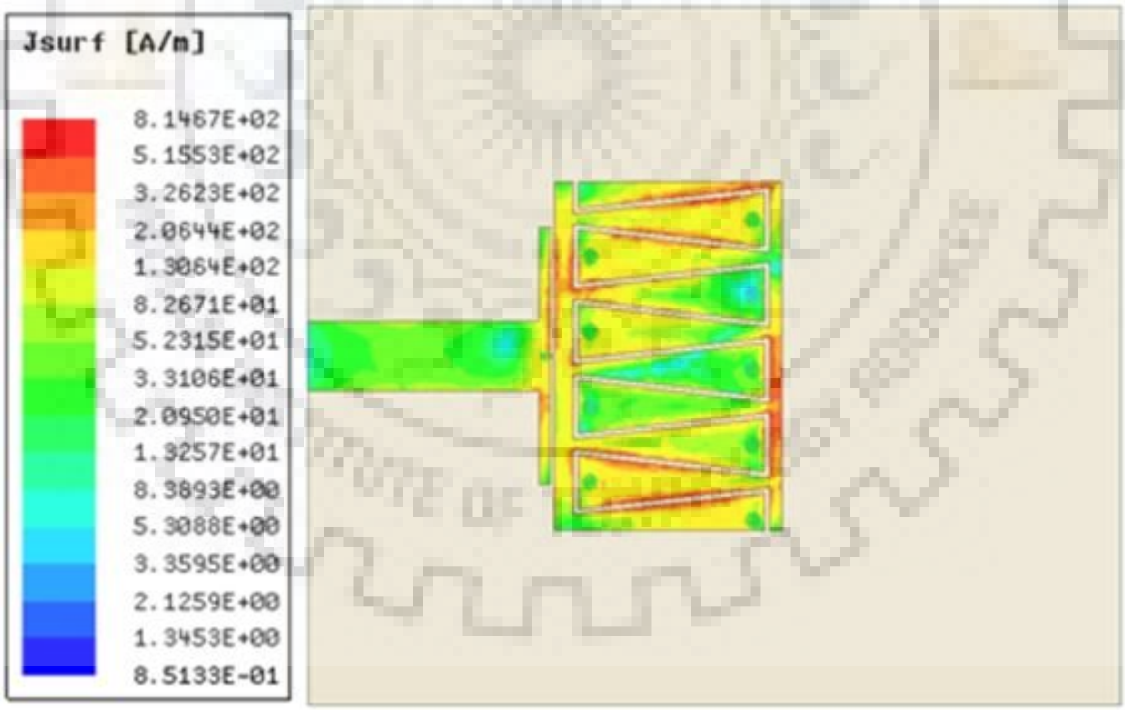


Fig 3.5 Simulated reflection coefficient for a unit cell using ADS

The proposed antenna provides dual-band operation at 3.4 GHz and 4.09 GHz. Resonant frequencies of the perturbed modes are tuned by varying diameter (d_c) of the vias of the cell. The surface current distribution of the antenna at their resonant frequencies (3.4 and 4.09 GHz) are shown in Fig 3.6 (a) & (b).



(a)



(b)

Fig 3.6 Surface current distribution at (a) 3.4GHz & (b) 4.09 GHz

3.2 Parametric Analysis

The variation in reflection coefficient, S_{11}, due to the parametric analysis of some dimensions of the antenna are shown in Fig 3.7 and 3.8. From the Fig 3.7, it can be inferred that by variation in the diameter of vias leads to variation in return loss characteristics, as the diameter changes the capacitance value of the resonant circuit changes which leads to shifting in resonance frequency from higher to lower band and vice versa. Also degrading or amplifying their values lead to a certain decrement in the $|S_{11}|$ value, which can be accounted with respect to impedance mismatching caused at a particular frequency. At d_c = 1.5 mm, we fixed the diameter of via for the lowest value of reflection coefficient. Another parametric study has been done with respect to the length of the resonator and its effect on return loss characteristics has been shown in Fig 3.7. For L_{gs} = 12.33 mm, which is exactly equivalent to $\lambda_g/4$, reflection coefficient goes below -10 dB for resonant frequencies, as shown in Fig 3.8.

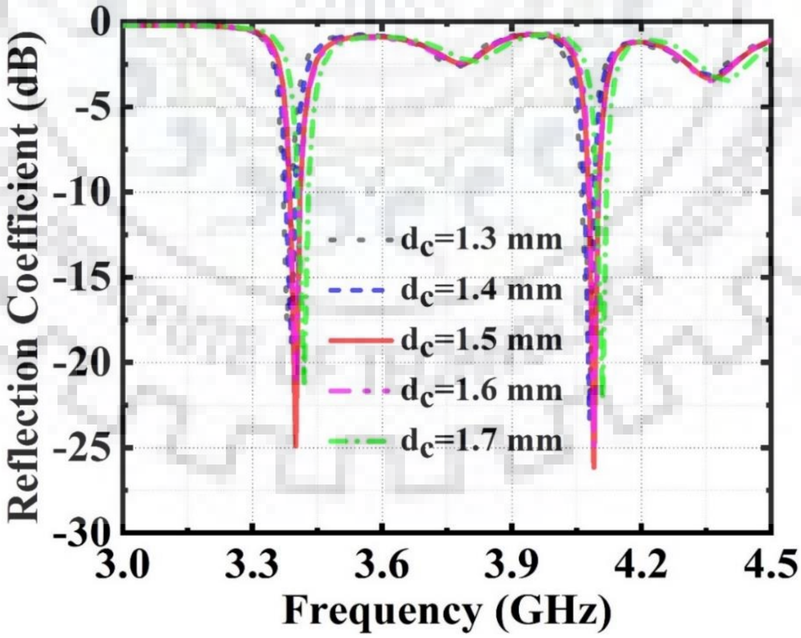


Fig 3.7 Reflection coefficient effects on d_c

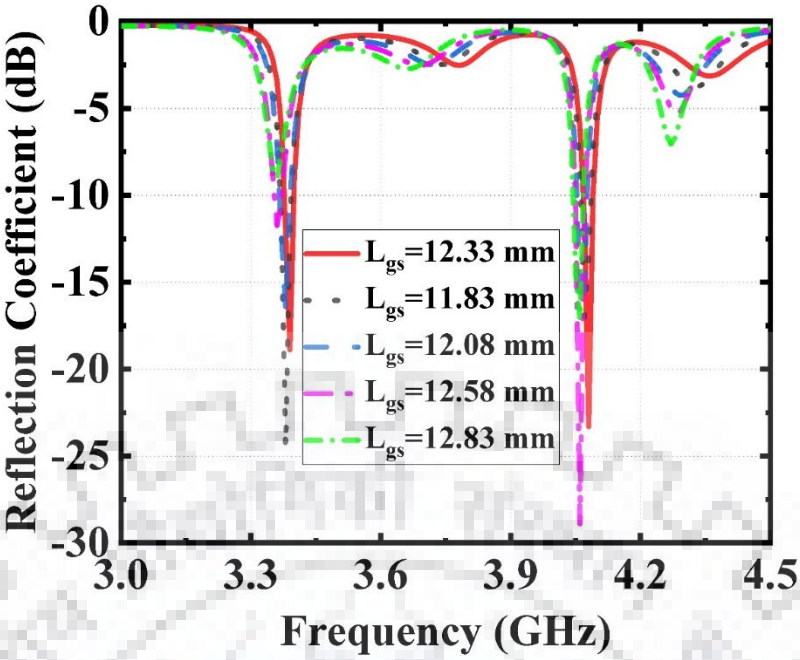


Fig 3.8 Reflection coefficient effects on L_{gs}

3.3 Experimental Results and Discussion

The proposed CRLH-TL antenna is designed and simulated using ANSYS HFSS ver.17.1 electromagnetic simulator to operate at a dual frequency that is at 3.4 GHz and 4.09 GHz. The fabrication prototype of the proposed antenna is shown in Fig 3.9. The reflection coefficient was measured using the Vector Network Analyzer (VNA). The measured and simulated reflection coefficient for the designed antenna is shown in Fig 3.11. It shows that the measured results are in good agreement with the simulated one. There is slight shift of the resonant frequency due to manually filling of the copper paste. The measured reflection coefficient is less than -10 dB from 3.59 GHz to 3.72 GHz and 4.13 GHz to 4.27 GHz. The fractional impedance bandwidths are 3.52 % and 3.33% respectively for the specified range of frequency above.

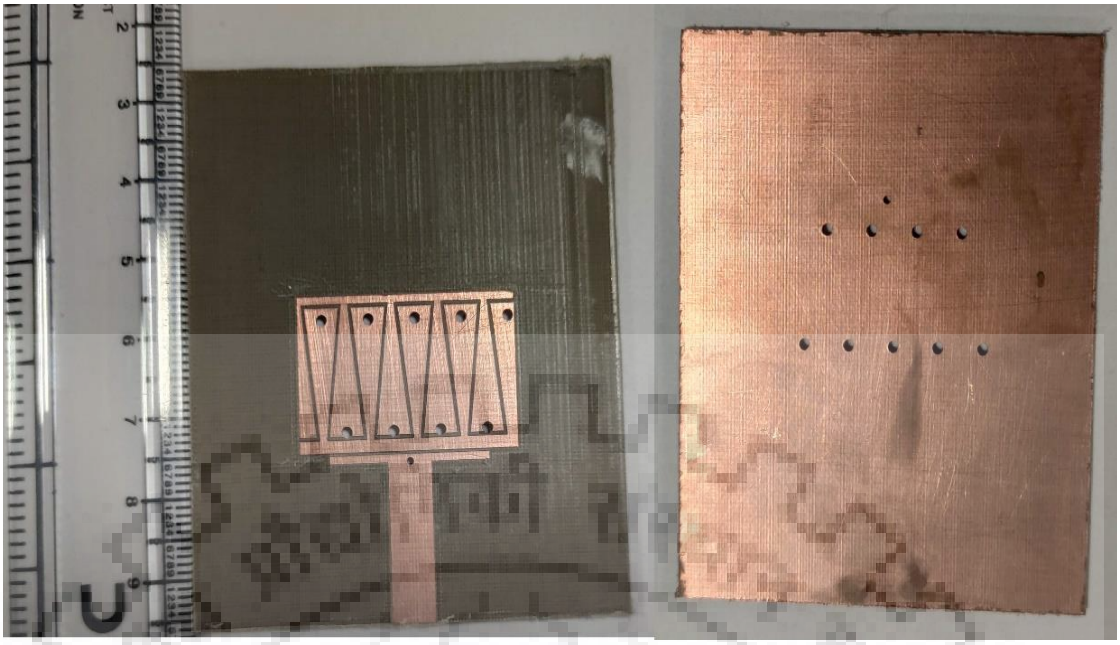


Fig 3.9 Fabricated prototype of the antenna

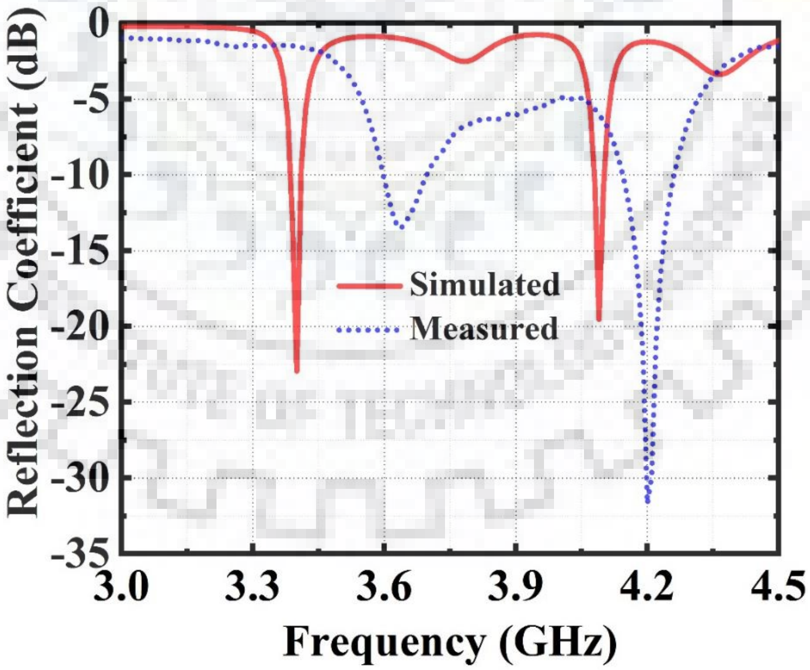


Fig 3.10 Simulated and measured reflection coefficient

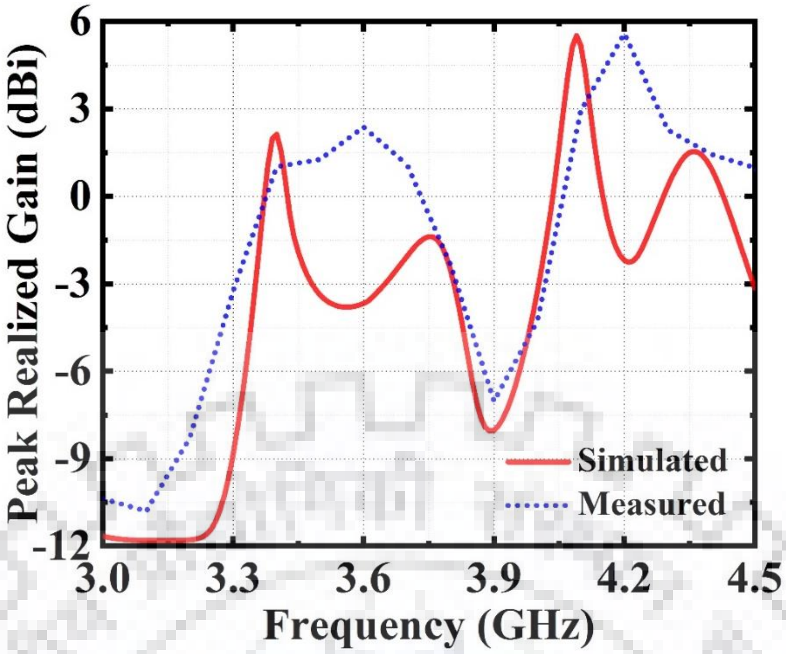


Fig 3.11 Simulated and measured peak realized gain

The measured and simulated peak realized gain of the antenna is shown in Fig 3.11. Both the results are almost the same at corresponding resonant frequencies. The peak gain achieved, after simulation and measurement, are 2.7 and 5.8dBi (Simulated: 2 and 5.7 dBi) at two resonant frequencies, respectively.

For measurement of radiation efficiency firstly, the reflection coefficient has been measured in free space and then bounded by a bowl (conductor) as shown in Fig 3.12, by this the reflected power comes back to the feeding port and gets compared by reflection coefficient in the free space. Finally using Wheeler cap method to determine the efficiency of the antenna, using the formula given in [62], is shown in Fig 3.13.

$$\eta_m = 1 - \frac{P_l}{P_i} = 1 - \frac{1 - |\Gamma_{wcm}|^2}{1 - |\Gamma_f|^2} = \frac{|\Gamma_{wcm}|^2 - |\Gamma_f|^2}{1 - |\Gamma_f|^2} \tag{3.1}$$

Fig 3.12 Experimental setup for radiation efficiency.

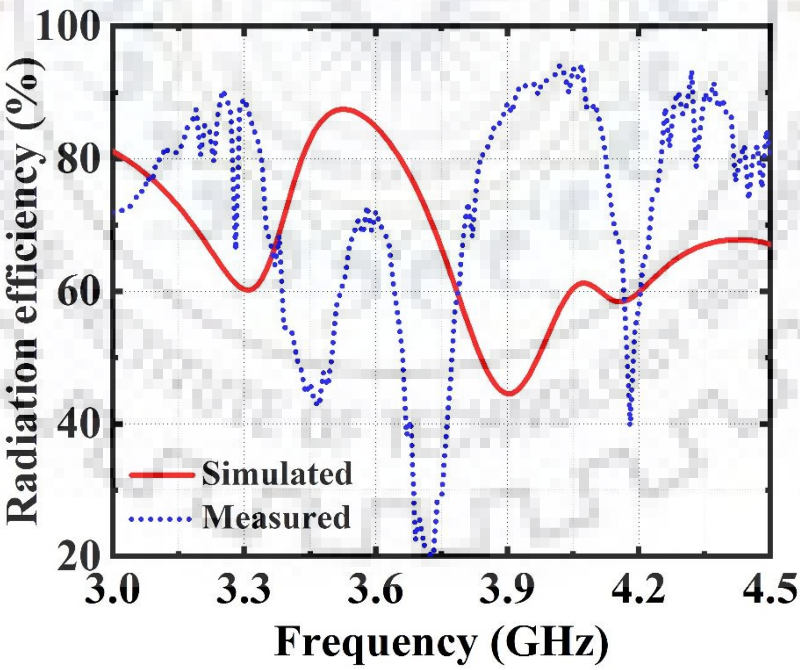


Fig 3.13 Simulated and measured radiation efficiency.

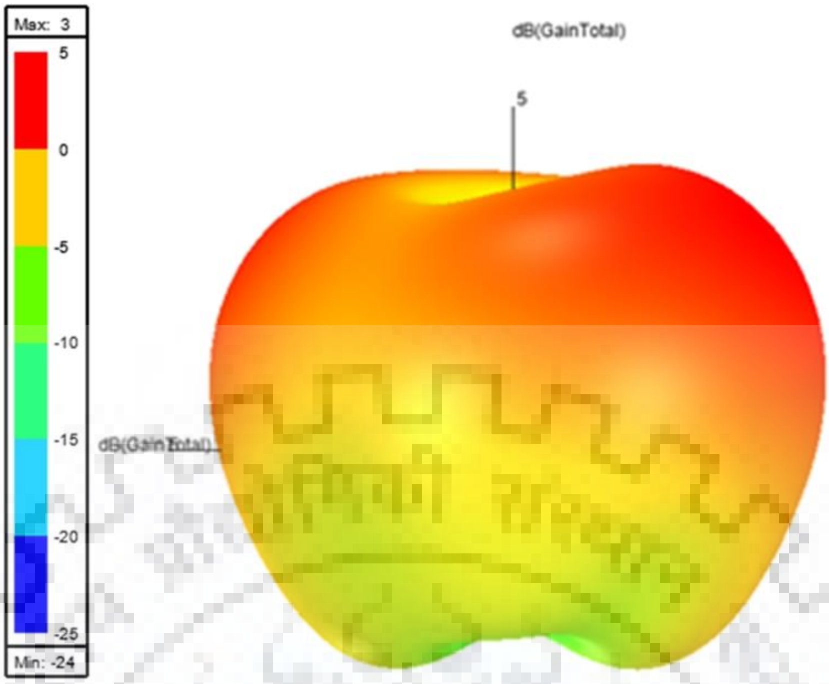


Fig 3.14 3-D radiation pattern at 3.44 GHz

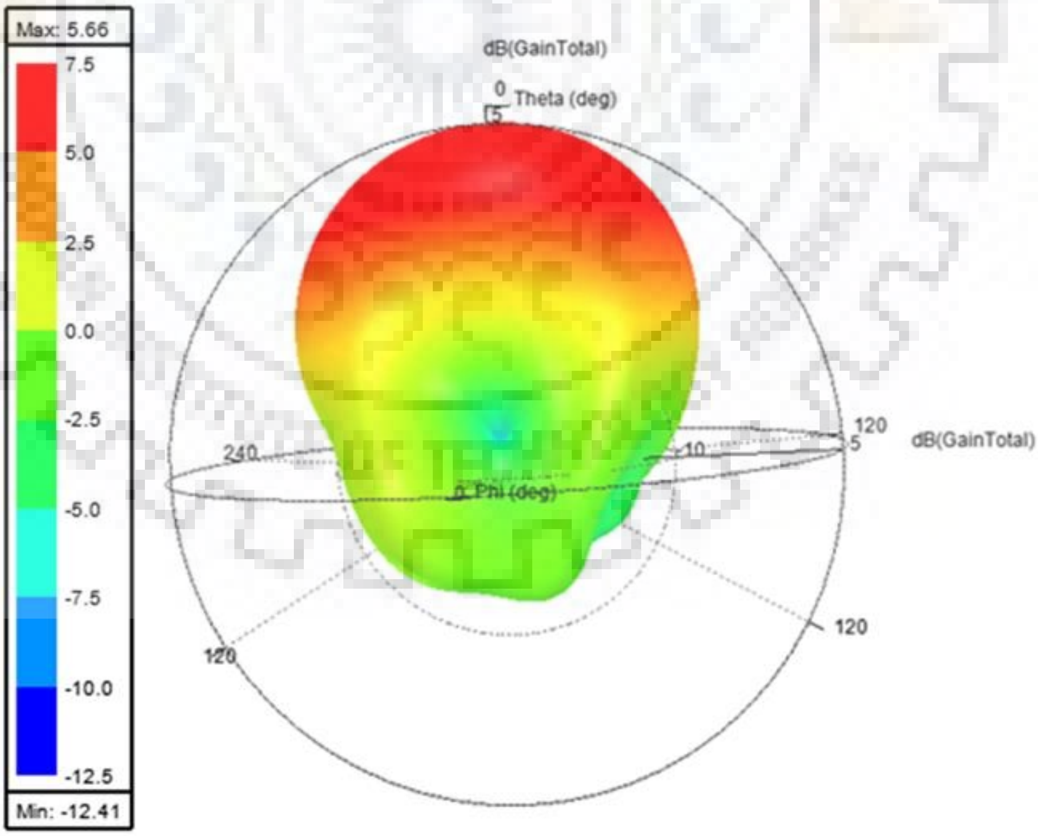
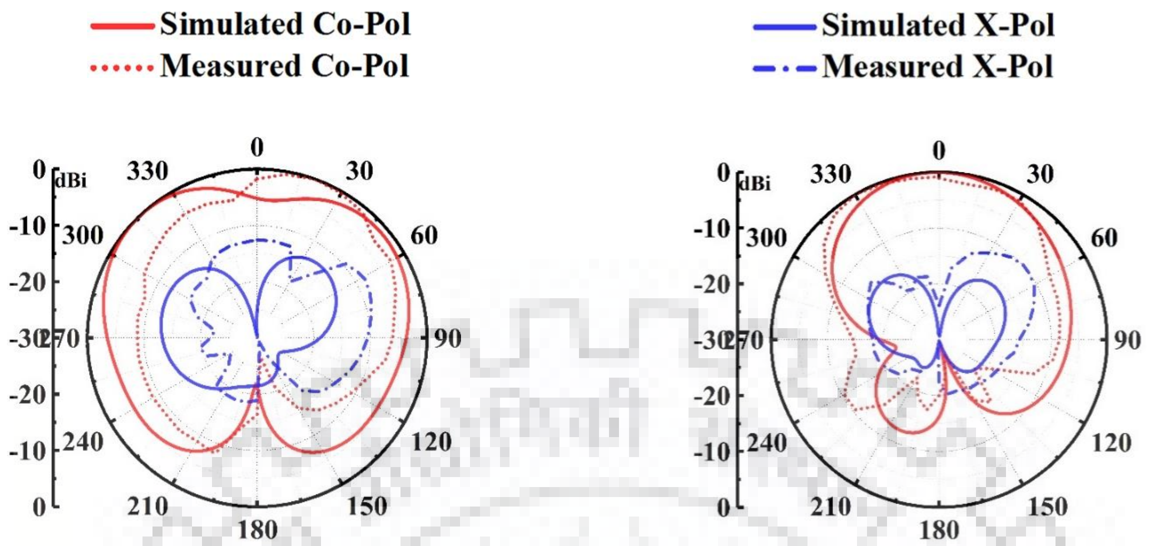
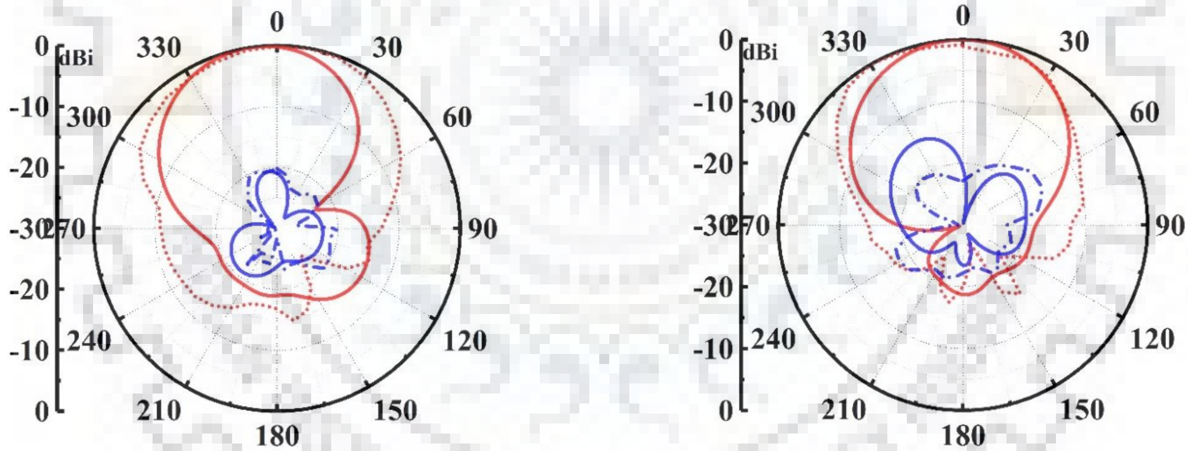


Fig 3.15 3-D radiation pattern at 4.09 GHz



(a) (b)

Fig 3.16 Radiation pattern of antenna (a) E-plane (b) H-plane at 3.65 GHz



(a) (b)

Fig 3.17 Radiation pattern of antenna (a) E-plane (b) H-plane at 4.2 GHz

Where η_m is the measured radiation efficiency, $|\Gamma_{wcm}|$ is the magnitude of reflection coefficient using Wheeler cap method and $|\Gamma_f|$ is the magnitude of the reflection coefficient in free space. From Fig 3.13, the measured radiation efficiency achieved are 71 % and 60 % (Simulated: 77 % and 60 %) at 3.65 and 4.2 GHz, respectively. There is slight variation in measured and simulated efficiency due to conductor loss, but the two curves are in good agreement with each other at corresponding resonant frequencies.

The simulated three-dimensional radiation pattern at 3.4 GHz and 4.09GHz are shown in Fig 3.14 & 3.15; the total gain achieved are 3 dBi & 5.7 dBi, respectively. By using measuring setup in the anechoic chamber, the radiation patterns for E plane and H plane at 3.65 and 4.2 GHz are shown in Fig 3.16 and 3.17. The measured and simulated radiation pattern at both frequencies are almost close to each other. The cross polarization is lower than co-polarization in both results and is -15 to -25 dB lower than normalized radiation pattern. The measured front to back ratio (FTBR) achieved are 10 and 25 dB at 3.65 GHz and 18 and 20dB at 4.2 GHz for E- plane and H-plane, respectively. The designed antenna radiates linear polarization and gives a unidirectional pattern.

4.1 Conclusion

In this report, a CRLH-TL Unit Cell Loaded Dual-Band SIW Antenna for WiMAX applications is proposed. The first proposed antenna operates at dual-band having a frequency that is at 3.65 GHz and 4.2 GHz. The measured reflection coefficient is less than -10 dB. The radiation efficiency over the band are 71 and 60 % and gain obtained are 2.7 and 5.8 dBi. There were certain drawbacks with the designed antenna which were majorly concerned with the efficiency and gain which we tried to overcome in the later part by using substrate intergrade waveguide technology in the design part.

In the second part of this report we extended the work done in above part by using SIW technology in the same design of proposed antenna with minor changes in dimensions with improved performance in terms of impedance matching, radiation efficiency, gain, reduced cross-polarization level for WiMAX application. The newly designed antenna operates at 2.65 GHz and 3.32 GHz. The measured results show that the SIW based improvised antenna have reflection coefficient less than -10 dB. The simulated maximum gains are 3.2 dBi, 7.1 dBi, respectively. The antenna has achieved a simulated radiation efficiency of 55 and 87 % at two different frequencies. The proposed antenna can be used for WiMAX application since the operating frequency range satisfies the operating band of WiMAX.

4.2 Future Scopes

After designing the proposed antenna and plotting all the required results, there is still some work left due to time constraint, which can be completed shortly. Following are some of the aspects of this report in the coming years.

The first one is trying to get a unidirectional radiation pattern in CRLH design instead of getting a bidirectional pattern. It can be improved by shifting the operation of frequency and performing more parametric analysis in the design. Second, in this report, we have achieved dual-band operation of the antenna, but multiband (in this case more than two) operation should be kept in focus to achieve for various application in the field of communication.

Third, to improve more gain and efficiency of CRLH-TL based antennas and to remove all the drawbacks regarding low FBR, and cross polarization, though we tried our best to improve those parameters than earlier research work still there is the place for improvement.

We have already designed the antenna for WiMAX application for frequency range 2.5-2.69 GHz and 3.3-3.7 GHz yet WiMAX can support more multiband frequency operation in the range 5.15-5.35, 5.47-5.725, and 5.725-5.825 GHz so, an effort has to be made in coming time to cover other range also.

References

[1] M. M. Alam, M. M. R. Sonchoy, and M. O. Goni, “Design and performance analysis of microstrip array antenna,” in *Proc. Prog. Electromagn. Res. Symp.*, Moscow, Russia, Aug. 18–21, 2009, pp. 1837–1842.

[2] S. Chen, D. Dong, Z. Liao, Q. Cai, and G. Liu, “Compact wideband and dual-band antenna for TD-LTE and WLAN applications,” *Electron. Lett.*, vol. 50, pp. 1111–1112, Jul. 2014.

[3] Z. Wu, L. Li, X. Chen and K. Li, "Dual-Band Antenna Integrating with Rectangular Mushroom-Like Superstrate for WLAN Applications," in *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1269-1272, 2016.

[4] A. Lai, C. Caloz, and T. Itoh, “Composite right/left-handed transmission line metamaterials,” *IEEE Microw. Mag.*, vol. 5, no. 3, pp. 34–50, Sep 2004.

[5] S. G. Mao, S. L. Chen, and C. W. Huang, “Effective electromagnetic parameters of novel distributed left-handed microstrip lines,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1515–1521, Apr. 2005.

[6] F. J. Herraiz-Martínez, V. González-Posadas, L. E. Garcia-Munoz, and D. Segovia-Vargas, “Multifrequency and dual-mode patch antennas partially filled with left-handed structures,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 8, pp. 2527–2539, Aug. 2008.

[7] Caloz, C. and T. Itoh, Electromagnetic Metamaterials, Wiley, New York, 2005.

[8] C. Caloz, A. Sanada, and T. Itoh, “A novel composite right-/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 3, pp. 980–992, 2004.

[9] J. Sorocki, I. Piekarz, K. Wincza, and S. Gruszczynski, “Right/left-handed transmission lines based on coupled transmission line sections and their application towards bandpass filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 2, pp.

384–396, 2015.application towards bandpass filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 2, pp. 384–396, 2015.

[10] J.-X. Niu, "Dual-band dual-mode patch antenna based on resonant type metamaterial transmission line," *Electron. Lett.*, vol. 46, no. 4, pp. 266–268, Feb. 2010.

[11] H.-X. Xu, G.-M. Wang, and J.-Q. Gong, "Compact dual-band zeroth order resonance antenna based on CRLH TL using fractal-shaped complementary single split ring resonator pair," *Chinese Phys. Lett.*, vol. 29, no. 1, p. 014101, 2012.

[12] F. J. Herraiz-Mart´ınez, V. González-Posadas, L. E. Garcia-Munoz, and D. Segovia-Vargas, "Multifrequency and dual-mode patch antennas partially filled with left-handed structures," *IEEE Trans. Antennas Propag.*, vol. 56, no. 8, pp. 2527–2539, Aug. 2008.

[13] C. Wang, B.-J. Hu, and X.-Y. , "Compact triband patch antenna with large scale of frequency ratio using CRLH-TL structures," *IEEE Antennas Wireless Propag*. Lett., vol. 9, pp. 744–747, 2010.

[14] J. K. Ji, G. H. Kim, and W. M. Seong, "Bandwidth enhancement of metamaterial antennas based on composite right/left-handed transmission line," *IEEE Antennas Wireless Propag.* Lett., vol. 9, pp. 36–39, 2010.

[15] J. G. Lee and J. H. Lee, "Zeroth order resonance loop antenna," *IEEE Trans. Antennas Propag., vol. 55*, no. 3, pp. 994–997, Mar. 2007.

[16] J.-H. Park, Y.-H. Ryu, J.-G. Lee, and J.-H. Lee, "Epsilon negative zeroth-order resonator antenna," *IEEE Trans. Antennas Propag.*, vol. 55, no. 12, pp. 3710–3712, Dec. 2007.

[17] S. Pyo, S. M. Han, J. W. Baik, and Y. S. Kim, "A slot-loaded composite right/left-handed transmission line for a zeroth-order resonant antenna with improved efficiency," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 11, pp. 2775–2782, Nov. 2009.

[18] S. Pyo, S. M. Han, J. W. Baik, and Y. S. Kim, “A slot-loaded composite right/left-handed transmission line for a zeroth-order resonant antenna with improved efficiency,” *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 11, pp. 2775–2782, Nov. 2009.

[19] W. Che, K. Deng, D. Wang and Y. L. Chow, "Analytical equivalence between substrate-integrated waveguide and rectangular waveguide," in *IET Microwaves, Antennas & Propagation*, vol. 2, no. 1, pp. 35-41, February 2008.

[20] Deslandes, D., Wu, K.: “Single-substrate integration technique of planar circuits and waveguide filters”, *IEEE Trans. Microw. Theory Tech.*, 2003, 51, (2), pp. 593–596

[21] Y. Dong; T. Itoh, "Substrate Integrated Composite Right-/Left-Handed Leaky-Wave Structure for Polarization-Flexible Antenna Application", *IEEE Trans. Ant. & Prop.*, vol. 60, no. 2, part 2, pp. 760- 771, 2012.

[22] H. Zhang, Y. C. Jiao, G. Zhao, and C. Zhang. "CRLH-SIW-based leaky wave antenna with low cross-polarisation for Ku-band applications." *Electronics Letters*, vol. 52, no. 17, 2016, pp. 1426-1428.

[23] Y. Mizomuri , I. Ohta “Investigation of leaky wave antenna using SIW type CRLH- TL with metal patches” *IEICE technical report* , pp 29-33, May 2009.

[24] Xu, F., Zhang, Y., Hong, W., Wu, K., Cui, T.J, “Finite-difference frequency-domain algorithm for modeling guided-wave properties of substrate integrated waveguide”, *IEEE Trans. Microw. Theory Tech.*, 2003, MTT-51, (11), pp. 2221– 2227.

[25] Yan, L., Hong, W., Wu, K., Cui, T.J. “Investigations on the propagation characteristics of the substrate integrated waveguide based on the method of lines”, *Proc. IEEE Microw. Antennas Propag.*, 2005, 152, pp. 35–42.

[26] Bozzi, M., Perregrini, L., Wu, K. “Modeling of conductor, dielectric and radiation losses in substrate integrated waveguide by the boundary integral-resonant mode expansion method”, *IEEE Trans. Microw. Theory Tech.*, 2008, 56, (12), pp. 3153– 3161.

[27] Bozzi, M., Pasian, M., Perregrini, L., Wu, K. “On the losses in substrate integrated waveguides and cavities”, *Int. J. Microw. Wirel. Technol*., 2009, 1, (5), pp. 395 –401.

[28] Bozzi, M., Perregrini, L., Wu, K.: ‘Modeling of losses in substrate integrated waveguide by boundary integral-resonant mode expansion method’. *IEEE Int. Microwave Symp. (IMS 2008) Digest*, Atlanta, GA, 2008, pp. 515– 518.

[29] Grigoropoulos, N., Izquierdo, B.S., Young, P.R.: ‘Substrate integrated folded waveguides (SIFW) and filters’, *IEEE Microw. Wirel. Compon. Lett*., 2005, 15, (12), pp. 829–831.

[30] Lai, Q., Fumeaux, Ch., Hong, W., Vahldieck, R.: “Characterization of the propagation properties of the half-mode substrate integrated waveguide”, *IEEE Trans. Microw. Theory Tech*., 2009, MTT-57, pp. 1996– 2004.

[31] Bozzi, M., Deslandes, D., Arcioni, P., Perregrini, L., Wu, K., Conciauro, G.: ‘Efficient analysis and experimental verification of substrate integrated slab waveguides for wideband microwave applications’, *Int. J. RF Microw. Comput. Aided Eng*., 2005, 15, (3), pp. 296– 306.

[32] Che, W., Li, C., Russer, P., Chow, Y.L.: ‘Propagation and band broadening effect of planar integrated ridged waveguide in multilayer dielectric substrates. *IEEE MTT-S Int. Microwave Symp*. Digest, Atlanta, GA, 15–20 June 2008, pp. 217–220.

[33] Bozzi, M., Winkler, S.A., Wu, K.: ‘Broadband and compact ridge substrate integrated waveguides’, *IET Microw. Antennas Propag*., 2010, 4, (11), pp. 1965– 1973

[34] Che, W., Deng, K., Wang, D., Chow, Y.L.: “Analytical equivalence between substrate-integrated waveguide and rectangular waveguide”, *IET Microw. Antennas Propag*., 2008, 2, (1), pp. 35– 41.

[35] A. Lai, K. M. K. H. Leong, and T. Itoh, “Infinite wavelength resonant antennas with monopolar radiation pattern based on periodic structures,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 868–876, Mar. 2007.

[36] J. G. Lee and J. H. Lee, “Zeroth order resonance loop antenna,” *IEEE Trans. Antennas Propag.*, vol.55, no. 3, pp. 994–997, Mar. 2007.

[37] M. Antoniades and G. V. Eleftheriades, “A folded-monopole model for electrically small NRI-TL metamaterial antennas,” *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 425–428, Nov. 2008.

[38] A. Sanada, C. Caloz, and T. Itoh, “Characteristics of the composite right/left-handed transmission lines,” *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 2, pp. 68–70, Feb. 2004.

[39] M. Zedler, C. Caloz, and P. Russer, “A 3-D isotropic left-handed metamaterial based on the rotated transmission-line matrix (TLM) scheme,” *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 12, pp. 2930–2941, Dec. 2007.

[40] S. Lim, C. Caloz, and T. Itoh, “Metamaterial-based electronically-controlled transmission line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 11, pp. 161–173, Nov. 2005.

[41] C. Caloz, A. Sanada, and T. Itoh, “A novel composite right/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth,” *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 3, pp. 980–992, Mar. 2004.

[42] A. A. Ibrahim, A. M. E. Safwat, and H. El-Hennawy, “Triple-band microstrip-fed monopole antennas loaded with CRLH unit cell,” *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1547–1550, 2011.

[43] A. A. Ibrahim and A. M. E. Safwat, “Microstrip-fed monopole antennas loaded with CRLH unit cells,” *IEEE Trans. Antenna Propag.*, vol. 60, no. 9, pp. 4027–4036, Sep. 2012.

[44] M. A. Antoniades and G. V. Eleftheriades, “Multiband compact printed dipole antennas using NRI-TL metamaterial loading,” *IEEE Trans. Antenna Propag.*, vol. 60, no. 12, pp. 5613–5626, Dec. 2012.

[45] J. Zhu, M. A. Antoniades, and G. V. Eleftheriades, “A compact triband monopole antenna with single-cell metamaterial loading,” *IEEE Antennas Wireless Propag.* Lett., vol. 8, pp. 258–261, 2009.

[46] M. A. Antoniades and G. V. Eleftheriades, “A broadband dual-mode monopole antenna using NRI-TL metamaterial loading,” *IEEE Trans. Antenna Propag.*, vol. 58, no. 4, pp. 1031–1038, Apr. 2010.

[47] K. Saurav, D. Sarkar, and K. V. Srivastava, “A via-less CRLH unit-cell loaded dual-band double-sided printed dipole antenna for GSM/bluetooth/WLAN applications,” in *Proc. IEEE AP-S Int. Symp.*, Orlando, FL, USA, Jul. 2013, pp. 1358–1359.

[48] C.-J. Lee, K. M. K. H. Leong, and T. Itoh, “Composite right/left-handed transmission line based compact resonant antennas for RF module integration,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 8, pp. 2283–2291, Aug. 2006.

[49] F. J. Herraiz-Martínez, V. González-Posadas, L. García-Muñoz, and D. Segovia-Vargas, “Multi-frequency and dual-mode antennas partially filled with left-handed structures,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 8, pp. 2527–2539, Aug. 2008.

[50] M. Schüßler, J. Freese, and R. Jakoby, “Design of compact planar antennas using LH transmission lines,” in *Proc. IEEE MTT-S Int. Microw. Symp.*, Jun. 2004, vol. 1, pp. 209–212.

[51] H. Iizuk and P. S. Hall, “Left-handed dipole antennas and their implementations,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 5, pp. 1246–1253, May 2007.

[52] P. B. Nesbitt and G. Mumcu, “A small slot dipole loaded with CRLH TL unit cells,” in *IEEE AP-S Int. Symp. Dig.*, Jul. 2011, pp. 1032–1035.

[53] K. Saurav, D. Sarkar and K. V. Srivastava, "CRLH Unit-Cell Loaded Multiband Printed Dipole Antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 852-855, 2014.

[54] S. Jamilan, M. A. Antoniades, J. Nourinia and M. N. Azarmanesh, "A Directivity-Band-Dependent Triple-Band and Wideband Dual-Polarized Monopole Antenna Loaded with a Via-Free CRLH Unit Cell," in *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 855-858, 2015.

[55] Y. D. Dong and T. Itoh, “Miniaturized substrate integrated waveguide slot antenna based on negative order resonance,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 12, pp. 3856–3864, Dec. 2010.

[56] S. Sam, H, Kang and S. Lim, “Frequency Reconfigurable and MiniaturizedSubstrate Integrated Waveguide Interdigital (SIW-IDC) Antenna”, *IEEE Trans. Antennas Propag.*, vol. 62, no. 3, pp. 1039-1045, Mar. 2014.

[57] A.P. Saghati and K. Entesari, “A Miniatiaturized Switchable SIW-CBS Antenna Using Positive and Negative Order Resonances”, *Proc. of IEEE International Symp AP-S*, pp. 566-567, *Jul* 2013.

[58] A. P. Saghati, A. P. Saghati and K. Entesari, "An Ultra-Miniature SIW Cavity-Backed Slot Antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 313-316, 2017.

[59] B. F. Zong; G. M. Wang; Y. W. Wang; L. Geng; D. Wang, "Compact Antenna Using Finger-Connected Interdigital Capacitor-Based Composite Right/Left-Handed

Transmission Line Unit Cell," in *IEEE Transactions on Antennas and Propagation*, vol. PP, no.99, pp.1-1.

[60] H. L. Zhang, X. Y. Zhang, and B. J. Hu, “A novel interdigital capacitor with accurate model for left-handed metamaterials”, in *Proc. Asia-Pacific Microwave Confe., pp.* 1463-1465, Dec. 2010.

[61] J. Zhu and G. V. Eleftheriades, "A Compact Transmission-Line Metamaterial Antenna With Extended Bandwidth," in *IEEE Antennas and Wireless Propagation Letters*, vol. 8, no. , pp. 295-298, 2009.

[62] H. Jin, K.S. Chin, W. Che, “Differential- fed patch antenna arrays with low cross polarization and wide bandwidths,” *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp.1069-1072, 2014.

[63] H. A. Wheeler, “The radiation sphere around a small antenna”, *Proc.IRE,47 (8)* pp.1325-1221, 1975.

[64] A. K. Nayak, S. B. Panda, H. B. Mohapatra and K. C. Rout, "Compact Antenna Using IDC Based CRLH-TL Unit Cell for L-Band Applications," *2018 International Conference on Information Technology (ICIT)*, Bhubaneswar, India, 2018, pp. 18-21

[65] A. K. Nayak and A. Patnaik, "SlW-based patch antenna with improved performance," *2017 IEEE Applied Electromagnetics Conference (AEMC)*, Aurangabad, 2017, pp.1-2. doi: 10.1109/AEMC.2017.8325732.

[66] A. K. Nayak and A. Patnaik, "Design of an SIW corrugated H-plane horn antenna with improved performance," *2017 IEEE Applied Electromagnetics Conference (AEMC)*, Aurangabad, 2017, pp.1-2. doi: 10.1109/AEMC.2017.8325734.