

METAMATERIAL INSPIRED MICROWAVE HORN AND PATCH ANTENNAS FOR MODIFIED STRUCTURAL AND RADIATION CHARACTERISTICS

A THESIS
submitted to



UNIVERSITY OF CALICUT

*in partial fulfillment of the requirements
for the award of the degree of*

DOCTOR OF PHILOSOPHY

in

PHYSICS

by

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DECEMBER 2019

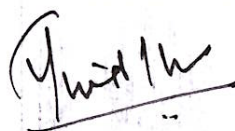
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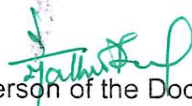
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Dedicated to

My parents

My wife and children

My brother and Sister

My teachers

ACKNOWLEDGEMENT

First of all, I praise God Almighty for providing me this opportunity and granting me the capability to proceed successfully. Undertaking this PhD has been a truly life-changing experience and it would not have been possible without the support and guidance that I received from many noble souls.

I would like to express my sincere gratitude and appreciation to my supervising guide Dr. V. P. Joseph, Head and Associate Professor, Research and P.G. Department of Physics, Christ College (Autonomous), Irinjalakuda, Thrissur, Kerala for his valuable guidance and constant encouragement. His guidance and timely interventions helped immensely during my research work and writing off this thesis. He has been an outstanding teacher and mentor throughout and I could not have imagined having a better advisor for my Ph.D. study. Thanks a lot, Sir...

A very special thank you to Rev. Dr. Jolly Andrews, Vice Principal and Assistant Professor, Dept. of Physics, Christ College, Irinjalakuda for your invaluable advice and feedback on my research and for always being so supportive of my work.

I would like to express sincere thanks to the Principal, Dr. Mathew Paul Ukken, Christ College, Irinjalakuda for his kind support. I also remember the former Principal, Late Rev. Dr. Jose Thekkan for his words of motivation during the early days of my research work. I also express my gratitude to the teaching and non teaching staff of Department of Physics, Christ College, Irinjalakuda.

I also express my sincere gratitude to my colleague: Nees Paul who recommended me to the Electromagnetics lab; and also to my research colleagues: Jovia Jose, Umadevi K. S., Sreedevi P. Chakyar, Sikha K. Simon, Bindu C. and Anju Sebastian- for their friendship and the kind support.

I would like to express my sincere gratitude to Prof. Joy P. M., HoD, Research and P.G. Department of Physics, St. Thomas' College (Autonomous), Thrissur for his constant encouragement and valuable support. I also acknowledge the support extended to me by my colleagues of Department of Physics, St. Thomas' College, Thrissur. I heart-fully express my sincere thanks to all my dear teachers and former HoDs of Dept. of Physics at St. Thomas' College, Thrissur. I also express my sincere gratitude to the College Management, Principal - Dr. K. L. Joy and to the former Principals of St. Thomas' College, Thrissur for their kind support.

It will be ingratitude if I fail to acknowledge the support extended by my family. My wife, Laveena has been extremely supportive of me throughout this entire process and has made countless sacrifices to help me get to this point. My children, Joel, Liz Maria and Jessel, have continually provided the requisite breaks from philosophy and the motivation to finish my degree with expediency. Their motivation, great interest, deep love and supreme sacrifice made this work fruitful. I would like to thank my mother and sister for their continued support and encouragement. I vividly remember my father and brother - who are in heaven, for their motivation and inspiration. I remember my relatives, well wishers and friends for their kind support and prayers too.

Praises to the Lord once again....

Joe Kizhakooden

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PREFACE

Day by day, the field of wireless communication advances in rapid pace with new scientific technologies. It makes the humankind to attain new heights in diverse areas which were once his dreams. The researchers across the world are in a race to develop new systems and devices to meet the various requirements of mankind. The researches in the field of antennas and communication have opened a wide variety of communication possibilities to connect the people worldwide. The scientists have developed different types of communication devices with wireless technology. The antennas are an essential part of any type of wireless communication devices. A large number of antenna systems for different frequency ranges are developed for the present communication scenario.

The present work brings out the idea of extending the use of electromagnetic metamaterial structures into the microwave communication field to make use of its negative permittivity and permeability effects on the antenna parameters. The widely used microwave horn antennas and monopole antennas are taken as the test samples for the study. Several basic structural alterations have been made in these conventional antennas with a purpose of enhancing its radiation characteristics in order to achieve the requirements of the communication scenario. This thesis describes how the novel metamaterial structures worthily enhance the use of the horn and monopole patch

antennas in the potential wireless communication field.

In chapter 1, discussions on the historical evolution of metamaterials, their applications in different fields with a special emphasis to the negative permittivity and permeability structures are presented. Since the present work is related with the metamaterial application in microwave antenna area, a brief outline about different microwave antenna and their applications are given.

In chapter 2, an introduction of metamaterial inspired structures is given. Recent developments in the field of communication using meta inspired structures is also discussed in detail. Since the research work is associated with the metamaterial inspired antenna structures, the theory behind the negative permittivity and negative permeability behavior of these structures is presented. A review of the past works related with the meta inspired structures is also given. The scope and importance of the present work in the current scenario is discussed at the end of the chapter.

In chapter 3, a detailed discussion about the experimental set up, measurement methods and antenna fabrication methods is given. The antenna parameters measured in the case of horn antenna and monopole patch antenna is described. The fabrication methods adopted to construct the proposed antennas are explained in the last section of the chapter.

In chapter 4, a novel type of metamaterial inspired negative permittivity horn antenna is introduced which is fabricated using a single slab of thin metallic wires in a specialized manner and is observed to have same radiation performance of an equivalent conventional metallic horn structure. The featherlight weight and the ability to remove the problems related with wind resistance and rain accumulation of this new structure may result in a rethinking of the use of horn antennas in astronomical data collection. The radiation characteristics studies of the antenna are presented. Measurements are carried out for horns fabricated in X-band, S-band and C-band frequencies and their radiation behavior is compared with metallic counterparts.

In chapter 5, the study of negative permeability metamaterial effect on monopole antenna is presented. The coupling between a single circular split ring resonating structure and the monopole for tuning the radiating frequency over a wide bandwidth is discussed. The study is extended to broadside coupled split ring resonator loaded

monopole patch antenna. The frequency tunability of the proposed antenna is also explored. The possibility of replacing different antennas for different applications in a single device with a single proposed frequency tunable BCSRR loaded monopole antenna is envisaged. The possibility of multiband operation employing two units of BCSRRs loaded on the two sides of a monopole patch antenna is also discussed. The study of antenna parameters and their analysis are also included.

In chapter 6, a summary of the works presented in the thesis is given. The inclusion of the meta inspired structures into the world of antennas along with the possible advantages are detailed. The chapter also discusses the relevance of the present study and its scope for future works.

CHAPTER 1

Introduction

1.1 Metamaterials

From the origin itself the evolution of mankind has accompanied his curiosity to study the interaction of light with matter. Through his vast journey of discoveries and active research, he is now able to control the propagation of light through the matter. The emergence of theories of electricity and magnetism and its unification with the field of optics have opened a wide area of research on interaction of electromagnetic waves with matter. From these observations he has understood that these interactions are dependent significantly on its intrinsic properties. He has observed and wondered with so many phenomena associated with the naturally occurred materials and has been victorious in finding their root causes. His excellent thoughts and creativity then

led to invent artificially engineered structures which exhibit unusual behaviors, not found with naturally occurred materials. It gave rise to the birth of a revolutionary concept in material history and accounted the realization of new artificial materials called ‘Metamaterials’.

Metamaterials have achieved a significant attention in the field of research and have flourished over the past twenty years with no symptoms of step back. The study of metamaterials is now emerged as a new branch of physics and engineering, and it is gaining a huge interest worldwide. Researchers make magical effects in the physical world by utilizing the unexplored and maneuvered properties of metamaterials that challenge the fundamental concepts of physics.

The term ‘Meta’ is derived from Greek which means ‘beyond’, and in this sense ‘metamaterial’ indicates the systems beyond the conventional materials. It was Rodger M. Walser [1], professor of physics at that time in University of Texas who coined the term ‘metamaterial’ first in 1999. In 2000, it appeared first in literature through Smith et al. [2] who published a paper on a structure having simultaneous negative permittivity and permeability values at microwave frequencies.

Different attempts to give a definition for metamaterial can be seen from the various corners of the scientific world. However an unambiguous and unique definition is yet to be established. A detailed discussion about the definition of metamaterial is given by A. Sihvola [3]. For the purpose of discussions on the present research work, the following definition can be taken. “A metamaterial is an artificially structured material which attains its properties from the unit structure rather than the constituent materials. It has an inhomogeneity scale that is much smaller than the wavelength of interest, and its electromagnetic response is expressed in terms of homogenized material parameters” [4].

The cellular unit size should be much less than the wavelength to consider it as an effective homogeneous medium. These engineered cellular units play the role of atoms in the medium on a macroscopic scale. This periodic or non periodic cellular structure exhibits unusual properties which are not usually found in nature. Since these properties depend on the structural constituents, the unlimited freedom to tailor the parameters of the constituents helps to innovate new devices according to our requirements. Not surprisingly, the applications of metamaterials are now extended to various fields like electromagnetism, optics, acoustics, non linear physics, material science, mechanics and electrical engineering.

1.1.1 Electromagnetic metamaterials

The electromagnetic field in a medium is governed by the intrinsic material properties of that medium. These properties are largely dependent on the two parameters which are electric permittivity (ϵ) and magnetic permeability (μ). The materials can be classified into four types according to the values of permittivity and permeability. The naturally occurring materials have positive values for permittivity and permeability and show ordinary properties as expected. The material medium which has negative value for permittivity but a positive value for permeability is known as epsilon negative metamaterial medium or ENG medium or negative permittivity medium. The ionized gas or free electron gas which are called plasma medium shows negative value for permittivity below its plasma frequency.

The other type of artificial medium which has a positive value for permittivity but a negative value for permeability is known as mu negative metamaterial medium or MNG medium or negative permeability medium. The ferromagnetic and antiferromagnetic materials exhibit negative permeability near ferromagnetic resonance [5]. If an artificial medium has negative values for both the permittivity and permeability, it is known as

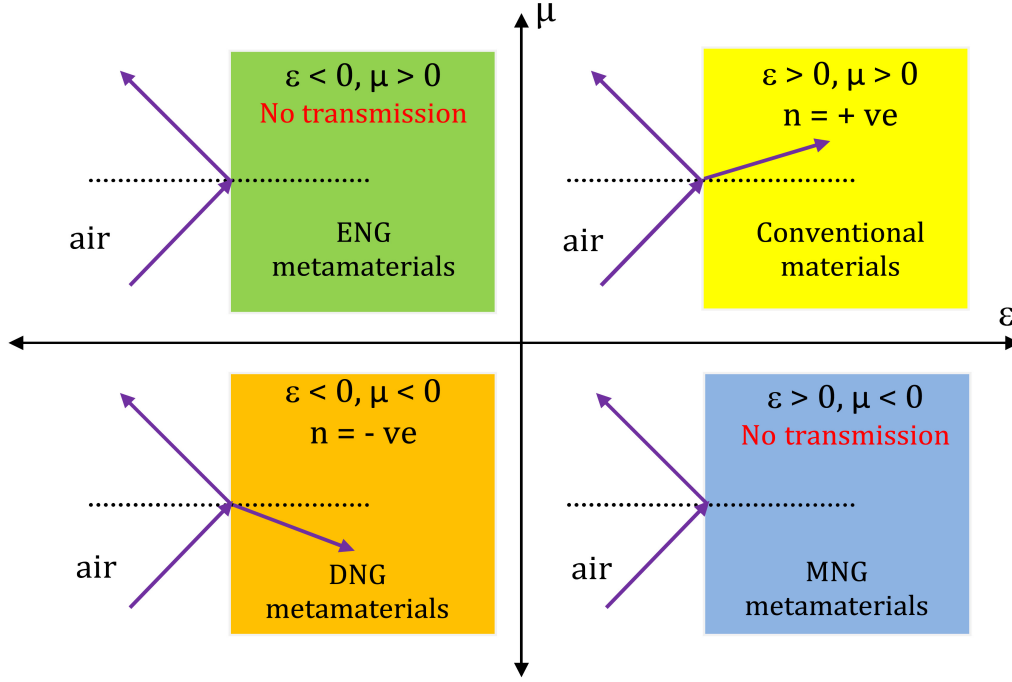


Figure 1.1: Classification of materials based on electric permittivity and magnetic permeability.

double negative metamaterial medium or DNG medium. It shows the unusual property of negative refractive index which cannot be found in nature. It is usually manufactured by the periodic arrangement of the negative permittivity structure and the negative permeability structure both together forms the basis unit. They are also known as left handed materials, negative index materials, negative phase velocity media and backward wave media. A schematic representation of the classification of materials in terms of electric permittivity and magnetic permeability is shown in the Fig. 1.1.

The above mentioned artificially engineered metamaterials show unprecedented electromagnetic responses which cannot be derived by conventional synthesis techniques. The structural unit cells, which are called as ‘meta atoms’ or ‘meta molecules’ of metamaterials, can be tailored in various shapes and sizes. The composition and

morphology of these cells are artificially tuned and arranged in the metamaterial system in a predetermined manner to derive unusual electromagnetic functionalities. The size of the unit cell should be substantially smaller with respect to the wavelength of interest but usually several orders bigger than the atomic size of the conventional materials. The average distance between these unit cells should be in subwavelength scale. This subwavelength scale inhomogeneity with unit cells in metamaterial medium can be shown macroscopically uniform in the view of external electromagnetic wave and causes to consider the system essentially a ‘material’, not a ‘device’. The electromagnetic responses of this material are determined by macroscopically homogenized effective medium properties like permittivity and permeability. As we know, if the inhomogeneity scale of unit cells is in the order of the wavelength, then the electromagnetic responses will be dominated by the interference and diffraction effects of the individual unit cells.

Looking into the history of electromagnetic metamaterials, we will wonder that, centuries ago, people used metamaterials deliberately in art pieces without a prior knowledge about the physics behind it. The famous Lycurgus Cup, the Roman glass chalice kept in the British Museum, which was made in fourth century AD using ruby glass with gold nano particles embedded in it, is probably the first known metamaterial [6]. By virtue of metamaterial property the cup appears green when viewed in reflected light but reddish when light transmitted through the glass.

In the modern history of science, the ‘twisted jute material’, an artificially engineered subwavelength material to produce chiral effect proposed by J. C. Bose [7, 8] in 1898, is considered as the first metamaterial even before the name coined. Artificial dielectrics, the name used in the place of negative permittivity metamaterials at that time, made from the periodic arrays of metallic wires, spheres or plates [9, 10, 11], and other structures like split ring resonators [12, 13], frequency filters array [14], chiral and

bianisotropic materials [15] are some other examples for earlier types of metamaterials developed before the name metamaterial was coined.

The three seminal works which laid the cornerstone for the research in modern metamaterial era are briefed below. Veselago [16] predicted a left handed material in which the electric field vector $\mathbf{E}$, the magnetic field vector $\mathbf{H}$ and the wave vector $\mathbf{k}$ forms a left-handed orthogonal set which would exhibit simultaneous negative values of permittivity and permeability. The second important work was related with the construction of a perfect lens by Sir J. B. Pendry [17] which was an initial attempt of exciting application of metamaterial. The third important work which realized the theoretical prediction of left handed materials to experimental validation was done by Smith et al [2].

Veselago also predicted several phenomena with the left handed metamaterials. It included frequency dispersion of the constitutive material properties, reversal of some fundamental phenomena like Vavilov-Cerenkov radiation, Doppler effect and Snell's law. It also included the introduction of perfect lenses, superlenses having subwavelength resolution, the interchange of divergence and convergence effects in concave and convex lenses respectively if the lenses are made of left handed medium, invisibility by electromagnetic cloak and new plasmonic equations of the constitutive material parameters for left handed media having resonant nature. Today the metamaterial research is progressing with a fast pace with its unprecedented electromagnetic properties.

1.1.2 Negative permittivity and permeability structures

The materials show responses to an electromagnetic wave according to its material properties described by the macroscopic parameters - electric permittivity and magnetic permeability. As discussed earlier, both electric permittivity and magnetic

permeability can take positive or negative values. The negative permittivity structure has negative value for permittivity but a positive value for permeability. Such type of materials can be found in nature and one example for it is plasma medium. All metals show negative electric permittivity up to its corresponding plasma cutoff frequency. But the fact is that for good conducting metals, the plasma frequency is near to UV spectrum. But since our frequency of interest is at the microwave ranges, a method must be devised to scale the plasma cut off frequency down to microwave frequency ranges.

The first pioneer search for ‘artificial dielectrics’, the name used for negative permittivity structures at that time, was done by Winston Kock, an engineer at Bell Laboratories in the 1940s. He proposed different types of lens structures with metallic plates or sphere arrays arranged in parallel and lodged in a dielectric matrix [9, 18]. He successfully investigated some kinds of periodic metal-dielectric structures having different effective refractive indices with larger and smaller values than unity and he called them as ‘phase delay’ and ‘phase advance’ structures to explain the properties of wave propagation through it.

Afterwards, early researchers in this field, Brown [10], Golden [19], and Rotman [11] introduced the ‘rodded medium’ in which metallic rods are periodically spaced in a lattice either in air or embedded in other dielectric material. It mimicked a plasma medium and the plasma frequency of this medium can be adjusted by changing the geometrical parameters of the rods.

In 1996, Sir J. B. Pendry [20] introduced an artificial plasma structure consisting of an array of conducting wires that can lower the plasma cut off frequency where he showed the electric permittivity having a negative value at the microwave frequency ranges. A schematic representation of a negative permittivity wire medium with the

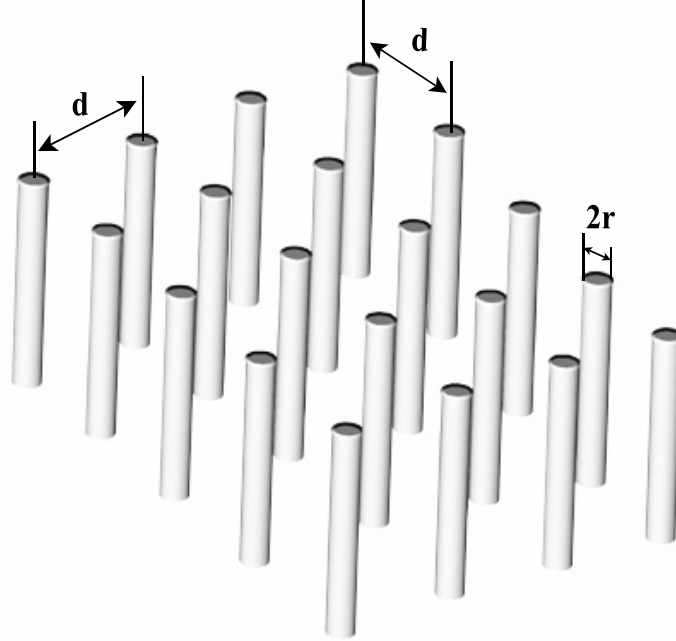


Figure 1.2: A schematic representation of a negative permittivity wire medium. The parameters ' d ' and ' r ' are meant for lattice parameter and radius of the wire respectively.

geometrical parameters is given in Fig. 1.2. The designing of plasma cut off frequency and permittivity value depends on the geometrical parameters of the wires in the array such as radius of the wire and the spacing of the wires in the array. The effective permittivity of the wire medium is very similar to the bulk metal medium but at a lower plasma cut off frequency. Theoretically it happens because of two reasons. The effective electron density in the medium is lowered due to large void space in the wire array region. The effective mass of the electron is increased substantially due to the magnetic field energy corresponding to the self inductance of the thin wires. Both these effects significantly decrease the plasma cut off frequency compared to that of bulk metal.

It was not easy to find a negative permeability structure as the magnetic response of the materials to the electromagnetic wave at frequencies higher than a few gigahertz is very poor compared to the electric response of the materials. Sir J. B. Pendry [21] made an attempt with a parallel array of conducting hollow cylinders but did not quite succeed to realize his expectation. He again tried with a pair of concentric hollow cylinders having splits at the opposite sides. It produced a capacitance along with the inductance resulting in a negative value for permeability for the structure at a small range of microwave frequencies. But the structure was highly anisotropic due to the presence of electrical conduction path along the axial direction.

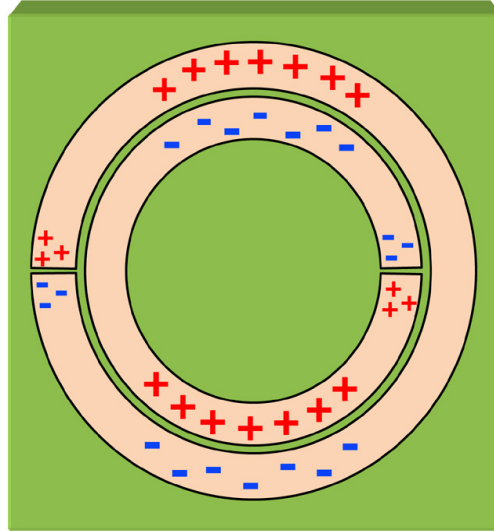


Figure 1.3: A schematic representation of a SRR structure with the charge distributions.

In an attempt to reduce the anisotropy of the structure, he reconfigured the structure with a planar array structure of concentric annular rings of different radii with splits at the opposite sides. The new structure known as Edge Coupled Split Ring Resonating structure (ECSRR), also called as SRR, eliminated the axial continuous

electrical conduction and gave a negative permeability over a narrow frequency band under a certain electromagnetic wave polarization. A schematic representation of a SRR structure with the charge distribution is given in the Fig. 1.3.

If the magnetic field of the incident electromagnetic wave is perpendicular to the plane of the SRR, circular currents will be induced in the annular concentric rings which in turn cause a charge accumulation across the splits. This will generate a capacitance between the gap of the two rings in addition to the capacitance across the splits of the rings and along with the inductance. Thus each SRR structure in the array will act as a LC circuit giving a resonance at a particular frequency. The effective permeability of the structure is a function of frequency and will be negative in a narrow frequency band above the resonant frequency.

Several researchers have proposed different shaped magnetic metamaterial structures for different applications. Square shaped SRR, a variant of ECSRR [22] and Complementary SRR (CSRR) are proposed by various research groups [23]. Broad-side Coupled SRR (BCSRR) [24] and Isotropic SRR [25] are proposed for reducing the unwanted bianisotropic effects. Omega shaped bianisotropic structure is proposed by Saadoun and Enghetea to use as a reciprocal phase shifter [15].

Turkmen et al. [26] proposed multiring SRR design for multiband communication applications and Beana et al. [27] presented spiral resonators having small electrical size. The triangular shaped SRR structure was introduced by Sabah [28]. The other types include V-shaped structure etched on the both faces of a substrate [29], S-shaped resonating structure [30], Flexible SRRs for tunable structures [31], Wire SRRs [32], tunable BCSRR [33] etc. and are meant for various specific applications.

The commonly used artificially engineered structures giving rise to negative permittivity metamaterials and negative permeability metamaterials are briefly discussed

in the above section. The structural unit size in the array should be much smaller than the wavelength of the interacting electromagnetic wave so that the wave will not see the fine details of the individual unit structures and then the periodic array can be considered as a homogeneous medium. So the effective permittivity and permeability values can be identified as the corresponding macroscopic properties of the whole medium. If this condition is not satisfied, then the wave will get diffracted or refracted from the individual unit structures which are not the properties of a homogeneous medium.

1.1.3 Applications of metamaterials

The ongoing interest in research on metamaterials leads to find its applications in widespread areas including optics, condensed matter physics, nanoscience, semiconductor engineering, electrical engineering, device engineering, photonics and more. The rapid pace of research activities in this vibrant field reverberates the realization of metamaterials with the new developments like plasmonic metamaterials, cloaking, superlenses, metamaterials for nanoantennas and nanoelectronics etc. Now the scientific world gazes day by day what wonders this laboratory engineered magic stuff will render next !

There are different types of electromagnetic metamaterials, namely microwave metamaterials, photonic metamaterials, chiral metamaterials, terahertz metamaterials, frequency selective surface based metamaterials, tunable metamaterials and non linear metamaterials. Microwave metamaterials are mainly used in applications like superlenses [34], beam steerers [35], microwave couplers [36], band pass filters [37], antenna radomes [38] etc.

Photonic metamaterials or optical metamaterials are one type of electromagnetic metamaterials which are designed to interact with the optical wavelengths [39]. Its

optical properties do arise from the sub wavelength interaction with the light spectrum, and not from the photonic band gaps. Chiral metamaterials formed by the arrays of planar chiral elements on planar metallic and dielectric films exhibit the ability to alter the polarization state of diffracted light [40]. Terahertz metamaterials interact at the terahertz frequencies and give a desired magnetic response with the negative permeability by which the property of tuning can be achieved [41].

Frequency selective surface based metamaterials have option to shift the frequencies in a medium [42]. It can control the reflection and transmission properties of an incident radiation wave. Tunable metamaterials have the ability to tune the frequency randomly by changing the refractive index values [43]. During the operation, the radiating frequency can be tuned by reconfiguring the structure of the tunable metamaterials. Nonlinear metamaterials are fabricated with some type of nonlinear components in which the non-linearity is due to the microscopic local field of the inclusions and not by the average macroscopic electric field of the source [44].

The scenario of metamaterial application includes diverse fields like sensors, management of solar power, public safety, high frequency communication in battle field, high gain antenna construction and remote aerospace technology. The integrated photonic devices fabricated by the combined properties of semiconductor and metamaterial are more efficient than the electric current controlled chips [45]. Metamaterial based biosensors are used in many areas like disease diagnostics, food safety and environmental monitoring by label free bio-sensing technology using subwavelength grating metamaterials [46]. Metamaterial absorbers having effective medium design dominate over conventional absorbers by better adaptability, more effectiveness, miniaturization advantages etc [47].

Using the acoustic metamaterial technology, the submarines can be hidden from the enemy sonar since the metamaterials can also easily manipulate the wavelength of sound [48]. They are also used to build quality sound proof rooms with the help of perfect acoustics. Moreover, Y. Chen et al. [49] investigated a “nano imprint lithography and hot embossing technology to fabricate planar nano metamaterials capable of making large area planar optic meta-materials and photonic structures such as dense gratings”. They are also used in suppressing unwanted sounds, medical diagnostics and material non-destructive testing.

Metamaterials find applications generally in miniaturized antenna systems as it has the capability of improving the antenna parameters. In metamaterial inserted antennas, the energy is stored in the metamaterial component and re-radiated through the antenna. Since the metamaterial has the inherent property of controlling the direction of electromagnetic signals, it is used to enhance the directivity of an antenna. It can be used along with antenna for miniaturizing its size and for enhancing bandwidth along with controlling radiation properties [50, 51, 52].

The metamaterial substrate can be designed as high input impedance substrate which prevents the signals travelling through the substrate resulting in high antenna efficiency [53]. The metamaterial superstrates are introduced to realize high directive antennas having improved radiation efficiency [54]. By loading metamaterial as a superstrate over a conventional antenna, its bandwidth is increased [55]. The power gain is achieved in certain conventional types of antennas by modifying it with metamaterial inclusions. The metamaterials are also used to reduce the beamwidth and thereby increase the directivity of antenna [56]. The side lobe levels are also decreased by the insertion of metamaterials in antennas [57].

A number of metamaterial antennas are developed for specific systems and requirements. Some of them are zero phase shift line based antennas for near field RFID and wireless local area network (WLAN) applications [58], compact type metamaterial based antennas for multi-input multi-output (MIMO) systems [59], mushroom antennas for Wi-Fi systems [60] etc.

1.2 Microwave Antennas

In the field of communication it is necessary to send and receive information in the form of electromagnetic signals over a long distance. Even though the transmission lines can carry the electromagnetic energy with the help of a guiding structure, they confine the energy only up to the region near or inside the transmission line. This reason limits its use for low frequency signals and for short distances.

For long distance communication purposes high frequencies are usually used, as the available bandwidth is wide and the attenuation loss is less. Thus an antenna is employed for this purpose which can radiate/receive the electromagnetic signals to/from a large distance without a guiding structure. It acts as a transitional structure between a guided wave and a free space wave or vice versa in an efficient and desired manner.

The electromagnetic spectrum is classified into different categories according to the frequency ranges of electromagnetic signals. The most commonly used microwave frequency category corresponds to a bandwidth of 1 GHz to 30 GHz. When this frequency is used, the size of the antenna can be reduced to centimeter range. The antennas used in this range are commonly known as microwave antennas. There are different types of microwave antennas according to the field of applications.

In the following section some important types of microwave antennas are discussed. Since the present research work deals with the application of metamaterials into the antennas, the widely used horn antenna and monopole patch antenna are taken as test samples. A brief outline of these types of microwave antennas and their applications in the communication field are followed.

1.2.1 Different types of microwave antennas

Microwave antennas are critical elements of any microwave radiation network. Different types of microwave antennas are developed since the beginning of microwave communication to meet the specific electrical and mechanical requirements. Each of these different types has its own characteristics that shaped it to fit for particular systems and situations. They can be categorized in terms of bandwidth or polarization or resonance or number of elements used. Some of the important microwave antenna types are mentioned below [61].

Dipole antennas, monopole antennas, loop antennas, helical antennas, Yagi-Uda antennas and log periodic antennas are wire type antennas which are made up of conducting wires and are generally less expensive and easy to construct. They are commonly used for low frequency applications i.e. up to 4 GHz. Horn antennas, slot antennas, lens antennas and reflector antennas are collectively known as aperture type antennas. This group of antennas is made up of conducting plates or meshes instead of wires which is configured to radiate or receive the electromagnetic signals in an efficient and desired manner. They are used for high frequency applications.

The reflector type of antennas includes corner reflector antenna, paraboloidal reflector antenna and Cassegrain reflector antenna. Lens antennas also convert spherical wave into a plane wave and produce high gain and pencil beams. Dielectric lens an-

tenna made up of dielectric materials is also seen in the field which has advantage of highly shaped beams over large operating bandwidths. Slot antennas are very low profile antennas and are commonly used in aircrafts and missiles. It is easily conformed basically to any configuration such that many advantages can be made.

Microstrip antennas which are also known as patch antennas are another important type of antenna used in the microwave communication. It consists of a metal patch bonded to one side of a dielectric substrate and has a metallic ground plane on the other side. Different shapes are given to the patch to meet the various design requirements. The commonly used shapes are rectangular, square, circular and some ring shaped patches. It is conformable to planar or non planar surfaces, low profile, less expensive and compatible. There are antenna arrays in which more than one antenna element are used. These elements are specifically arranged in space to get desired characteristics. The vector addition of the fields due to individual elements gives the total radiated power of the antenna array.

1.2.2 Horn antenna and monopole patch antenna

In the previous section, different types of microwave antennas are discussed. In the present research work, two antennas, namely horn antenna and monopole patch antenna are taken as test samples for meta inspired modifications as they are simple and widely used in the microwave communication applications since their introduction. This section gives a brief outline about these antennas.

The Indian Physicist J. C. Bose [62] introduced the horn antenna in 1897 in a lecture at the London's Royal Institution. He performed an experiment using a horn at a frequency of 60 GHz, in which he called it as a 'collecting funnel'. At the turn of the century the interest on horn antennas became diminished as lower frequency bands

were mainly used for the long distance transmission while horn antenna was proved incompatible for the purpose. But the focus on horn antennas was again revived during the second world war and a booming interest appeared in microwave frequency regions. Now horn antennas are commonly used in many applications like microwave communication, radars, primary feeds for reflector antennas etc.

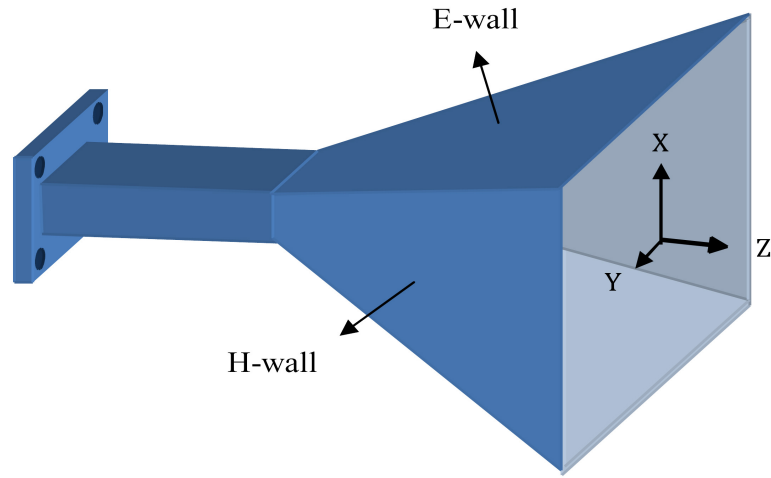


Figure 1.4: Schematic presentation of a conventional pyramidal metallic horn antenna.

Since the open ended waveguide has a small directivity and broad beam width, it is not advised for practical applications. So the open end of the waveguide is flared in both the side wall dimensions to form a horn shape. Now the structure is known as the (pyramidal) horn antenna which gives narrow beamwidths for radiation patterns in both the principal planes, i.e. planes of E-field and H-field. It turns out uniform phase front for the signals with a larger aperture compared to open waveguide and causes high directivity. The antenna can be easily integrated with the waveguide feed and can control the performance easily. A schematic diagram of a conventional rectangular pyramidal horn is given in Fig. 1.4. It makes a transition of electromagnetic waves from the waveguide mode to the free space mode.

For the dominant mode excitation (TE_{10}), the electric field vector will be in the X-direction and the transverse component of the magnetic field vector will be in the Y-direction. The two principal planes, XZ plane and YZ plane, are known as E-plane and H-plane respectively. H-walls of the horn are the side walls whose aperture edges are parallel to the E-plane and E-walls are those walls whose aperture edges are parallel to the H-plane. If the flaring is kept only in one plane, it is called sectoral horn. The total radiated field of the horn is the combination of direct field and the diffracted portions of it from the aperture edges. The diffraction causes undesired radiations in the form of minor lobes. Conical and corrugated horns provide better performance by reducing the level of the diffracted fields from the aperture edges [63, 64].

The patch antenna systems are often described as one of the significant breakthroughs in the history of antennas. Now it has grown up to a level which can give most versatile solutions to many systems requiring an antenna radiator. It is most popular and adaptable since it has attractive features like low production cost, easy integration with other circuit components, compactness and good control over radiation. The antenna is first proposed by Deschamps G. A. in 1953 [65, 66] and the practical model is proposed by Munson and Howell in 1970 [67, 68]. Afterwards it has gained a huge attention to the researchers and made exciting applications in wide areas of microwave systems.

The patch antenna belongs to the category of printed antennas. The radiating elements of the antenna are printed or etched on the two sides of the dielectric substrate of a printed circuit board. It usually contains a radiating patch on one side of the dielectric substrate and has a grounded plane on the other side. Since the radiating element is extended over the ground plane, it will act as a monopole antenna. The radiating patch can be of any shape including rectangular, square, circular, annular, triangular and elliptical. Since the rectangular patch is easy to design, it is one of

the most preferred shape. The thickness of the patch is selected to be thin such that it is much less than the free space wavelength. The radiating elements are generally made up of conducting materials like copper and gold. The monopole patch is excited by a feed element. In the present work, the monopole patch itself is used as the feed element.

Fig. 1.5 gives a schematic representation of a microstrip antenna with monopole as the radiating source. The radiating frequency of the monopole patch antenna is determined by the dimensions of the monopole patch and the ground plane.

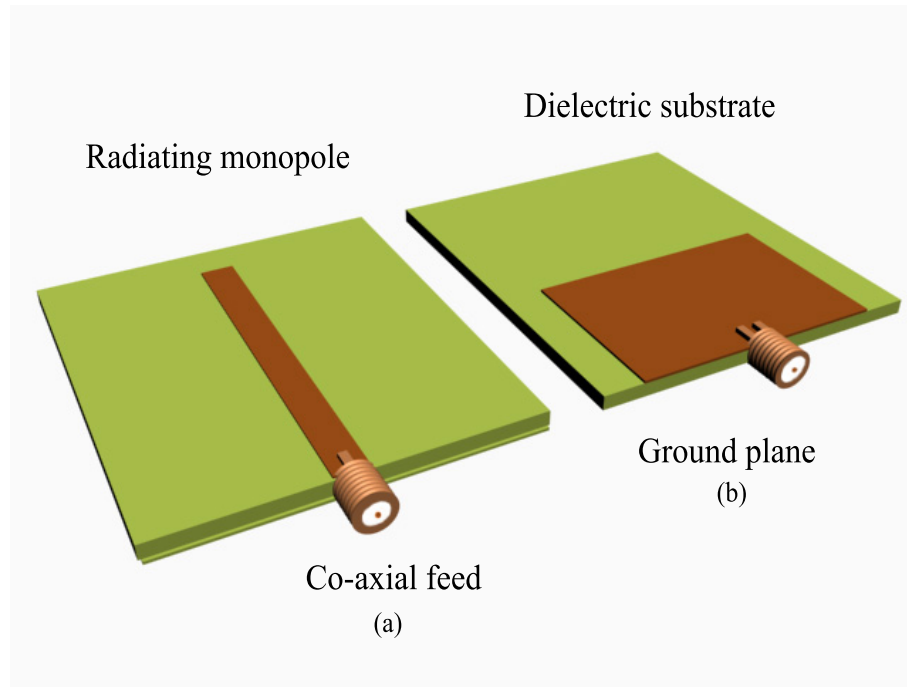


Figure 1.5: Schematic representation of (a) top and (b) bottom views of a microstrip monopole antenna.

This type of antenna falls in the resonant category which is efficient over relatively narrow operation bandwidth. This inherent narrow bandwidth is a disadvantage in considering it for certain practical applications but different remedial techniques are

employed for widening the bandwidth in such situations. The radiations from the monopole patch antenna mainly originates from the fringing fields existing between the edges of the conducting patch and the ground plane [69].

1.2.3 Applications of horn and monopole patch antennas

In antenna history, the horn antenna is considered as one of the simplest and most widely used antenna in the high frequency communication field. Its widespread applications in different fields are based on its simplicity in construction, large antenna gain, versatility, tractable excitation facility, low Voltage Standing Wave Ratio (VSWR), relatively wide bandwidth and proclaimed overall performance. It is mainly used as a feed element for the large aperture antennas like dish antenna, which is used for astronomical data collection, satellite tracking and worldwide communication purpose.

Besides the use of horn antenna as a feed element for the reflector antennas, lens antennas and compound antennas, its ample application can also be seen in phase antenna arrays. Its profound usage can also be seen in the area of calibration and gain measurements of other large gain antennas where it serves as a universal standard. It also finds application in gadgets related to electromagnetic sensing, bio-medical field, non destructive testing and radio frequency heating.

In earlier days, horn antennas were widely used in terrestrial microwave communication for line of sight transmission. From the beginning itself, the horn antenna has been used in satellite communications. In the Stardust satellite launched by NASA in 1999 to track and collect data from the Wild 2 comet, a X-band conical horn antenna was used as the feed element for the on-board communication reflector dish antenna [70]. Small horn antennas in the form of box-horn array was designed to use in collision

avoidance systems in vehicles [71]. Large type of horn antennas are also constructed worldwide for astronomical data collection. One of the famous discoveries made by the astronomical data study using large type horn antenna was the discovery of 21 cm radiation from the hydrogen atom [72].

In order to correct the possible phase errors at the aperture, horns are designed by including dielectric lenses at the aperture end [73]. To increase the bandwidth of the horn, metallic ridges inside the horn are also investigated [74]. In order to achieve pattern symmetry in both planes, lower cross polarization levels and higher aperture efficiency, dielectric horns [75] and metallic horns with corrugations inside the horn are also introduced [76]. The corrugations introduce anisotropic boundary conditions on the horn walls which in turn offers additional freedom to control the radiation patterns. Nowadays corrugated horns are much popular as feed elements in reflector type antennas.

Monopole patch antenna has many significant applications in the communication field. Its advantages and the developed techniques to overcome its disadvantages have exalted its popularity in the scope of microwave antennas. The space occupied by the monopole patch antenna to manage satisfactory operation is much lesser than the wire type and aperture type antennas. Its minimal material thickness is exploited to integrate easily with the surface of the component parts of aircrafts or missiles or even computers. Since it can be developed easily by standard printed circuit etching techniques, the manufacturing cost is minimized. Moreover the gain of the monopole patch antenna is typically less than 8 dBi which is very less compared to other antennas, an array of patch antennas is formed in order to increase the gain. It is very easy to construct patch antenna arrays using the etching techniques. Also they are basically considered as efficient radiators since they are resonant type antennas.

In its early days, the use of monopole patch was restricted to a hand full of systems because of its disadvantages like narrow impedance bandwidth and the unwanted excitation of surface waves due to the presence of dielectric substrate [77]. But in mid 1990s, it became a universally accepted antenna as the researchers developed the techniques to overcome the disadvantages. The monopole patch antenna technology is incorporated in low bandwidth radar systems. It is used as a fundamental radiator in space borne systems to observe the environmental changes on earth [78]. Its compact and weightless feature is exploited to reduce the payload of the satellite [79]. The monopole patch antenna arrays are benefited to develop inexpensive motion detection systems and tagging systems [80].

Another application area of monopole patch antennas is the telemetry systems used to communicate with the missiles or such projectiles since the broad radiation pattern of the antenna enhances the communication spatial coverage. These antennas are now being used in aircrafts to provide communication services to passengers via satellite services. It also serves as a main mission antenna in the satellite communication systems.

Another area which makes use of the monopole patch antenna is the mobile communication base station terminals. For higher frequency systems, such as 3G base terminal stations based on monopole patch antennas are more prevalent. Today the variants of monopole patch antenna are also widely used as radiators in mobile communication handsets. It is also utilized in biomedical telemetry systems [81].

1.3 Motivation behind the present work

In the previous sections, the properties of metamaterials and their applications in various fields are briefed. The advent of metamaterials has revolutionized the sce-

nario of conventional materials by opening diverse possibilities. The various types of microwave antennas used for specific systems and applications were also discussed. As the present work related with the metamaterial applications on microwave antennas, two widely used microwaves antennas, namely horn antenna and monopole patch antenna, are taken as test samples.

Horn antennas with large aperture are used for the radio astronomical telescopes. Since it is a huge structure and made with thick metallic plates, a large quantity of material is needed for its construction whereby the production cost increases. Another problem is related with the antenna installation. Since the antenna is heavier, it is very difficult to install and erect it. A large infrastructure is required to mount the antenna and it makes the project again expensive. Another concern is about the climatic conditions. During the rainy and windy seasons, the large aperture will act as a collecting funnel for wind and water. So further attention is required in avoiding such hurdles. Since the horn antenna is used as a feed for communication dishes in satellites, the conventional metallic horns increase the weight of the payload.

The monopole patch antennas are widely used in the microwave wireless communication systems since it is very compact, less expensive, light weight, easy to install and easy to integrate with other components in the circuit. Since a modern communication device is used for different applications, the number of antennas used in a single device are often more than one. For example a smart phone can be connected with different devices via Bluetooth, Wi-Fi, Hotspot, Long Term Evolution (LTE) etc. The additional number of antennas requires more space and associated circuits.

In the present research work, it is discussed how the metamaterial structures can be used to overcome the above mentioned issues. The aim of the first work is to introduce a negative permittivity artificial plasma metamaterial medium in the place of

metallic walls of conventional horn to reduce the weight of the antenna to negligibly small values. There is no much deviation for the radiation characteristics of the proposed design from that of the conventional metallic horn. As a second aim, a multiband monopole patch antenna using a negative permeability metamaterial broadside coupled split ring resonating structure (BCSRR) is developed. A frequency tunable BCSRR loaded monopole patch antenna which will cover all the frequencies of potential communication applications is also constructed. A single unit of these novel antennas can eliminate the requirement of additional number of conventional monopole antennas in any wireless communication device.

1.4 Thesis outline

The present work brings out the idea of extending the use of electromagnetic metamaterial structures into the microwave communication field to make use of its negative permittivity and permeability effects on the antenna parameters. The horn antennas and monopole antennas are widely used in different communication applications from the beginning stages of microwave wireless communication technology. Several basic structural alterations have been made in these conventional antennas with a purpose of enhancing its radiation characteristics in order to achieve the requirements of the communication scenario. After the invention of metamaterial structures, researchers drew their attention to avail the additional benefits of applying metamaterial properties in these antenna structures. This thesis describes how the novel metamaterial structures worthily enhance the use of the horn and monopole patch antennas in the potential wireless communication field.

The present chapter discusses the historical evolution of metamaterials, their applications in different fields with a special emphasis to the negative permittivity and permeability structures. Since the present work is related with the metamaterial ap-

plication in microwave antenna area, a brief outline about different microwave antenna and their applications are given.

In chapter 2, an introduction of metamaterial inspired structures is given. Recent developments in the field of communication using meta inspired structures is also discussed in detail. Since the research work is associated with the metamaterial inspired structures like wire medium, circular split ring resonator and broadside coupled split ring resonator, the theory behind the negative permittivity and negative permeability behavior is presented. A review of the past works related with the metamaterial inspired structures is also given. The scope and importance of the present work in the current scenario is discussed at the end of the chapter.

In chapter 3, a detailed discussion about the experimental set up, measurement methods and antenna fabrication methods is presented. At the beginning of the chapter, the details about the Vector Network Analyzer (VNA) used and the anechoic chamber are given. The antenna parameters measured in the case of horn antenna is then described. To study the radiation characteristics of horn antenna, the parameters like axial gain, radiation pattern, Half Power Beam Width (HPBW), side lobe level and VSWR are explained. In the case of monopole antennas, the parameters like reflection coefficient, bandwidth, antenna gain and radiation pattern are explained. The fabrication methods adopted for making single layer plasma horn antenna, multilayer plasma horn antenna, S-band plasma horn antenna, C-band plasma horn antenna, single circular split ring resonator loaded monopole antenna, broadside coupled split ring resonator loaded multiband monopole antenna and frequency tunable broadside coupled split ring resonator loaded monopole antenna are presented.

In chapter 4, metamaterial inspired negative permittivity horn antenna is introduced which is fabricated using a single slab of thin metallic wires in a specialized

manner and is observed to have same radiation performance of an equivalent conventional metallic horn structure. This novel plasma antenna can replace the conventional one in all microwave applications. The featherlight weight and the ability to remove the problems related with wind resistance and rain accumulation of this new structure may result in a rethinking of the use of horn antennas in astronomical data collection. The radiation characteristics studies of the antenna like axial gain, radiation pattern, HPBW, side lobe level and VSWR are presented. Multilayer plasma horn antenna is also fabricated and its radiation characteristics are studied in comparison with the single layer structure. Measurements are carried out for horns fabricated in X-band, S-band and C-band frequencies and their radiation behavior is compared with metallic counterparts.

In chapter 5, the study of negative permeability metamaterial effect on monopole antenna is presented. The coupling between a single circular split ring resonating structure and the monopole for tuning the radiating frequency over a wide bandwidth is discussed. The study of antenna parameters like return loss, antenna gain, bandwidth and radiation pattern are done. The study is extended to broadside coupled split ring resonator loaded monopole patch antenna. The frequency tunability of the proposed antenna is explored. The possibility of replacing different antennas for different applications in a single device with a single proposed frequency tunable BCSRR loaded monopole antenna is envisaged. The possibility of multiband operation employing two units of BCSRRs loaded on the two sides of a monopole patch antenna is also discussed. The study of antenna parameters and their analysis are also included.

Chapter 6 gives a summary of the works presented in the thesis. The inclusion of the meta inspired structures into the world of antennas along with the possible advantages are detailed. The chapter also discusses the relevance of the present study and its scope for future works.

CHAPTER 2

Review on Metamaterial Inspired Antennas

2.1 Introduction

In last chapter, the historical evolution of metamaterials along with their manifold applications was discussed. The periodic arrangement of certain artificially engineered structural unit cells in a subwavelength scale makes meta medium a homogeneous one. This homogeneous medium exhibits unique properties for a certain range of frequencies. In the metamaterial application arena, the presence of this metamaterial homogeneous medium is often seen to transform some conventional structures appropriate to specific applications. Such a bulk homogeneous medium is called as ‘metamaterial based structures’. But in some applications, a few number of metamaterial unit cells or even single unit cell is enough to produce metamaterial effects in the conventional struc-

tures. Such types of structures are known as ‘metamaterial inspired structures’. The unit cells mimic the metamaterial properties of the bulk homogeneous medium. A detailed study of distinguishing metamaterial based structures and metamaterial inspired structures can be seen in several research papers [82, 83, 84, 85].

A variety of metamaterial inspired structures is investigated for different applications in diverse fields. A one dimensional microwave displacement sensor based on metamaterial inspired structure is reported by Horestani et al [86]. It has advantages of high dynamic range and linearity compared to the ordinary microwave sensors. A sensitive vibration sensor capable of detecting even weak ground vibrations based on metamaterial inspired structure is reported by Sikha et al [33]. It finds applications in tamper proofing, earth quake sensing, quarrying and mining. A direct and efficient method for complex permittivity measurement of materials at microwave frequencies by considering the near field distributions using a metamaterial inspired structure is proposed by Sreedevi et al [87]. Some other methods are also reported for determining permittivity using meta inspired structures [88, 89].

Kaur et al. [90] proposed a dual band metamaterial inspired microwave absorber having wide incidence angle and polarization insensitivity for energy harvesting applications in Global System for Mobile (GSM) and Industrial, Scientific and Medical (ISM) bands. Different types of metamaterial inspired vacuum electron devices such as metamaterial inspired reversed cerenkov oscillator [91], metamaterial enhanced resistive wall amplifiers [92], metamaterial inspired microwave generator [93], metamaterial inspired slow wave structures for other vacuum electron devices [94] etc. are investigated by various research groups. These devices have more advantages than ordinary vacuum electron devices in terms of high gain, high efficiency, small size and high power. They find promising applications in electronic communications, radar, electronic warfare, accelerators, imaging, microwave heating and many other areas [95, 96, 97, 98, 99].

A compact metamaterial inspired band pass filter which does not require an external matching network is reported by Palandoken et al [100].

Recent developments using metamaterial inspired properties in nanostructures are described by Isabelle Staude et al [101]. It describes how the silicon nanostructures behave with metamaterial inspired structures and its future applications and scopes. The recently reported metamaterial inspired electroelastic systems are capable of structure-borne wave energy harvesting. These metamaterial energy harvesting systems convert the incoming structure-borne wave energy into electrical signals by coupling the metamaterial components with electroelastic domain [102]. Another important application of metamaterial inspired structures are in the area of antennas. Since the present work is related with microwave antennas, a detailed discussion about metamaterial inspired antennas and its theoretical background are given in the following sections.

2.2 Metamaterial inspired antennas

The idea of employing metamaterial medium in the near field of conventional antennas was a quest of antenna researchers to miniaturize the size of the antenna and to explore characteristics modifications. The above research resulted in several interesting findings such as enhanced radiation performance, better performance bandwidth, directivity and increased antenna gain. The concept of introducing metamaterial medium into the antenna field was first realized by Nader Engheta [103] in the case of one dimensional resonators. The idea was further extended to other types of microwave antennas like monopole antennas, dipole antennas [104], leaky wave antennas [105] and patch antennas [106].

The bulk metamaterial medium is considered as a homogeneous medium and its properties are determined by macroscopic parameters - electric permittivity and mag-

netic permeability - governed by the dispersion laws. But in the reported works, instead of a homogeneous bulk medium, only a few inclusions of metamaterial unit cells or single unit cell are used. The unit cell exactly mimicked the metamaterial medium by giving its properties like negative permittivity or negative permeability. Thus an antenna included with single metamaterial sample or a few of it in its near field gives additional benefits of a bulk metamaterial medium. Now these antenna structures are called as metamaterial inspired antennas since the design of antennas has been realized by applying metamaterial concepts.

Now there are three ambiguities arising in considering the single metamaterial sample or a few of it as a medium for producing metamaterial properties. The first one is associated with the inherent anisotropy of the single structure, the second one is related with its dimensions and the third one is its design to achieve the same macroscopic parameters of the bulk medium. These three issues are satisfactorily discussed by F. Bilotti et al. [82] by taking a couple of examples concerned with the two types of metamaterial based antennas i.e. negative permittivity based [105] and negative permeability based antennas [106].

The issue of the inherent anisotropy of the metamaterial inclusions can be solved by the proper alignment of the inclusions, according to the electric and magnetic field polarizations at the near field of the antenna. Considering the second issue in determining the size of the inclusions, Alu et al. [105, 106] substantiated that, in principle, there is no theoretical limit in the size of the metamaterial inclusions loaded on the two previously mentioned negative parameter based antenna structures. Some practical models of artificial magnetic inclusions and artificial electric inclusions are given by F. Bilotti et al. [107, 108] and S. Hrabar et al [109, 110]. They conclude that the electrically smaller inclusions will cause narrowing of operating bandwidth. The third issue in considering the inclusion as a homogeneous bulk medium is theoretically dis-

cussed by M.G. Silveirinha et al [111, 112]. Since the electromagnetic fields interacting with the inclusion are linearly polarized in the reactive near field of the antenna, the inclusion should be designed in such a way that it exactly behaves like an ideal metamaterial for this polarization and angle of incidence. Even though the present material parameters of the inclusion cannot be considered as the constitutive parameters of the bulk medium, it can stand as the operational definition for the effective parameters of the specific inclusion at hand with the metamaterial effect.

Since the present work deals with the application of metamaterial inspired negative permittivity structure into horn antenna and metamaterial inspired negative permeability structure into monopole patch antenna, a detailed discussion about these structures is given in the following sections.

2.3 Metamaterial inspired negative permittivity antenna structures

In the previous chapter, we have discussed briefly how an array of wire medium acts as an artificial plasma medium below its plasma frequency with a negative permittivity. It reflects the electromagnetic waves of frequencies below the plasma frequency but transmits the waves above this frequency. Many researchers have reported the advantages of the metamaterial inspired negative permittivity structures in microwave antennas. Instead of a bulk homogeneous metal medium, a few inclusions of certain types of wire medium have mimicked the negative permittivity structure properties in terms of effective medium parameters. A review of their attempts and results is briefly explained in the following section.

2.3.1 Review on metamaterial inspired negative permittivity antennas

Metamaterial inspired structures have brought significant changes in the microwave antenna world. A better control over the radiation performance of antennas is achieved

by the invasion of metamaterial inspired structures into antenna theory. The requirements of specific systems or situations concerned with the antenna performance can be easily procured by means of certain metamaterial inspired structures. It includes advantages in antenna miniaturization, antenna gain, directivity, beamwidth, cost of production etc. The scientific reports indicating the advantages of artificially engineered negative permittivity inspired structures in microwave antennas are discussed below, giving a special emphasis on horn antenna.

A. Jafargholi et al. [113] investigated the effect of loading epsilon-near-zero wire metamaterial unit near to a microstrip patch antenna. It has significantly increased the bandwidth of the antenna. A. Erentok et al. [84] presented metamaterial inspired efficient electrically small antennas which are naturally matched to a $50\ \Omega$ source without using a matching network. They promised high radiation efficiency with very good impedance matching between the source and antenna. C. Arora et al. [114] proposed a microstrip patch antenna array with a metamaterial inspired superstrate using wire strips to improve gain and bandwidth.

Several variants of traditional horn structure including modifications using metamaterial inspired wire medium have been presented in the past years to enhance its radiation performances. In their work, Mei Qing Qi et al. [115] loaded a metamaterial lens inside the horn antenna to achieve a tapered amplitude distribution at the aperture field which, in turn, suppressed the side lobe radiations. P. Duangtang et al. [116] inserted a metamaterial wire medium at the conical horn aperture to improve the gain of the conventional conical horn without changing the antenna dimensions.

H. Shi et al. [117] constructed an anisotropic metamaterial slab and inserted at the horn aperture to turn a linearly polarized wave from the horn to a circularly polarized one. P Kamphikul et al. [118] proposed a metamaterial inspired structure of curved-

woodpile electromagnetic band gap for the improvement of gain of a conventional rectangular horn antenna.

A Tomaz et al. [119] reported a directivity enhanced horn antenna by loading a wire medium inside the horn. A comparative study of conventional horn and wire medium inserted horn by analysing both the experimental and simulation results is given in their work. S. Hrabar et al. [120] investigated an epsilon-near-zero metamaterial structure to shorten the length of the horn without reducing the gain. C.P. Scarborough et al. [121] presented a metamaterial enabled low side lobe horn with a E-plane metamaterial free standing wire grid for a linearly polarized feed horn in the super-extended C-band meant for satellite reflector antennas.

The applications of various types of negative permittivity metamaterial inspired structures in microwave antennas, especially in horn antennas have been discussed. In the following section, a description of theory behind the negative permittivity behavior of the wire medium is given.

2.3.2 Theory behind the negative permittivity behavior of wire medium

A brief outline of investigations on a negative permittivity structure is discussed in section 1.1.2. The researchers were seriously trying to make a medium showing negative permittivity since 1940. These investigations have gradually led to the realization of a negative permittivity medium using an array of thin wires by J. B. Pendry et al. A brief theory regarding the negative permittivity behavior of a wire medium is given below.

The interaction of an electromagnetic wave with materials is mostly dependent on its electric permittivity. For a metal the electric permittivity is a function of frequency of the interacting wave. According to the Drude free electron model, the frequency

dependence of permittivity function is given by

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega} \quad (2.1)$$

where ‘ Γ ’ is the damping factor which gives the electron collision rate and ‘ ω_p ’ is the plasma frequency given by

$$\omega_p = \sqrt{\frac{Ne^2}{\varepsilon_0 m}} \quad (2.2)$$

where ‘ N ’ is the electron density, ‘ e ’ is the electric charge of an electron and ‘ m ’ is the mass of the electron. For all incident frequencies below the plasma frequency, the metal reflects the electromagnetic wave and for frequencies above the plasma frequency it transmits the wave. But the plasma frequency for a good conducting metal is usually near to the UV spectrum. Since our frequency of interest is microwave, the plasma frequency should be lowered. Sir J. B. Pendry [20, 122] proposed an array of wire medium in the place of bulk metal medium to lower the plasma frequency into microwave range and explained its properties on the basis of effective medium approach.

Consider an array of wire medium arranged in a two dimensional manner such a way that the electric polarization of the external electromagnetic wave is parallel to the wires as shown in the Fig. 2.1. This can be taken as a homogeneous effective medium for the external electromagnetic wave, since the wires are arranged in subwavelength scale in the array so that the wave cannot ‘see’ the properties of individual wires, but can only ‘feel’ the macroscopic effective properties of the bulk wire medium. Now the permittivity $\varepsilon(\omega)$ in equation 2.1 changes to the effective medium permittivity function $\varepsilon_{eff}(\omega)$ given by

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega} \quad (2.3)$$

where the two parameters ‘ Γ ’ and ‘ ω_p ’ are depend on the geometry of the wire array

and the material properties.

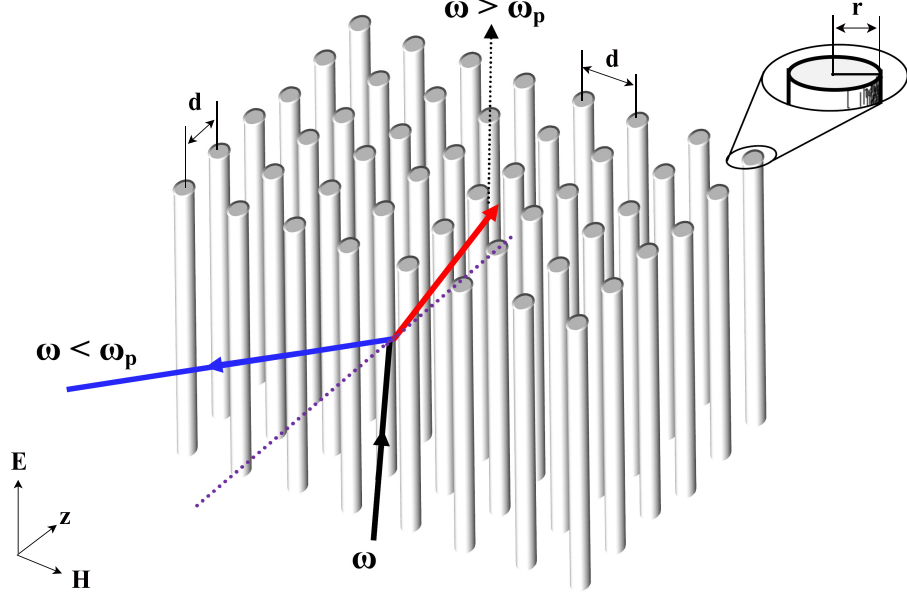


Figure 2.1: A schematic representation of interaction of electromagnetic wave having angular frequency ω with a plasma wire medium. ω_p represents the plasma frequency of the wire medium.

The plasma frequency of wire medium is lowered to the microwave frequency ranges because of the changes in the two parameters, say electron density and electron mass of the bulk metal medium. The effective electron density of the wire medium is substantially lower compared to bulk metal since most of the volume occupied by the bulk metal is now replaced with thin wires of the artificial medium. So the effective electron density reduces by a factor, $\frac{\pi r^2}{d^2}$ such that it becomes, in a volume averaged manner as,

$$N_{eff} = N \frac{\pi r^2}{d^2} \quad (2.4)$$

where 'r' is the radius of the wire, 'd' is the lattice parameter and 'N' is the actual electron density of the bulk metal.

The reason for increase in effective electron mass is satisfactorily explained by Pendry [20]. The interaction of time varying electromagnetic wave with the wires will induce a time varying current in the wires. This time varying current produces a self inductance in the wire which opposes the rate of change of current in the wire, according to Lenz's law. This will reduce the velocity of electrons in the wire and now the effective mass of the electron is considered to be increased due to the momentum conservation.

Pendry estimated this effective mass of electron by applying the concepts of generalized momentum and magnetic vector potential 'A' with certain conditions. The conditions are (1) the radius of the wire in the wire array should be much less than the lattice parameter between the wires in the array, (2) the lattice parameter should be equal in two directions and (3) the wires are made from a good conductor such that the free electrons are confined in the surface of the wires. Now the effective mass of electron in this environment takes the form [20],

$$m_{eff} = \frac{\mu_0 r^2 e^2 N}{2} \ln\left(\frac{d}{r}\right) \quad (2.5)$$

Now the plasma frequency of the effective medium of wire array by equation 2.2 is

$$\omega_p^2 = \frac{N_{eff} e^2}{\varepsilon_0 m_{eff}} = \frac{2\pi c^2}{d^2 \ln\left(\frac{d}{r}\right)} \quad (2.6)$$

Several other theoretical derivations are seen in some other works [123, 124, 125, 126]. If the radius of the wire is so chosen as it is less than one tenth of the lattice parameter 'd', the plasma frequency [127] can be estimated to

$$f_p = c \left(d \sqrt{2\pi \left[\ln \frac{d}{2\pi r} + 0.5275 \right]} \right)^{-1} \quad (2.7)$$

If the wires are made of perfect conductor, the damping constant in equation 2.3 vanishes. Then the effective permittivity function by equation 2.3 becomes

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad (2.8)$$

Since the real metals shows a finite conductivity, there will be an ohmic loss in conducting wires which will modify the inductance of the wire with an imaginary part and it is approximated to

$$L \rightarrow L + \frac{\sigma \pi r^2}{i\omega} \quad (2.9)$$

where σ is the conductivity of the wire. Taking the new inductance into the consideration and the corresponding changes in plasma frequency, the effective permittivity function [4] becomes

$$\varepsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega(\frac{\omega + i\varepsilon_0 d^2 \omega_p^2}{\pi r^2 \sigma})} \quad (2.10)$$

Thus the effective plasma frequency depends only on the geometry of wire array, one can easily bring down the plasma frequency into microwave frequency region. The permittivity becomes negative for waves with frequencies less than the effective plasma frequency and it will get reflected from the wire array. It becomes positive for the frequencies above plasma frequency and now the array acts as transparent medium. A schematic representation of this process is also shown in Fig. 2.1.

2.4 Metamaterial inspired negative permeability antenna structures

A metamaterial inspired negative permeability antenna structure usually consists of a radiating antenna and single negative permeability unit cell which will be an electrically small resonator. The unit cell resonator is placed very near to the feeding

section of patch radiator in such a way that it can easily interact with the fields of the radiator. In this case a better impedance matching is provided by the metamaterial inspired structure to the antenna so that it can be easily matched to the source without any matching circuit and offers a very good overall efficiency. Several types of metamaterial inspired elements are investigated and the results obtained by experimental methods are in good agreement with that of the simulation methods.

In the present research work, the metamaterial inspired elements like single circular Split Ring Resonator (SRR) and Broadside Coupled Split Ring Resonator (BCSRR) are used. The radiation properties of monopole patch antenna with coaxial feed is modified with SRR and BCSRR. The following section gives a review of the past works done in the area of patch antennas modified with metamaterial resonating elements.

2.4.1 Review on metamaterial inspired negative permeability antennas

Metamaterial inspired negative permeability antenna structures have been reported by different researchers. Most of them used resonator type metamaterials for their miniaturization technique, gain enhancement and increased bandwidth. Researchers have tested differently shaped resonating structures according to the required alignment and geometrical conditions of a metamaterial unit cell. It gave additional benefits compared to the conventional antennas which made them popular in the communication field. A literature review of metamaterial inspired monopole patch antennas is briefed below to understand the recent developments in the field.

Raoul O. Ouedraogo et al. [50] reported highly miniaturized patch antenna using complementary split-ring resonators placed horizontally between the patch and the ground plane. A good impedance match and radiation characteristics are achieved by optimizing the geometry of the split rings for the sub-wavelength resonance of the patch antenna. V. Rajeshkumar et al. [128] presented a compact triple band antenna

by employing a rectangular slot and a metamaterial inspired split ring structure for stable radiation patterns with low cross polarization and high average antenna gain. J. G. Joshi et al. [129] presented a rectangular microstrip patch antenna loaded by metamaterial inspired planar square split ring resonators.

M. A. Rahman et al. [130] proposed a circularly split ring resonator based frequency reconfigurable antenna in which antenna can be used to switch between two different frequency responses. H. Cheribi et al. [131] proposed another type of frequency reconfigurable antenna with two double split ring resonators of different size which was excited by a co-planar fed monopole patch antenna. They created new resonances and notches at different frequencies which can be controlled by inserting switches at the slits. R. S. Daniel et al. [132] presented a multiband monopole antenna loaded with complementary split ring resonator for GSM, Wi-Max and C-band applications.

M. Barbuto et al. [133] proposed a multifunctional SRR loaded monopole antenna in which four switches are used to control four radiation frequencies which find applications in mobile communications. A dual band metamaterial inspired monopole antenna is presented by S Sahu et al [134]. In their work, a 5-element linear array of hexagonal omega metamaterial structure is loaded near the monopole patch to obtain a dual band operation. D. Sarkar et al. [135] proposed a triple-band dual-polarized monopole antenna using a rectangular complementary split-ring resonator and an inverted L shaped slit in which a linearly polarized quasi-monopolar radiation pattern was produced by the resonator.

Another type of dual-band metamaterial-inspired small monopole antenna is reported by J. Zhu et al. [136] for WiFi applications. C. Li-Li [137] investigated circularly polarized patch antenna which can achieve low radar cross section and high gain per-

formance by using a metamaterial superstrate. F Bilotti et al. [138] has explained in detail about the designing of different μ -negative metamaterial inspired monopole patch antennas. T. K. Upadhyaya et al. [139] proposed an engineered tunable dual-band metamaterial antenna based on stacked split ring resonator array. This μ -negative SRR array fixed at two sublayers of stacked microstrip patch antenna substrate offered tuning capability to the antenna with marginal trade-off between antenna gain and cross-polarization.

J. Choi et al. [140] introduced a frequency reconfigurable metamaterial resonant antenna in which a mushroom structure-based zeroth order resonant antenna is used. Y. Lee et al. [141] presented a microstrip patch antenna on metamaterial substrates loaded with complementary split-ring resonators which gave additional benefits like size reduction and bandwidth improvement. Sulaiman et al. [142] proposed an omega shaped metamaterial unit which is used as a substrate of patch antenna. The size reduction and improvement in return loss were the highlights of the antenna, but it was only suitable for narrow band applications.

2.4.2 Theory behind the negative permeability behavior of single ring SRR

The idea of manipulating the metamaterial properties, in this case negative permeability, into the artificially engineered structures can be understood from the study of the magnetic field interaction with a circular metal plate. In this section, a theoretical study is undertaken to discuss how a structure like single split ring resonator came into the scene of metamaterials from a simple circular metal plate.

Consider a circular metal plate placed in a time varying electromagnetic field in such a way that the magnetic field vector is normal to the flat surface of the circular plate (Fig. 2.2 (a)). It can be observed that there is an interaction between the magnetic field and the circular metal plate even though it is very weak. The interaction is

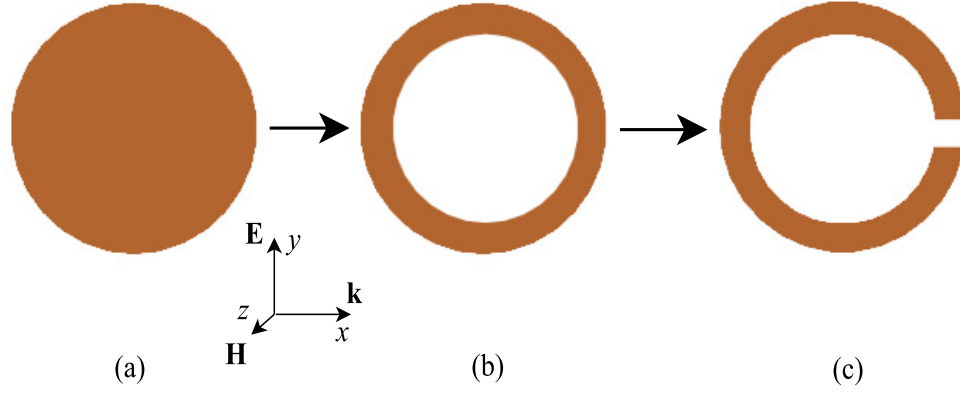


Figure 2.2: Schematic representation of evolution of SRR from circular metallic plate.

according to Faraday's law of electromagnetic induction i.e. the time varying magnetic field induces a time varying circular current in the round metal plate. Then according to Lenz's law, a principle of conservation of charge, this current produces a magnetic flux in such a direction that which will oppose the change in external magnetic field. Since this behavior is of diamagnetic nature, in this environment the circular metallic plate can be considered as a diamagnetic structure whose permeability is slightly less than unity.

Moreover the circular current induced in the round metallic plate is confined mostly in its outer perimeter [21]. Hence there is no role for the inner part of the metallic plate in this scene. After removing the inner part, now the circular metallic plate evolves into a thin annular ring (Fig. 2.2 (b)). In fact, the response of this metallic annular ring to the external time varying field is purely inductive in nature and also a metallic ring structure cannot show a resonant behavior. If a capacitance behavior is added to the ring, then it will offer a chance for resonance. That is, a resonance behavior can be created in the ring due to the oscillations produced by the inductance and the capacitance.

In order to introduce a capacitance associated with the ring, a small split is made in the ring which causes a break in the path of circular current as depicted in Fig. 2.2 (c). Thus a charge accumulation of opposite polarity is formed across the splits when it is excited with the external magnetic field and now the ring acquires a capacitive behavior. The new structure shows a LC resonance behavior and it is called as a single Split Ring Resonating structure (SRR). The resonant frequency is given by

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (2.11)$$

where L is the inductance determined by the height and width of the ring and C is the capacitance at the split. The split can be approximated as a parallel plate capacitor. The evolved magnetic dipole moment depends on the magnetic polarizability dyadic tensor (α_{zz}^{mm}) and this tensor is related with the frequency of the electromagnetic wave as [143]

$$\alpha_{zz}^{mm} \propto \left(\frac{\omega_0^2}{\omega^2} - 1 \right)^{-1} \quad (2.12)$$

From this equation, we can infer that the polarizability tensor tends to high negative value at frequencies higher than the resonant frequency and the corresponding magnetic dipole moment becomes negative and give permeability a negative value. This happens immediately after the resonant frequency and when the resonant frequency becomes high, due to inertial effects, no induction triggers.

Moreover a cross polarization is occurred due to the introduction of the gap in the ring. A magnetic polarization is generated in the z-direction by electric field and an electric polarization is generated by magnetic field in y-direction. Hence the single SRR is considered as an anisotropic medium. It is undesired as the electric polarization overshadows the magnetic polarization and the magnetic response is reduced.

2.4.3 Theory behind the negative permeability behavior of ECSRR and BCSRR

In the previous section the evolution of a single circular ring from a circular metal plate is detailed whereby the magnetic response to the electromagnetic wave is seen enhanced. The gap introduced in the ring is able to provide a capacitance behavior to the ring which in turn gives a resonance property. Moreover the gap introduces an electric polarizability in the single SRR as the accumulated charges across the gap induce a noticeable electric dipole moment which overacts the desired magnetic dipole moment [144].

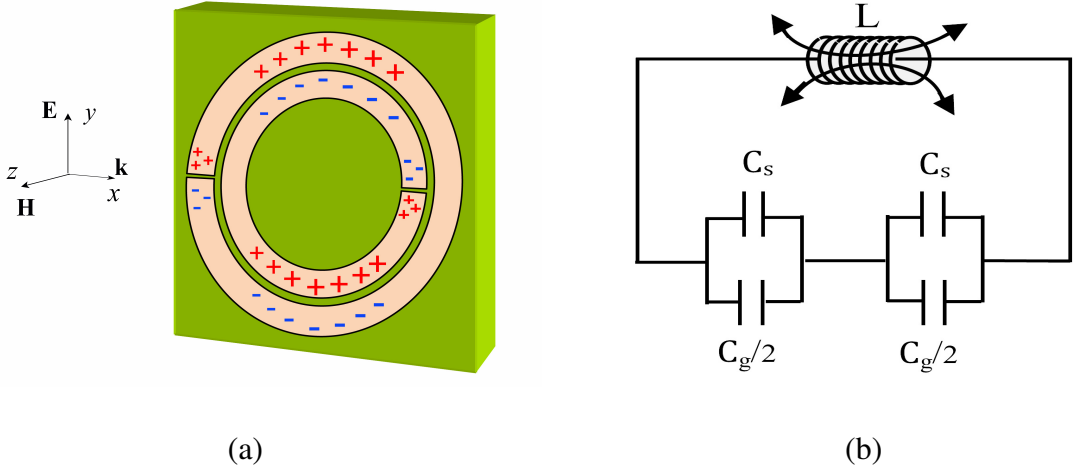


Figure 2.3: (a) A schematic representation of an ECSRR with magnetic field vector of the excited electromagnetic wave along the z-direction and (b) equivalent circuit of ECSRR in terms of L and C .

However the capacitance can be further increased by making some changes in the ring structure. An additional ring with a slight difference in diameter is placed concentrically to the first ring in the same plane with their splits coming opposite to each other as shown in Fig. 2.3 (a). The new structure is formed to act as a metamaterial

atom and is known as Edge Coupled SRR (ECSRR). The ECSRR structure essentially produces a quasistatic LC resonance with the external electromagnetic field. An equivalent circuit of the resonator is shown in Fig. 2.3 (b) [145].

Consider an ECSRR particle as shown in the Fig. 2.3 (a). An external time varying magnetic field is applied along the z-direction i.e. normal to the plane of SRR. An electromotive force is induced across the rings and hence an electric current will flow through the rings creating a total magnetic dipole moment in the ring. The gap between the rings behaves like a distributed capacitance and C represents the capacitance per unit length of the rings. If C_g represents the total capacitance between the rings, then the capacitance of the each half of the ECSRR dividing along the xz plane becomes $\frac{C_g}{2}$ such that total gap capacitance becomes $\frac{C_g}{4}$. The split capacitance represented by C_s formed by the quasi-static voltages at the split is very small in comparison with capacitance across the gap between the rings. The total inductance of the rings is represented by L . According to the detailed analysis given in the [144], the resonant frequency is given as

$$\omega_0^2 \simeq \frac{2}{\pi r_0 C L} \quad (2.13)$$

where r_0 is the average radius of the ECSRR structure. From this equation we can understand that the ECSRR behaves essentially like a LC resonant circuit. This quasi static analysis also accounts for a magnetic dipole moment along the z-direction as discussed earlier and it is estimated to [143]

$$m_z = \alpha_{zz}^{mm} B_z^{ext} \quad (2.14)$$

where α_{zz}^{mm} is the polarizability dyadic tensor which represents the z-directed magnetic polarizability due to z-directed external magnetic field, B_z^{ext} . The approximate value

of this z-directed magnetic polarizability is given as

$$\alpha_{zz}^{mm} \simeq \frac{\pi^2 r_0^4}{L} \left(\frac{\omega_0^2}{\omega^2} - 1 \right)^{-1} \quad (2.15)$$

It shows that the magnetic polarizability attains a high negative value when the frequency of the excited electromagnetic wave is greater than the resonant frequency of the ECSRR. Then the magnetic dipole moment will align in the opposite direction of the magnetic field of the external wave and hence the ECSRR shows a diamagnetic behavior which leads to a negative permeability at frequencies just above resonance.

Moreover a careful observation leads to the fact that the ECSRR not only behaves as a magnetic dipole but also an electric dipole. But this is expected as the quasi-static charges and potentials developed in the rings produce an electric dipole moment along the y-direction. A detailed analysis gives an estimated value for this electric dipole moment as [143]

$$p_y = i\alpha_{yz}^{em} B_z^{ext} \quad (2.16)$$

where α_{yz}^{em} is the electric polarizability produced along the y-direction due to the external magnetic field in the z-direction and is estimated to

$$\alpha_{yz}^{em} = 2\omega_0 \pi r_0^3 C_0 d_{eff} \frac{\omega_0}{\omega} \left(\frac{\omega_0^2}{\omega^2} - 1 \right)^{-1} \quad (2.17)$$

where C_0 is the capacitance per unit length when the dielectric is removed as explained in [143] and d_{eff} is the effective gap between the two rings.

Due to these effects, the ECSRR exhibits the unwanted anisotropic property. But compared to single SRR, the electric polarizability is reduced by introducing the second ring concentrically to it having an opposite split. The electric dipole moments due to the outer ring and the inner ring are in opposite direction, but due to the difference in

the diameters of the rings, the electric dipole moments will not completely cancel out. It gives a net value in the y-direction.

In the study of R. Marques et al. [24, 143, 146], they have investigated a further anisotropy in ECSRR. By applying Onsager symmetry principle [147] to eqn. 2.16, it is obtained that the electric field along the y-direction of the ring due to the excited electromagnetic wave also results in a magnetic dipole moment along the z-direction. In their work, the possibility of electric dipole moment in x and y-directions of the ring are also discussed and given as

$$p_x = \alpha_{xx}^{ee} E_x^{ext} \quad (2.18)$$

$$p_y = \alpha_{yy}^{ee} E_y^{ext} + i\alpha_{yz}^{em} B_z^{ext} \quad (2.19)$$

where α_{xx}^{ee} is the x-directed electric plarizability produced due to the x-directed external electric field E_x^{ext} and α_{yy}^{ee} is the y-directed electric polarizability produced due to y-directed external electric field E_y^{ext} .

Now the total magnetic dipole moment along the z-direction is given by

$$m_z = -i\alpha_{yz}^{em} E_y^{ext} + \alpha_{zz}^{mm} B_z^{ext}. \quad (2.20)$$

From these observations, we can describe the ECSRR particle as a bi-anisotropic particle.

In order to avoid this undesired bi-anisotropic behavior of the negative permeability ECSRR structure, R. Marques et al. proposed a new structure called as Broadside Coupled Split Ring Resonating structure (BCSRR). They have made slight modification in the ECSRR structure to eliminate the magnetoelectric coupling existing in it so as to avoid the bi-anisotropy while keeping all of its other interesting features. The structure is modified as follows. One ring, say, the inner ring of the ECSRR is removed

and another ring of same dimensions of the outer ring is fabricated and placed just behind the outer ring such as the splits still coming opposite as shown in the Fig. 2.4 or in other words two rings of same dimensions with splits at opposite ends are fabricated on either side of a substrate.

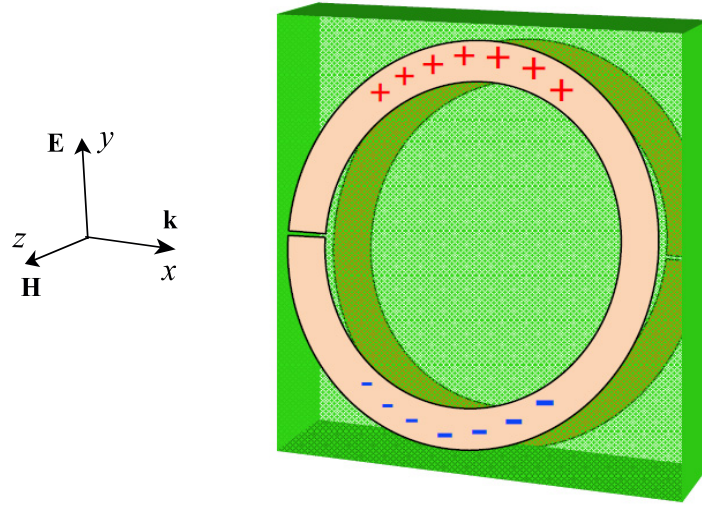


Figure 2.4: A schematic representation of a BCSRR unit with magnetic field vector of the excited electromagnetic wave along the z-direction.

Now, an excitation of magnetic field of electromagnetic wave along the z-direction of the ring induces electric currents in the rings according to Fleming's law, as described in the case of ECSRR. If L represents the total inductance of the BCSRR rings and C represents capacitance per unit length between the rings, the magnetic polarizability takes the same form of equation 2.15. The equivalent circuit is also same as that of the ECSRR as shown in the Fig. 2.3 (b) even though there are differences in magnitudes of capacitance and inductance.

Induced electric current produces charge accumulation in rings in such a way that there is no net electric polarization remaining in the structure. That is if we divide

the BCSRR unit along a plane containing both splits, the charges accumulated in one part is exactly opposite in polarity of the other part. This cancellation of electric polarization avoids the magnetoelectric coupling in BCSRR particle and hence the bi-anisotropy, compared to the ECSRR structure. All other features of the BCSRR remains almost same as in ECSRR.

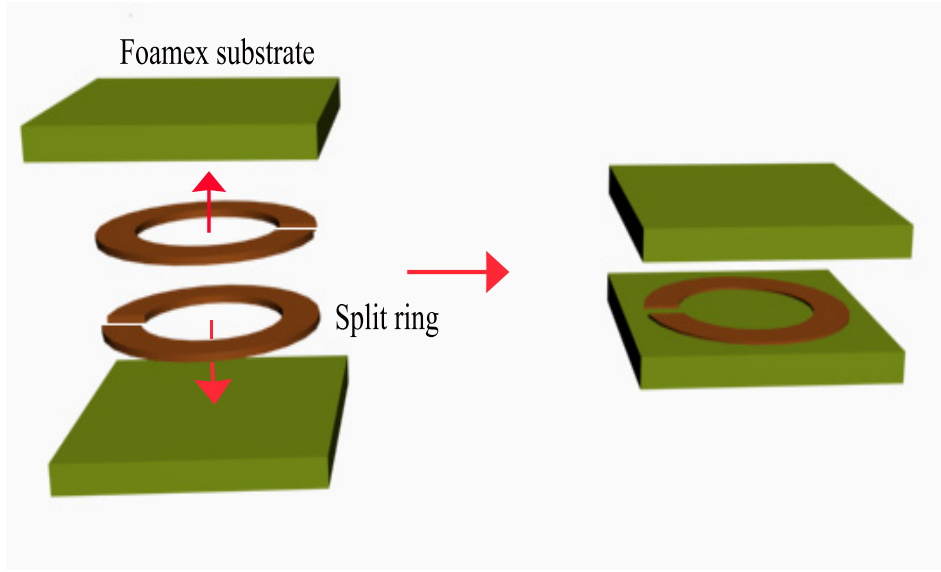


Figure 2.5: BCSRR fabricated by two separately made thin copper rings.

Moreover, the BCSRR structure provides an additional interesting feature if it is fabricated in a novel way as reported by Sikha et al [33]. Instead of making the two rings on either side of a single dielectric, two rings are separately made and they are arranged in a coaxial manner as shown in Fig. 2.5. The capacitance per unit length between the rings of this novel BCSRR can be increased considerably compared to ECSRR structure by simply increasing the width of the rings and/or by reducing the spacing between the rings and/or by introducing a very thin dielectric slab between the rings having desired permittivity.

2.5 Scope of the present work

The present research work is an attempt to utilize the properties of metamaterial inspired structures to enhance the performance of microwave antennas, by considering metallic horn and monopole patch as test antennas. Since both types of antennas are widely used in microwave communication arena, the findings of the present research work are more significant in improvising their radiation properties. The fruitful results of the metamaterial inspired structures presented in this work may be achieved by two possible ways, one is with the negative permittivity structure and the other is with the negative permeability structure. These two experimentally verified and scientifically recognized metamaterial structures but with the novel ideas of manipulating their properties to the conventional horn and monopole patch antenna types may deliver augmented attributes to the communication field.

A novel type of artificial plasma horn antenna may be realized using a metamaterial inspired wire structure utilizing its negative permittivity behavior. The wire structure, which is designed to act as a plasma medium, will reflect the electromagnetic waves below the plasma frequency due to the negative permittivity behavior of plasma medium. The wire medium does not allow the waves to transmit through it as now it acts as a homogeneous medium below the plasma frequency. In this research work, this property of plasma wire medium is utilized to modify the metallic horn antenna by reducing its weight considerably. This modification may suit it to use in the areas like satellite communication where antenna weight is a major concern.

The other possibility proposed in this work is the modification of monopole patch antenna. Single circular SRR and Broadside Coupled Split Ring Resonator (BCSRR) are the suggested metamaterial inspired structures utilized to obtain negative permeability properties. These units exhibit resonance properties due to the inductance and

capacitance associated with their geometrical shapes. These metamaterial components absorb the electromagnetic energy from the reactive near field of monopole patch antenna which may result in re-radiating the energy. This may lead to an additional radiating frequency that may be achieved by the presence of metamaterial unit which in turn may give the additional benefit of multiband operation to the antenna. The resonant frequency can be adjusted by changing the inductance and capacitance associated with the metamaterial unit. This possibility may be utilized to construct frequency tunable antennas. Thus the motivation is to make a multiband and frequency tunable monopole patch antenna which covers all the frequencies of potential communication applications.

Thus this research work gives a scope in producing the antennas with added advantages discussed with the help of metamaterial inspired negative permittivity and negative permeability structures.

CHAPTER 3

Methodology: Measurements and Fabrication

3.1 Introduction

Nowadays a large number of antennas are proposed and constructed to meet the various requirements of the communication field. To describe the performance of different antennas, certain parameters are used and are generally known as antenna parameters. By measuring these parameters, the performance of antennas can be compared. Various types of measurement methods are used for calculating the antenna parameters. This chapter describes an overview of the experimental set up used for the study of these antenna parameters and the methods adopted for measuring these parameters. The fabrication methods used for constructing the proposed antennas are also discussed in this chapter.

3.2 Experimental setup

This section describes the major experimental facilities used for the present work to measure the antenna parameters accurately. It includes

- Vector network analyzer (VNA)
- Anechoic chamber
- Turn table
- Wide band dual ridge horn

Figure 3.1 gives the photograph of the above equipments and facilities used to analyze the radiation properties.

3.2.1 Vector network analyzer (VNA)

Vector network analyser is the main part of the antenna measurement setup. The radiation performance of an antenna can be monitored using the VNA in terms of S-parameters and its operation can be assessed to check the suitability for a specific system or situation. A portable type of Keysight N9915A Fieldfox VNA, as shown in the Fig. 3.1 (a), is used for the measurement. It has following important facilities to take the measurements effectively and easily.

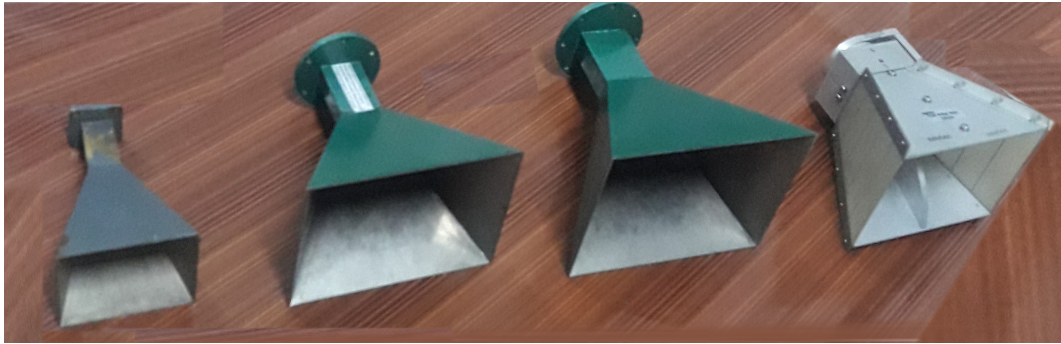
- It has two ports. Either of the two ports can be used as the source or the receiver.



(a)



(b)



(c)

Figure 3.1: Photographs of (a) vector network analyzer, (b) anechoic chamber in the form of a test box with the turn table placed inside and (c) wide band dual ridge horn (right end) along with X, C and S-band pyramidal metallic horn antennas.

- The four S-parameters, namely S_{11} , S_{12} , S_{21} and S_{22} which are a measure of reflection and transmission characteristics, can be taken simultaneously with a single connection.
- The amplitude and also the phase of the signal can be measured.
- It provides different types of calibration standards.

3.2.2 Anechoic chamber

Usually the antenna radiation characteristics are studied inside an anechoic chamber. Since the measurements are to be taken in a free space environment where the electromagnetic interference will be absent, the anechoic chamber provides such an atmosphere to take the readings of antenna parameters in a lab. The inner sides of the anechoic chamber are covered with microwave absorbing substances. And also the shape of these microwave absorbing substances are designed in such a way that the microwaves incident on them are completely absorbed by multiple reflection. It also reduces the external noise caused by the electromagnetic waves. For the present study a chamber in the form of an anechoic test box given in the Fig. 3.1 (b) is used.

3.2.3 Turn table

The turn table with the Antenna Under Test (AUT) mounted on it set inside the anechoic test box can be rotated to take its radiation pattern. The antenna can be easily rotated continuously or step by step with a defined angle. The time taken for a complete rotation with the options of changing dwell time, forward time for a step and hold time can also be predetermined. The alignments can be easily adjusted to position the antenna in the required direction. The turn table is a micro processor controlled one and all the settings for rotation can be done easily.

3.2.4 Wide band dual ridge horn antenna

A wide band dual ridge horn is used as a transmitter antenna and it can radiate frequencies efficiently in the range of 2 GHz - 18 GHz with proper antenna gain. It is also used as the reference antenna for measuring antenna gain of the AUT. The photograph of the wide band antenna along with S, C and X-band pyramidal horn

antennas used in this study is given in Fig. 3.1 (c).

3.3 Measurement of antenna parameters

This section deals with the commonly used antenna parameters to express the radiation performance of an antenna. In this present work, the following antenna parameters are measured to study the performance of the proposed antenna structures [148, 149]. They are

- Radiation pattern
- Half Power Beam Width (HPBW)
- Side lobe level
- Gain
- Voltage Standing Wave Ratio (VSWR)
- Return loss
- Antenna bandwidth

The methods adopted to take the measurement of antenna parameters are also discussed.

3.3.1 Radiation pattern

Radiation pattern of an antenna gives a graphical representation of the actual or relative field intensity at a fixed distance from the antenna as a function of space co-ordinates. A typical labeled rectangular radiation pattern of antenna showing the

main lobe and side lobes is given in Fig. 3.2. It is usually taken in the far field of the antenna since in the far field the plane wave characteristics will be obtained and the possible non-linear radiation terms will be of negligible magnitude. The condition for far field is that the distance between the transmitting and receiving antennas should be greater than the distance equal to $\frac{2D^2}{\lambda}$ where D is the larger aperture dimension of the antenna and λ is the wavelength of the electromagnetic wave.

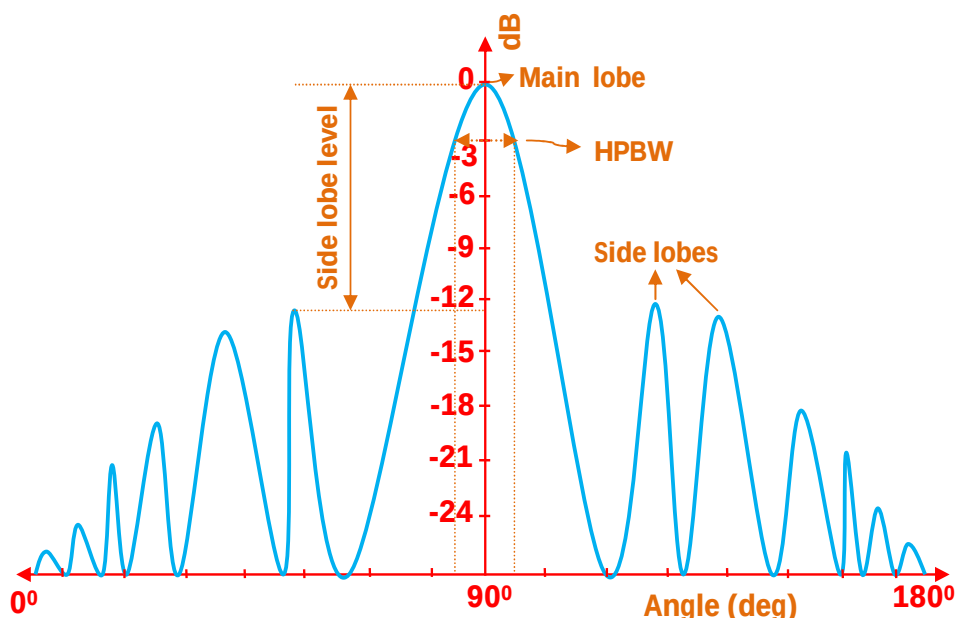


Figure 3.2: A schematic representation of radiation pattern of an antenna.

For measurement, the AUT is connected in receiving mode and it is rotated through an axis passing through the aperture plane of the test antenna while the transmitting antenna is kept stationary. Since the solid 3D free space radiation pattern cannot be shown adequately with the field strength data on a paper, usually 2D radiation patterns of two principal planes are drawn.

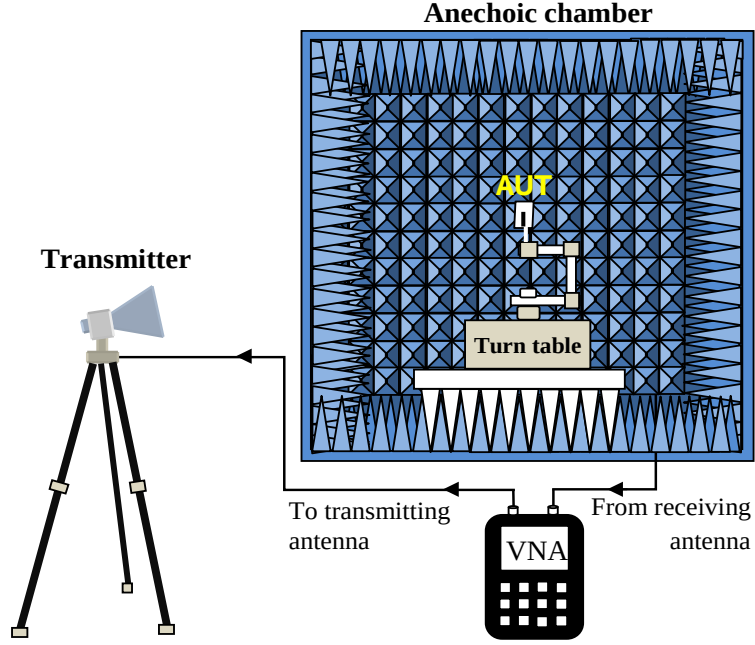


Figure 3.3: Schematic diagram of the radiation pattern measurement setup.

In the case of horn antenna, both the transmitter and receiver are placed face to face in the far field region with their $\mathbf{E}$ vectors in the same direction in order to get maximum S_{21} in the VNA. Afterwards, it is normalized. Now the E-plane radiation pattern also known as azimuthal pattern, is taken by rotating the AUT in the E-plane of the transmitting horn. Also the H-plane radiation pattern known as elevation pattern is taken by rotating the AUT in the H-plane of the transmitting horn. Similarly the E-plane and H-plane radiation patterns of the monopole patch antenna is taken by connecting it as the receiving antenna. These patterns are also called co-planar patterns since the planes of $\mathbf{E}$ and $\mathbf{H}$ vectors of both transmitting antenna and AUT are in the same direction. In order to check the possible polarization errors of the AUT, cross polar patterns are also taken after arranging the antennas with their $\mathbf{E}$ vectors

in perpendicular directions. A schematic representation of the experimental set up for plotting the radiation pattern is shown in Fig. 3.3.

3.3.2 Half Power Beam Width (HPBW)

The beam width of a pattern is the angular separation of two opposite identical points in the major lobe. Different types of beamwidths are defined. A most widely used beamwidth is the half power beamwidth (HPBW). It is the angular separation between the two opposite identical points in the major lobe of the power pattern, but the two points are 3 dB down with respect to the maximum. It is demonstrated in the Fig. 3.2.

3.3.3 Side lobe level

The side lobe of a radiation pattern is the largest minor lobe. It is usually adjacent to the main lobe (i.e. 1st side lobe). The side lobe level is measured as the difference between the main lobe maximum and the side lobe maximum of a normalized radiation pattern as shown in Fig. 3.2. A side lobe level of more than -10 dB is undesirable since a significant energy is radiated different from the intended direction. It will also affect the resolution of the antenna.

3.3.4 Gain

The parameter ‘gain’ gives a description about the performance of an antenna. It expresses how the antenna redistributes the input power efficiently at the output. Even though the gain is closely related to directivity, the latter only explains the directional property of the antenna, and not about its radiation efficiency. The gain is usually measured with respect to an isotropic antenna which radiates equally in all directions.

Thus the gain represents the measure of radiation intensity in a particular direction with respect to that of the isotropic antenna. The axial gain describes the gain in its axial direction.

Even though there are other methods to measure the gain of an antenna, in this thesis the gain transfer method is used [149, 150]. Two wide band horns, whose gain chart with respect to an isotropic antenna is available, are used as the reference antennas for this measurement. Here the gain chart gives the gain of the wide band horn in *dBi* versus frequency (*dBi* represents the gain with respect to the isotropic antenna). The experimental set up is the same as that shown in the Fig. 3.3. At first the two wide band horns are positioned in the far field condition in such a way that one horn acts as a transmitter faced to the other which is the receiver. The transmission coefficient S_{21} is measured by VNA and it is calibrated to 0 dB. Now this is the reference for the antenna under test (AUT). Afterwards the receiver antenna is replaced with the AUT without changing the distance between them and the new S_{21} value gives the gain of the AUT with respect to the wide band antenna. From the gain chart, the dBi gain for the corresponding frequency is noted and the gain of the AUT with respect to the isotropic antenna is calculated using the formula,

$$\text{Gain of AUT in dBi} = \text{Gain of reference horn in dBi} + S_{21} \text{ of AUT in dB}$$

3.3.5 Voltage Standing Wave Ratio (VSWR)

While interfacing a waveguide or a transmission line to an antenna, a part of the incident energy may be reflected back due to mismatch. The ratio of this reflected energy to the incident energy gives a measure of VSWR. It is given as

$$VSWR = \frac{V_{max}}{V_{min}} \quad (3.1)$$

where V_{max} and V_{min} is the maximum and minimum standing wave voltages at the interface. If it is expressed in decibels, it is called as Standing Wave Ratio (SWR) and is given as,

$$SWR = 20 \log_{10} VSWR \quad (3.2)$$

In terms of reflection coefficient Γ , it is given as

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma} \quad (3.3)$$

If there is no reflected wave as for an ideal antenna, then $VSWR = 1$. But for practical antennas, its value will be in between 1 and ∞ . The VSWR is measured for the proposed antennas by directly connecting it to the source port of the VNA and its S_{11} parameter is measured for the operating frequency band.

3.3.6 Return loss (S_{11})

The S_{11} characteristics versus frequency gives the return loss of an antenna. In the measured frequency range, if there is a notch or decrease of power in S_{11} characteristics, it means that the antenna is radiating in that particular frequency while all other frequencies are reflected back. Thus the resonant frequency of resonant antenna types can be measured using S_{11} characteristics. The experimental value of resonant frequencies of proposed monopole patch antennas are determined by plotting the S_{11} characteristics versus frequency graph using the VNA.

3.3.7 Antenna bandwidth

In the case of horn antenna, the characteristics like pattern, gain, polarization etc. are not necessarily varied with respect to the frequency critically. Then the frequency bandwidth has no unique characterization and has no much practical importance in

specifying it. Being a wide band radiation, the plasma horn antenna also has no much significance in considering the frequency bandwidth. Since the metamaterial inspired monopole patch antennas show resonant radiation within a narrow bandwidth, its measurement is very significant.

The bandwidth of a monopole patch antenna is usually expressed in 2:1 VSWR impedance bandwidth which is based on the frequency range for which the VSWR values are less than 2. The impedance bandwidth can also be evaluated in terms of percentage and is calculated from the S_{11} characteristics by measuring the frequency difference between the two identical points having S_{11} values at -10dB. Since $VSWR = 2$ corresponds to a reflection coefficient of $\frac{1}{3}$, the return loss becomes $-20 \log \frac{1}{3} = -10dB$. Since the monopole patch antenna is a narrow band antenna, the impedance bandwidth is expressed in terms of fractional bandwidth and usually written in percentage.

$$\text{Impedance bandwidth (in \%)} = \frac{f_H - f_L}{f_c} \times 100 \%$$

where f_H and f_L are the frequencies at the -10 dB points in the S_{11} characteristics curve and f_c is the average of f_H and f_L . It is also known as -10 dB impedance bandwidth.

3.4 Fabrication of novel plasma horn antennas

This section describes the methods used for the construction of proposed novel plasma horn antennas. For the purpose of studying performance of this metamaterial inspired horn antenna, a wire medium, as discussed in chapter 2, is used in the place of metallic walls of traditional horn. The pyramidal plasma horns of S-band (2 - 4 GHz), C-band (4 - 8 GHz) and X-band (8 - 12 GHz) frequency ranges are constructed to compare their radiation performance with that of the corresponding pyramidal metallic horns from 3 GHz to 9 GHz. The following types of pyramidal plasma horn antennas

are fabricated for this purpose.

- Single layer X-band plasma horn
- Multilayer X-band plasma horn
- C-band plasma horn
- S-band plasma horn

3.4.1 Single layer X-band plasma horn

A single artificial pyramidal plasma layer horn antenna for the X-band frequency range (8 GHz - 12 GHz) is constructed using thin copper wires. In metamaterial inspired aspect, one dimensional array of wires is enough to produce the metamaterial properties if the diameter of the wire is greater than the skin depth of the material. On the other hand, if the thickness of wire is negligibly small, the wave energy will not be completely reflected from the proposed single layer. In such cases, for obtaining complete reflection of the incident energy, inclusion of additional layers becomes relevant.

For the fabrication of proposed plasma layers, copper wires are used since it has a good conductivity in the order of $5.96 \times 10^7 Sm^{-1}$ at $20^\circ C$ and it is easy to obtain very fine copper wires in a less expensive manner. Since the diameter of the wire and also the lattice parameter of the array determine the plasma frequency of the wire array, they are designed according to the plasma frequency equation given by eqn. 2.7,

$$f_p = c \left(d \sqrt{2\pi \left[\ln \frac{d}{2\pi r} + 0.5275 \right]} \right)^{-1}$$

Here a wire of radius, $r = 50 \mu m$ with a lattice spacing of $d = 5 mm$ is used to design

the wire medium with plasma frequency at 18.44 GHz and the frequencies used for study are below it. Then the wire array will act as a plasma medium. The designed wires are fixed on a thin dielectric frame of foamex of small dielectric constant ($\epsilon_r = 1.2$) with thickness $t = 1.65$ mm at the mentioned lattice spacing.

Next step in the construction of the plasma horn is to make a metallic launcher which will help in the transmission of energy from waveguide to a plasma horn structure without any mismatch at the apex region (Please refer Fig. 4.4(a)). The flaring of the launcher will reduce the undesired reflection from the throat of the artificial horn which helps to give low VSWR values. The flare length of the launcher is approximately selected to the wavelength of the mid frequency of the selected frequency band. The whole wire structure is then mounted on the launcher appropriately for the TE_{10} mode excitation.

3.4.2 Optimization of plasma horn

Since now the wires are to be arranged in a one dimensional array, different possibilities of aligning the wires in the frame are open. They are given below.

- The wires are aligned parallel to the electric field vector in H-walls and perpendicular to $\mathbf{k}$ in E-walls as shown in the Fig. 3.4 (a)
- The wires are aligned perpendicular to the electric field vector in H-walls with an angular spacing of 2° and parallel to $\mathbf{k}$ in the E-wall with an angular spacing of 2° as shown in the Fig. 3.4 (b).
- The wires are aligned parallel to the electric field vector in H-walls and parallel to $\mathbf{k}$ with an angular spacing of 2° in E-walls as shown in the Fig. 3.4 (c).

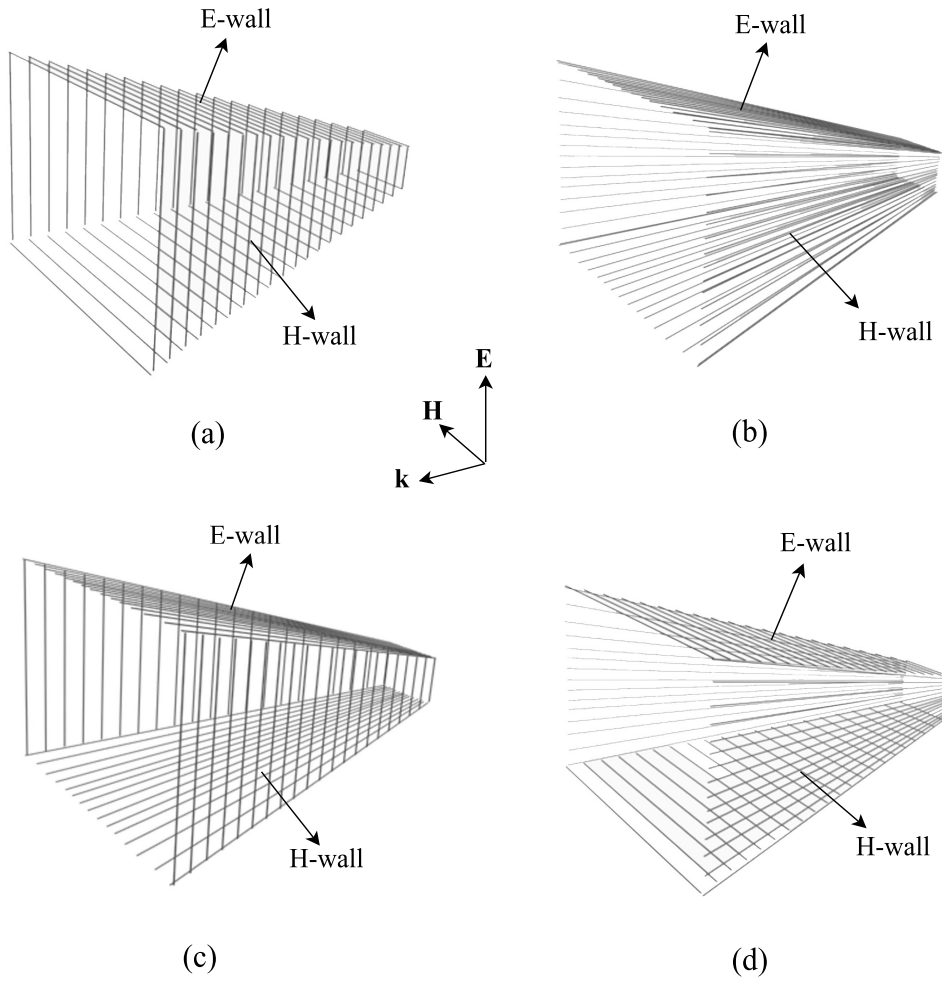


Figure 3.4: (a) Plasma horn structure-1, (b) Plasma horn structure-2, (c) Plasma horn structure-3 and (d) Plasma horn structure-4.

- The wires are aligned parallel to $\mathbf{k}$ vector in H-walls with an angular spacing of 2° and perpendicular to the $\mathbf{k}$ vector in E-walls as shown in the Fig. 3.4 (d).

All the four possibilities are realized with the same wire geometry and lattice spacing. Their radiation patterns are compared with that of the conventional metallic

horn and from their performance, it is understood that the third configuration in Fig. 3.4 (c) gave the same radiation behavior of the conventional metallic antenna. So this configuration is selected as the optimized form of plasma horn antenna.

The dimensions of the single layer plasma pyramidal horn fabricated for X-band are as given below.

- The cross section of X-band wave guide is 2.3 cm x 1 cm.
- The aperture cross section of the antenna is 9.5 cm x 7.5 cm.
- The axial length of the horn is 11.5 cm.
- The aperture cross section of the launcher is 3.2 cm x 2 cm.
- The flare length of the launcher is 2 cm.

3.4.3 Multilayer X-band plasma horn

In order to study the performance of a pyramidal plasma horn with more plasma layers, a multilayer plasma horn antenna is fabricated with the same dimensions of the X-band pyramidal horn antenna. Three sets of additional plasma layers of the same type of optimized structure are fabricated to attach with the four side walls of the single layer X-band plasma horn. Each layer is inserted side by side in order to form a two dimensional plasma array horn antenna. The lattice spacing in both directions of the array is same. A schematic representation of multilayered horn with these plasma layers is shown in the Fig. 3.5.

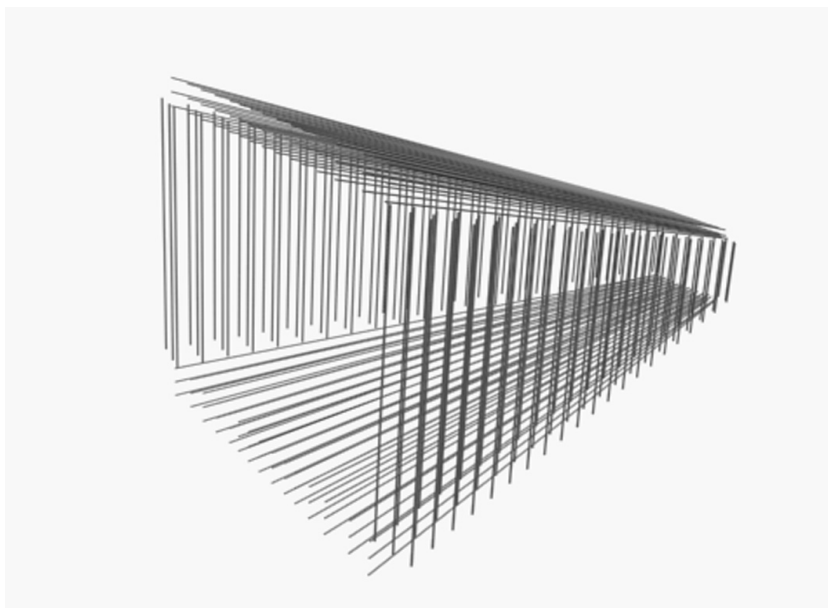


Figure 3.5: A schematic representation of multilayered plasma horn antenna.

3.4.4 C-band plasma horn

A single layer pyramidal plasma horn antenna for the C-band frequency range (4 GHz to 8 GHz) is constructed. This is to check whether the novel plasma model is applicable in C-band range to give the same radiation performance of the conventional C-band metallic horn antenna. The diameter of the wire and the lattice parameter are designed so as to get a plasma frequency at 7 GHz. Since this plasma frequency is within the experimental band region (3 GHz - 9 GHz), it is possible to analyze the antenna behavior below and above this cut off frequency. It is expected that it would give the same radiation performance of the conventional metallic horn below the plasma frequency because the plasma medium behaves as a reflector. But above the plasma frequency the permittivity becomes positive and it would not give any desirable radiation pattern as the plasma medium transmits the power through it. The design

parameter of C-band horn antenna are as follows.

- The radius of the wire and lattice parameter are designed according to the expression for plasma frequency given in the previous section.
- For a plasma frequency at 7 GHz, the radius of the wire is $50\ \mu m$ and the lattice spacing is $8.5\ mm$.
- The cross section of the C-band waveguide is $3.5\ cm \times 1.5\ cm$.
- The aperture cross section is $18\ cm \times 13\ cm$.
- The axial length of the horn is $13\ cm$.
- The flare length of the launcher is $3\ cm$.

3.4.5 S-band plasma horn

A S-band single layer pyramidal plasma horn is also constructed and its radiation performance is examined in between frequencies 3 GHz and 4 GHz. The same wire radius and lattice parameter for plasma frequency at 7 GHz is used in this case since the S-band frequency range is below this plasma frequency. The design parameters are as follows.

- The cross section of the S-band waveguide is $4.7\ cm \times 2.2\ cm$.
- The cross sectional dimensions of the aperture are $20\ cm \times 14\ cm$.
- The axial length of the horn is $15\ cm$.
- The length of the flare part of the launcher is approximated to $4\ cm$.

3.5 Fabrication of monopole patch antennas

In this section, the methods applied for the fabrication of the negative permeability metamaterial inspired structures are presented. As mentioned earlier a single unit cell of metamaterial is enough to mimic the metamaterial properties of the bulk medium. Thus the monopole patch and the metamaterial unit cell loaded in the near field of the monopole patch constitute the radiator and now the whole setup makes a metamaterial inspired antenna. Single circular split ring resonator and its modified version called broadside coupled split ring resonator are the two types of metamaterial unit cells fabricated for the purpose of the present work. The monopole patch and the SRR/BCSRR unit cells placed in the near vicinity of monopole patch constitute the radiating elements. The fabrication stages of the following proposed antennas are explained in the coming sections.

- Single circular SRR loaded monopole patch antenna.
- BCSRR loaded multiband monopole patch antenna.
- Frequency tunable BCSRR loaded monopole patch antenna.

3.5.1 Single circular SRR loaded monopole patch antenna

The main advantage of this type of antenna is the ease of fabrication. Usually the rings are fabricated on a dielectric substrate such as that of PCB by etching method. But here rings are constructed from a very thin copper sheet and is fixed on certain substrate by simply pasting on it or fixing it even by a loss less insulating tape.

A set of annular rings with different inner-outer radii and split widths are designed with a drawing software and printed on a photo paper. Afterwards the photo paper

is placed on one side of a copper sheet of thickness $20\ \mu\text{m}$ such that the printed side is in contact with the copper sheet. After pressing the printed paper placed on the copper sheet for sufficient time with the help of a hot iron box, whereby the printed ring patterns are glued to the copper perfectly, the photo paper is removed gently. The other side of the copper sheet is covered with an adhesive insulating tape. Now the sheet is chemically etched using ferric chloride solution to separate out the SRR rings as shown in the Fig. 3.6. The chosen dimensions of the SRR ring for the present study to obtain a radiating frequency in the desired range are inner radius (r) 4 mm, outer radius (R) 6 mm and split width (s) 0.5 mm.

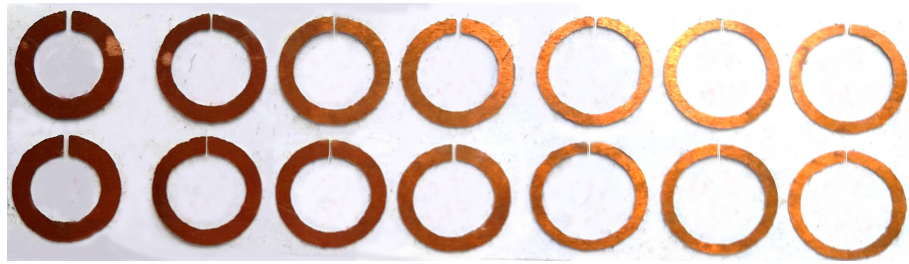


Figure 3.6: Different single split rings fabricated with different dimensions (outer radii, $R = 6\ \text{mm}$, $5.5\ \text{mm}$ and $5\ \text{mm}$; inner radii, $r = 5\ \text{mm}$, $4.5\ \text{mm}$ and $4\ \text{mm}$; split width, $s = 0.1\ \text{mm}$, $0.3\ \text{mm}$ and $0.5\ \text{mm}$) by chemical etching method.

A monopole patch of length 30 mm and breadth of 4.3 mm is etched on one side of the FR4 double sided printed circuit board. A ground plate of length 21 mm and breadth 13 mm is etched on the other side of the PCB as shown in the Fig. 3.7. The dimensions of the substrate is 45 mm x 26 mm x 1.1 mm. This monopole patch is excited by a coaxial feed. The fabricated single annular test ring is fixed on a small FR4 dielectric square piece of side 12 mm in such a way that the split of the ring faces the monopole patch as shown in the Fig. 3.8. It is then slowly moved towards the active field of the monopole patch antenna by means of a mechanical arrangement.

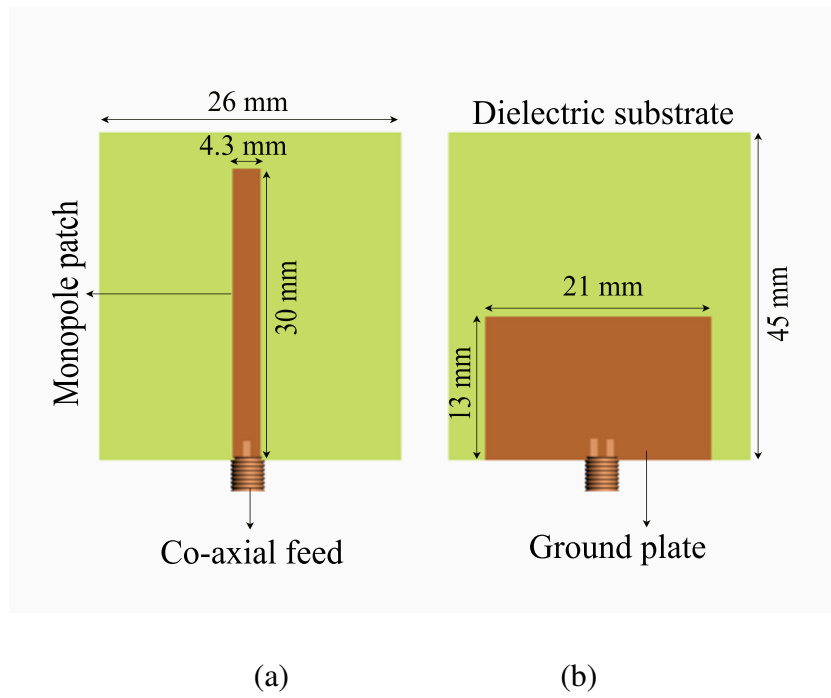


Figure 3.7: Schematic representation of (a) top and (b) bottom surfaces of monopole patch antenna.

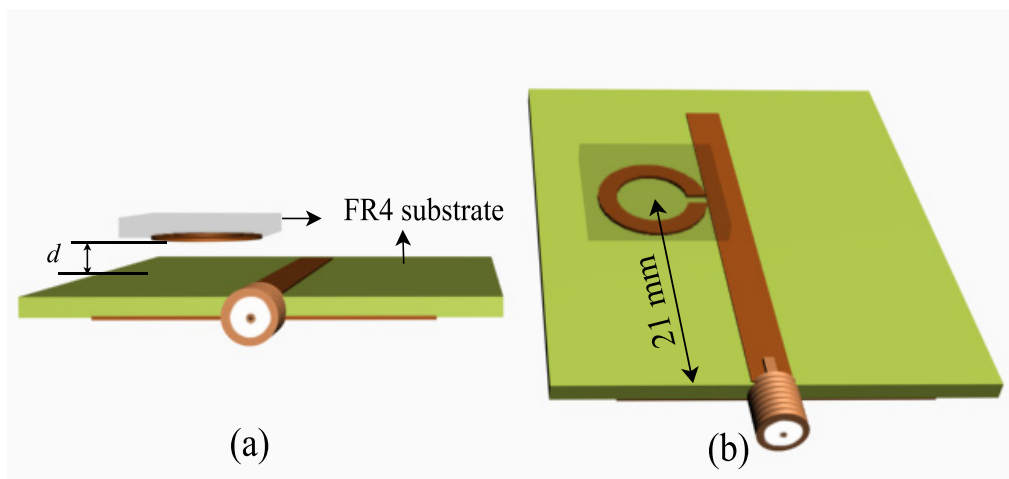


Figure 3.8: Schematic representation of single circular SRR monopole patch antenna, (a) side perspective showing the spacing and (b) top perspective showing the split ring.

3.5.2 BCSRR loaded multiband monopole patch antenna

For making a BCSRR loaded multiband monopole patch antenna, the following steps are exercised.

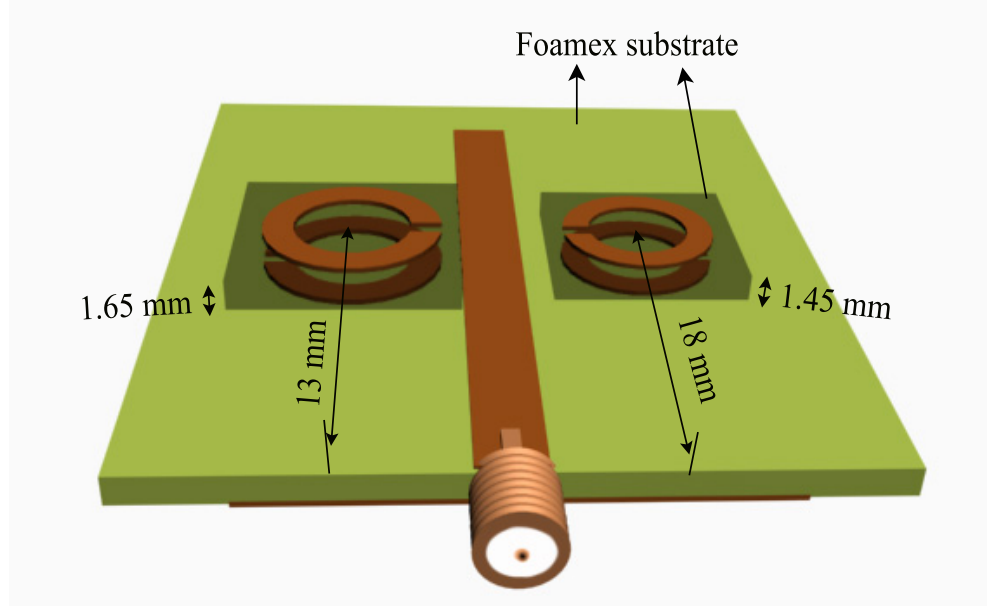


Figure 3.9: Schematic representation of BCSRR loaded multiband monopole patch antenna.

- A pair of copper rings with same dimensions are fabricated by the method explained in the previous section.
- The monopole patch has the dimensions of 30 mm x 4.3 mm and ground plate has the dimensions 29 mm x 13 mm, but they are cut out from a copper sheet of thickness 20 μm instead of etching. They are then fixed on the two sides of a foamex sheet of dimensions 45 mm x 45 mm x 1.45 mm as shown in the Fig. 3.9. The foamex sheet serves as a low loss dielectric substrate ($\epsilon_r = 1.2$ and loss tangent, $\tan\delta = 0.001$).

- In order to get two distinct resonances along with the monopole radiation, two BCSRR units are made with 12 mm/8 mm and 12 mm/9 mm as outer/inner radii. In one unit, a small square piece of foamex sheet of side 12 mm with a thickness 1.65 mm is used as a dielectric substrate. In the second unit, another square piece of same dimension but thickness 1.45 mm is used.
- One BCSRR unit is fixed very near and left to the monopole at a distance of 13 mm from the feed end and the second one is fixed at the right of the monopole at a distance of 18 mm from the feed end as shown in the figure.

3.5.3 Frequency tunable BCSRR loaded monopole patch antenna

A frequency tunable BCSRR loaded monopole patch antenna is fabricated by the following steps. A schematic diagram of frequency tunable BCSRR loaded monopole patch antenna is shown in Fig. 3.10.

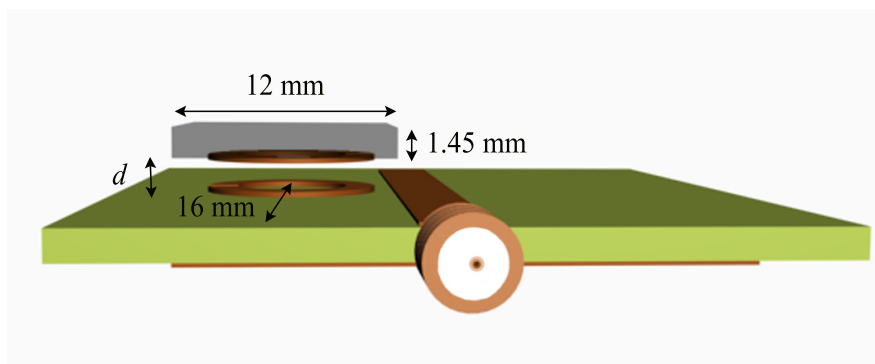


Figure 3.10: Schematic diagram of frequency tunable BCSRR loaded monopole patch antenna.

- The BCSRR rings and the monopole patch antenna are fabricated by the same method used in the previous case. The 12 mm/8 mm dimensions are taken for the outer/inner radii.

- Here, no dielectric substrate is inserted between the rings of the BCSRR.
- In this case one ring of the BCSRR is fixed on the antenna substrate very near to the monopole as its split faces towards the monopole.
- The other ring is fixed on a square piece of foamex sheet having side 12 mm and it is moved towards the first ring with the help of a mechanical arrangement, as it forms a BCSRR unit.

3.6 Conclusion

The experimental set up for taking the measurements of antenna parameters are described. A brief outline of the main facilities used for the measurement is given. The important antenna parameters to study the radiation characteristics of the proposed antennas are presented in detail. The methods used for measuring each of these parameters are explained. The methods adopted for fabricating different types of proposed antennas are also discussed at the end.

CHAPTER 4

Results and Analysis of Metamaterial Inspired Negative Permittivity Horn Antenna

4.1 Introduction

This chapter focuses on the results and analysis of the metamaterial inspired negative permittivity plasma horn antenna.¹ The important radiation parameters are measured in order to study the characteristics of this novel proposed antenna. It includes radiation pattern, cross polarization, half power beamwidth, side lobe level, gain, and VSWR. Initially, as mentioned in chapter 3, the possible orientations of single layer wire plasma structure in the side walls (E-walls and H-walls) of the proposed horn are analyzed and optimized for the results by comparing it with the radiation pattern of an equivalent conventional metallic horn for a X-band pyramidal structure. Afterwards,

¹This work has been published in *Microwave and Optical Technology Letters*.

this novel idea of using plasma walls is extended to fabricate other horn antennas in C-band and S-band and its characteristics are verified. A multilayer plasma horn antenna is then fabricated and the changes occurred in the radiation performance are studied.

4.2 Optimization studies of wire medium alignment in the horn structure

The four types of wire arrays discussed in the chapter 3 are fabricated with the designed geometrical dimensions for the wire according to equation 2.7 and their radiation patterns are drawn and a comparative study with the conventional metallic horn patterns is followed in order to optimize the alignment of the wires in the array of the proposed horn structure. For optimization purpose the radiation patterns are drawn for the X-band horn excited with TE_{10} mode specifically at a frequency of 8.5 GHz. In order to verify the negligible involvement of the launcher on radiation pattern, its performance is also analyzed.

The schematic diagrams of fabricated wire alignments in the array are shown in the Fig. 4.1. The diameter and the periodicity of the wires are so selected to make the plasma frequency at 18.44 GHz as mentioned in chapter 3. As a first case, the wires in the one dimensional array fixed as H-walls and E-walls of the proposed horn are arranged parallel to the aperture edges as shown in the Fig. 4.1 (a) and is denoted as plasma horn structure-1. In the second case, the wires in the array fixed as H-walls and E-walls of the proposed horn are placed in perpendicular direction to the aperture edges but with a 2° angular spacing between the wires as shown in Fig. 4.1 (b) and this structure is denoted as plasma structure-2.

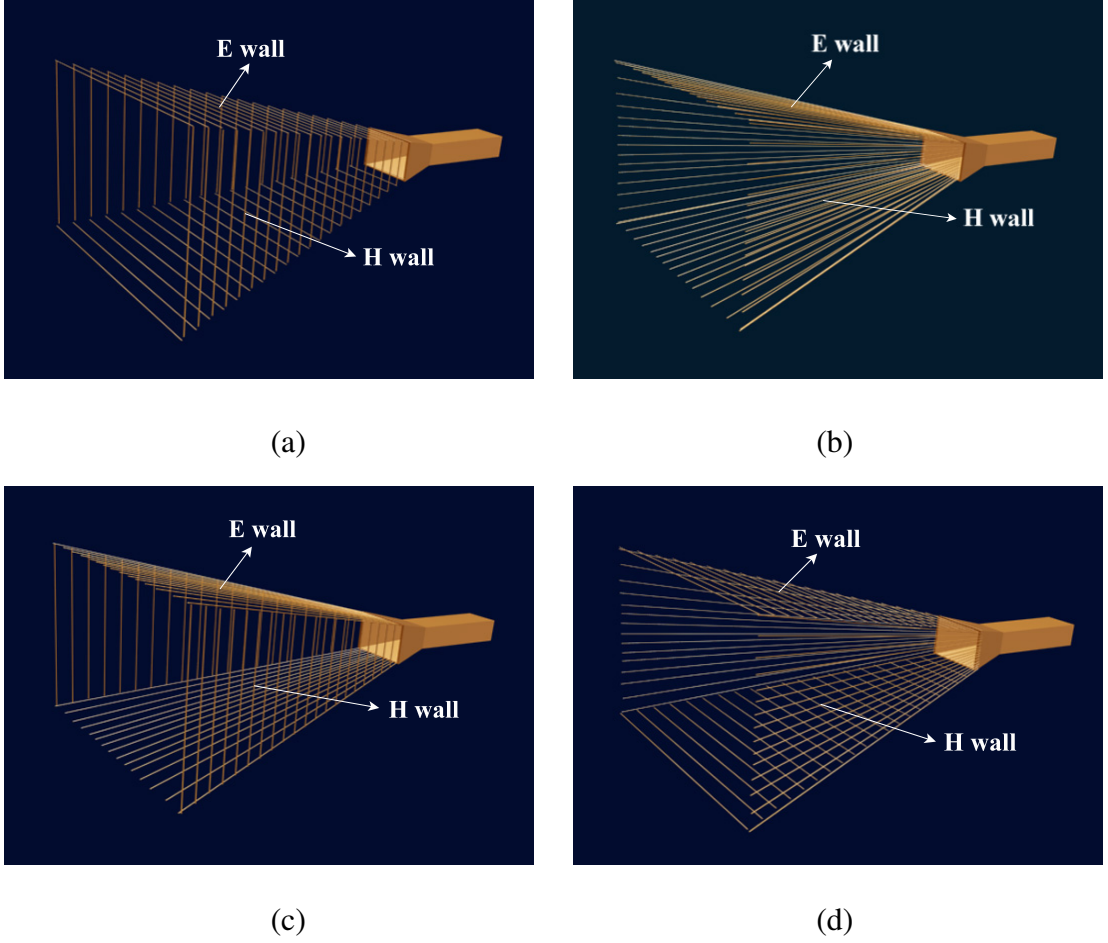


Figure 4.1: Schematic drawing showing the possible designs of plasma horn antenna. (a) Plasma horn structure-1, (b) Plasma horn structure-2, (c) Plasma horn structure-3 and (d) Plasma horn structure-4.

In the third case, as shown in Fig. 4.1 (c), the wires in the E-walls are kept same as in the second case while the wires in the H-walls are kept same as in the first case and it is called as plasma structure-3. In the last case, as shown in the Fig. 4.1 (d), the wire array fixed as the E-walls and H-walls are just reverse of the alignment done in the third case and it is called as plasma structure-4. All the E-plane radiation patterns and H-plane radiation patterns of these four structures are drawn and the radiation pattern

of one particular structure having maximum axial gain is normalized first and all the other three radiation patterns are then normalized with respect to it. The E-plane radiation patterns are shown in Fig. 4.2 and the H-plane radiation patterns obtained are given in Fig. 4.3.

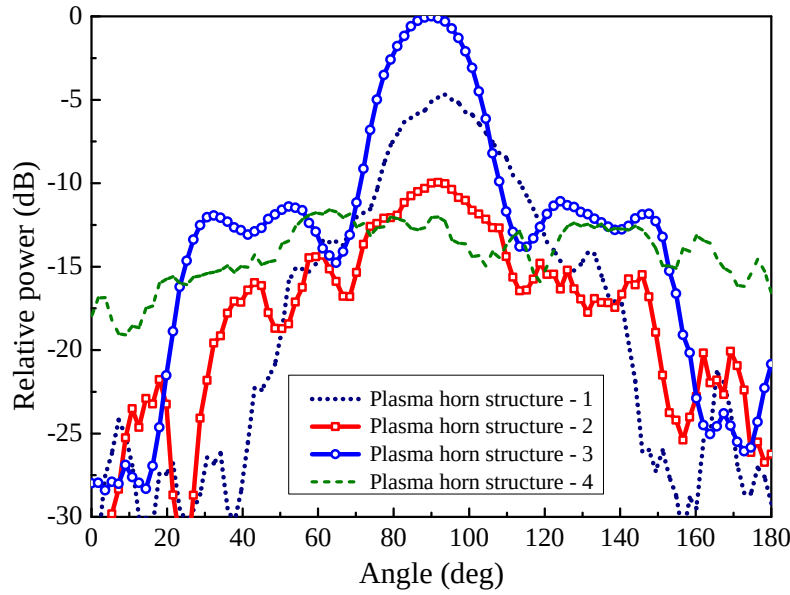


Figure 4.2: E-plane radiation patterns of different alignments of wire arrays to optimize the horn structure.

From the E and H-plane radiation patterns depicted in Figs. 4.2 and 4.3, it is observed that the alignment for plasma structure-3 produces a good antenna gain compared to the other three plasma horn structures. And also it almost gives equivalent E-plane and H-plane radiation patterns of the conventional horn antenna. The patterns of all other structures except plasma horn structure-3, deviate seriously from the expected pattern shape of metallic horn antenna and show only small directivity. Henceforth, plasma structure-3 is optimized and proposed for the metamaterial inspired negative permittivity horn antenna.

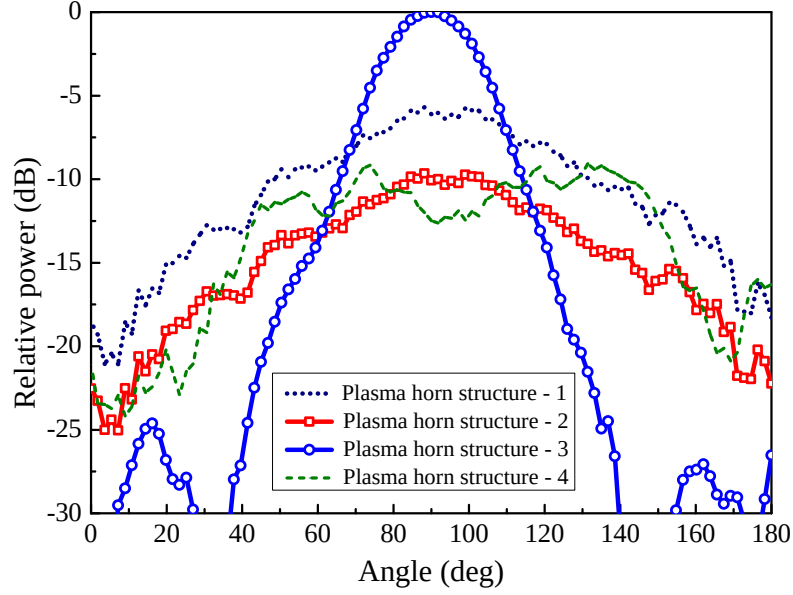


Figure 4.3: H-plane radiation patterns of different alignments of wire arrays to optimize the horn structure.

In the optimized structure, the wires in the H-walls are parallel to the $\mathbf{E}$ vector of the radiating field ($TE_{10}mode$) so that the boundary condition for E (tangential component) behaves similar to that of its metallic counterpart. With respect to the E-walls, the direction of the wires are parallel to the propagating wave vector $\mathbf{k}$ in order to guide the electromagnetic wave properly through the horn structure. Also in this case the perpendicular magnetic part of the TE_{10} wave is perpendicular to the orientation of wires so that the surface currents generated according to the boundary conditions of the tangential magnetic fields support the flow of the signal propagation in z-direction. Meanwhile the z-component of the magnetic field of TE_{10} wave will be perpendicular to the alignment of wires in the H-walls which will result in the same boundary related supportive effects in terms of surface currents (y-direction). Thus the required boundary conditions for both the flared surface needed for efficient radiation are met to a good extent for the proposed optimized design. For other possible

orientations of copper wires in the wire array, the boundary conditions are not satisfied as for the conventional horn antenna.

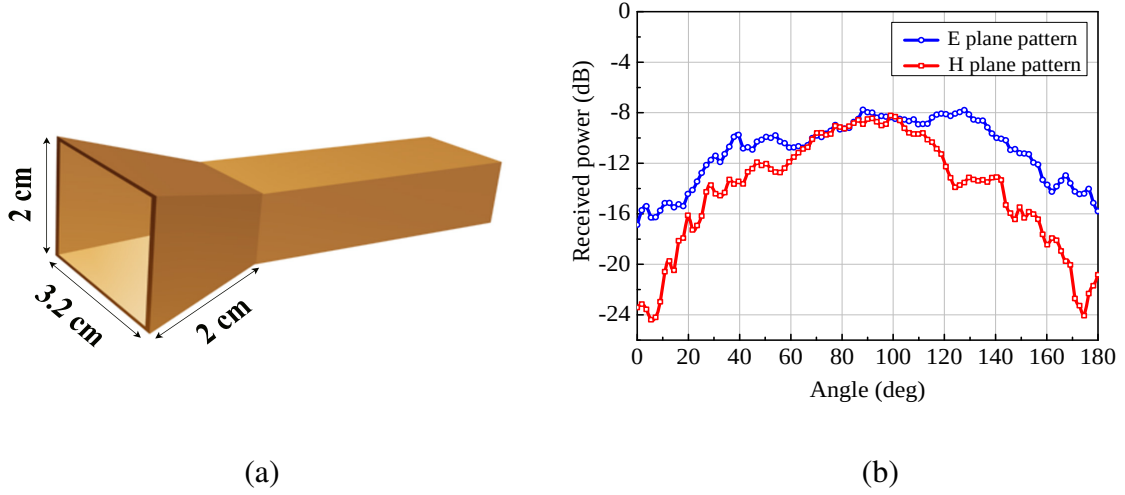


Figure 4.4: (a) Schematic representation of the launcher (X-band) and (b) E-plane and H-plane radiation patterns of the launcher.

A schematic representation of the launcher is given in Fig. 4.4 (a). In order to study the radiation performance of the launcher, the E-plane and H-plane radiation patterns of it are also plotted in Fig. 4.4 (b). From the figure, it is understood that the launcher alone is not capable of distributing energy with directivity. But the proposed novel wire array fixed as the side walls of the horn acts as a plasma reflector for the waves of frequencies below its plasma cut off frequency and the radiation patterns equivalent to the conventional metallic horn structure are produced. Thus the role of the launcher is only to help the electromagnetic wave to transduce it from the waveguide to the plasma horn region without causing much increase in the VSWR.

4.3 Single layer X-band plasma horn

This section investigates the radiation characteristics of the proposed novel X-band plasma horn and compares it with the traditional metallic horn.

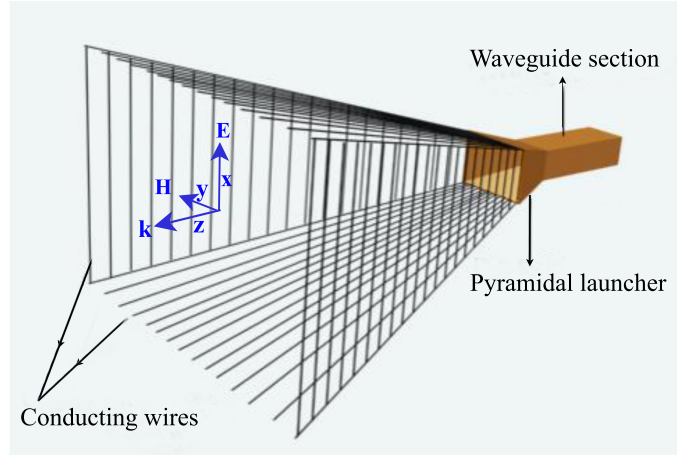


Figure 4.5: Schematic diagram of the optimized plasma horn antenna showing the transverse $\mathbf{E}$ and $\mathbf{H}$ vectors of TE_{10} mode wave.

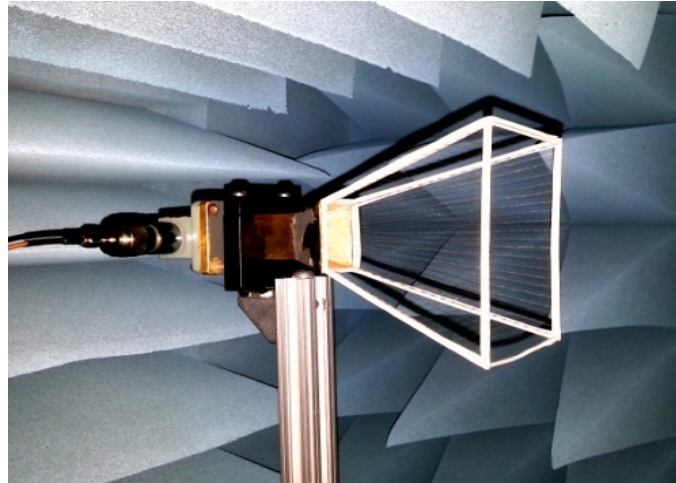


Figure 4.6: Photograph of X-band plasma horn antenna placed inside an anechoic test box.

The schematic diagram and the photograph of the fabricated single layer X-band plasma horn antenna are given as Figs. 4.5 and 4.6. As mentioned earlier, the wire

medium for the proposed structure is designed and fabricated according to the eqn. 2.7 with radius $50\ \mu\text{m}$ and lattice spacing $5\ \text{mm}$.

4.3.1 Radiation patterns



Figure 4.7: Experimental setup showing the radiation pattern measurement of AUT placed in a anechoic test box using VNA and wide band dual ridge horn as transmitter.

The radiation patterns for the metallic conventional horn and the proposed plasma horn are taken for different frequencies using the experimental setup shown in Fig. 4.7. The E-plane radiation patterns obtained for both metallic and plasma antennas corresponding to 8.5 GHz are given in the Fig. 4.8. For the purpose of further verification, it is simulated and the corresponding graphs are also included in the figures. The

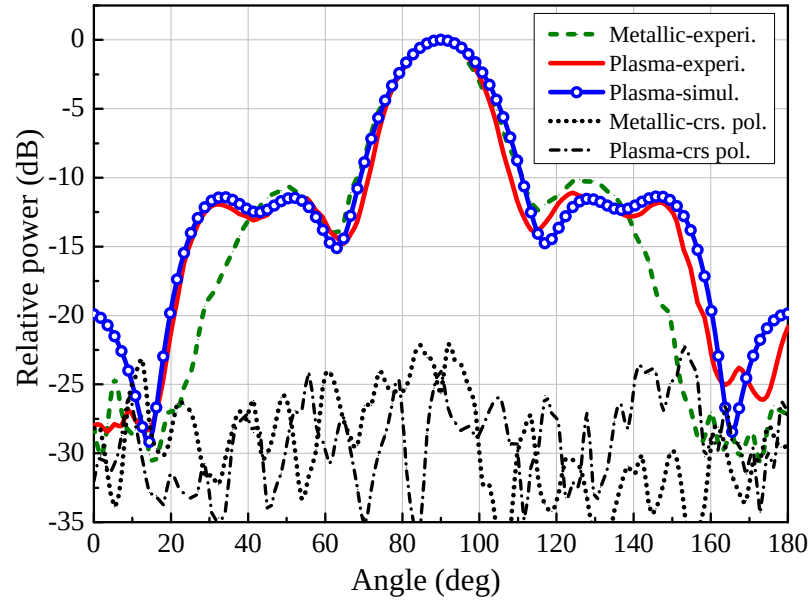


Figure 4.8: Comparison of E-plane radiation patterns of metallic horn and plasma horn along with their cross-polar patterns at 8.5 GHz.

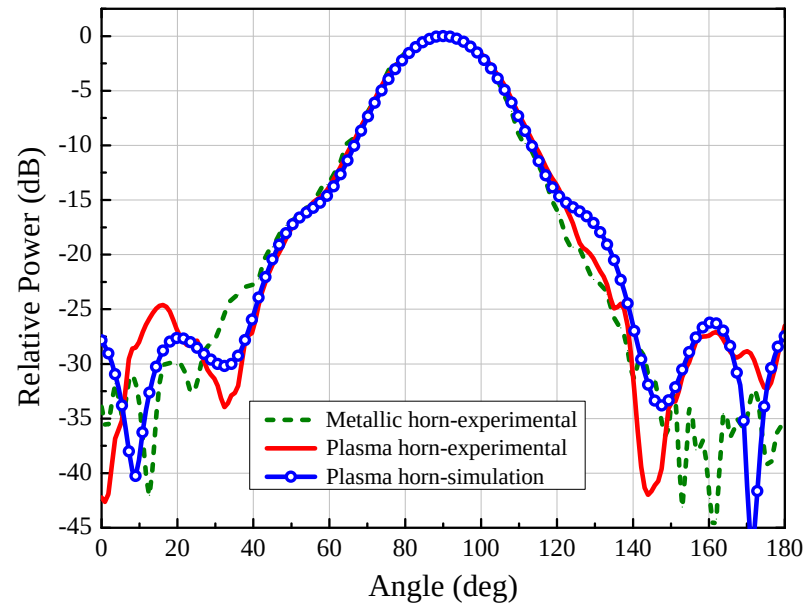


Figure 4.9: Comparison of H-plane radiation patterns of metallic horn and plasma horn at 8.5 GHz.

three curves show almost identical patterns. The cross-polar patterns obtained are also included along with the co-polar patterns. The H-plane radiation patterns for both the antennas are also taken (8.5 GHz) and the corresponding results including the simulation output are depicted in Fig. 4.9. From these observations, it can be concluded that the proposed horn antenna gives the same radiation behavior as that of its conventional metallic counterpart finding at its potential applications owing to its negligible weight without compromising the efficiency in radiation.

In order to study the other antenna parameters and also to compare the radiation performance of the proposed antenna structure at different frequencies, the radiation patterns at different frequencies are also taken. The E-plane and H-plane radiation patterns of the proposed plasma horn antenna at two typical cases, 8.3 GHz and 8.7 GHz, are compared with the corresponding metallic horn antenna and are shown in the Fig. 4.10. It can be observed that the plasma horn keeps the same radiation behavior of the conventional metallic horn for other frequencies also. The side lobes of the plasma horn are lower compared to the metallic horn for almost all cases which is an added advantage as the side lobes contain the undesired distribution of energy in that direction.

4.3.2 HPBW

The HPBW (-3 dB beamwidth) at different frequencies are calculated from the E-plane and H-plane radiation patterns of the metallic horn and plasma horn. The HPBWs of E-plane patterns at different frequencies of both the horns are depicted in Fig. 4.11 and the corresponding graph for H-plane patterns is given in Fig. 4.12. From these observations it can be easily understood that the proposed plasma horn is a suitable candidate in the place of conventional metallic horn since the transmitting /receiving area remains almost same for both the cases.

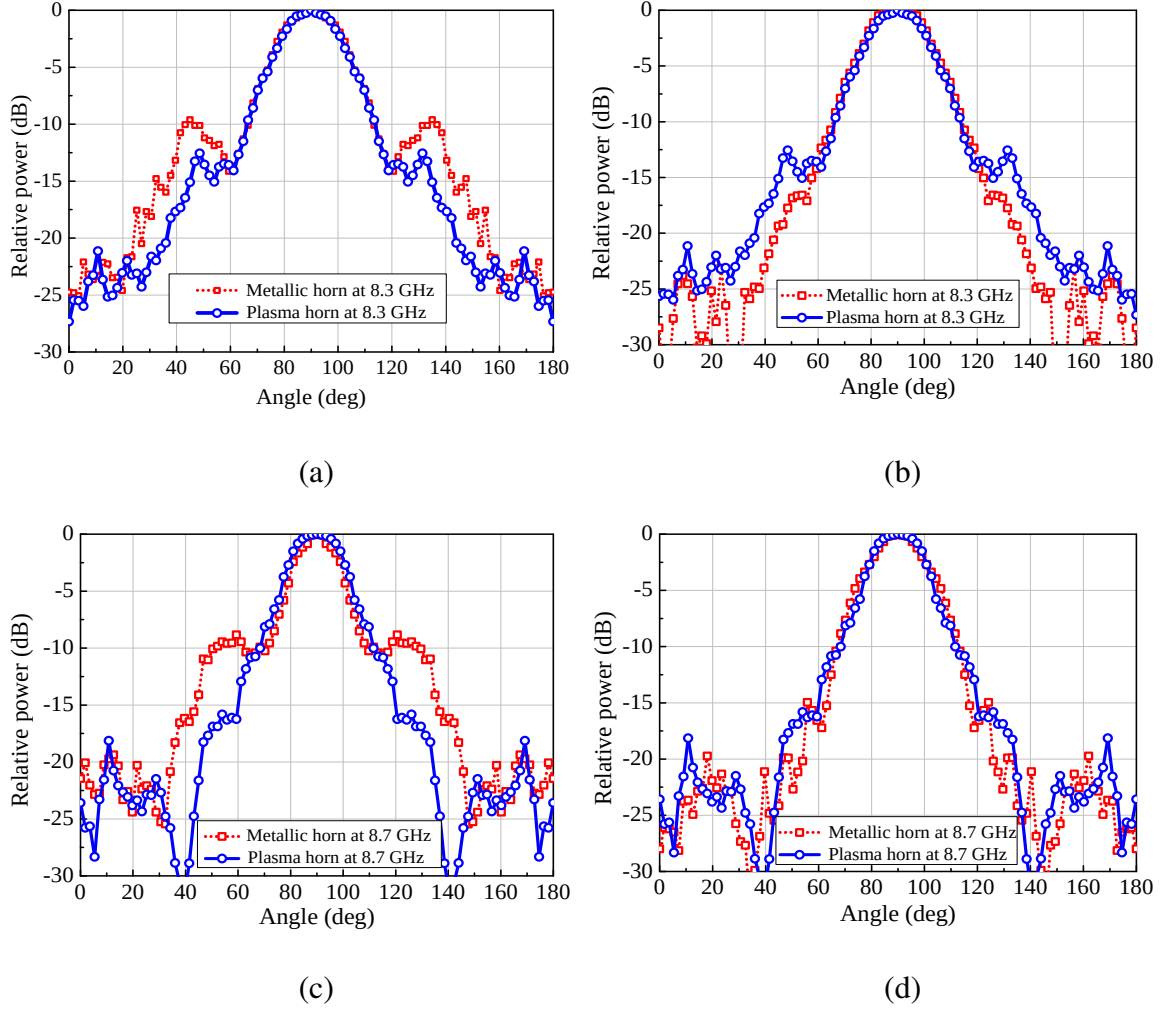


Figure 4.10: Comparison of radiation patterns of metallic and plasma horns at different frequencies. (a) E-plane radiation patterns at 8.3 GHz, (b) H-plane radiation patterns at 8.3 GHz, (c) E-plane radiation patterns at 8.7 GHz and (d) H-plane radiation patterns at 8.7 GHz.

4.3.3 Side lobe level

It is measured as the difference between the power levels of the maxima of the major lobe and the first side lobe. The side lobe levels are measured from the E-plane

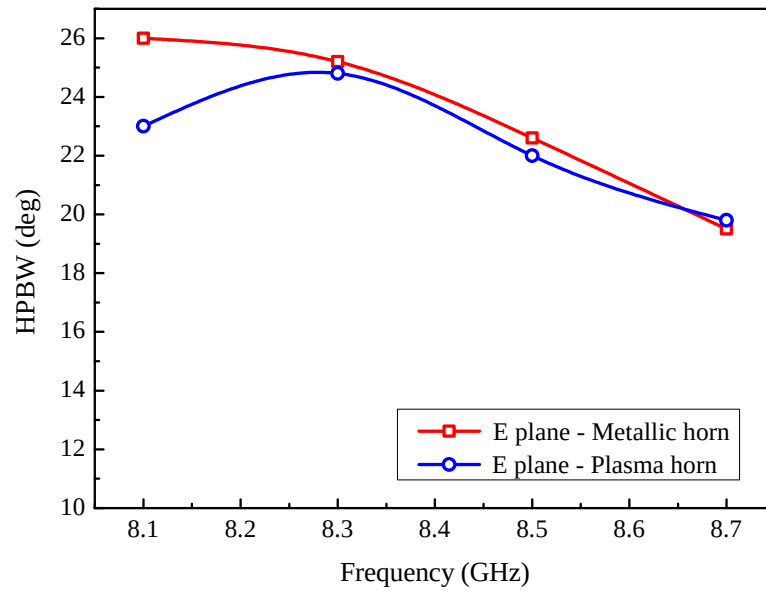


Figure 4.11: E-plane HPBW versus frequency graph of metallic horn and plasma horn.

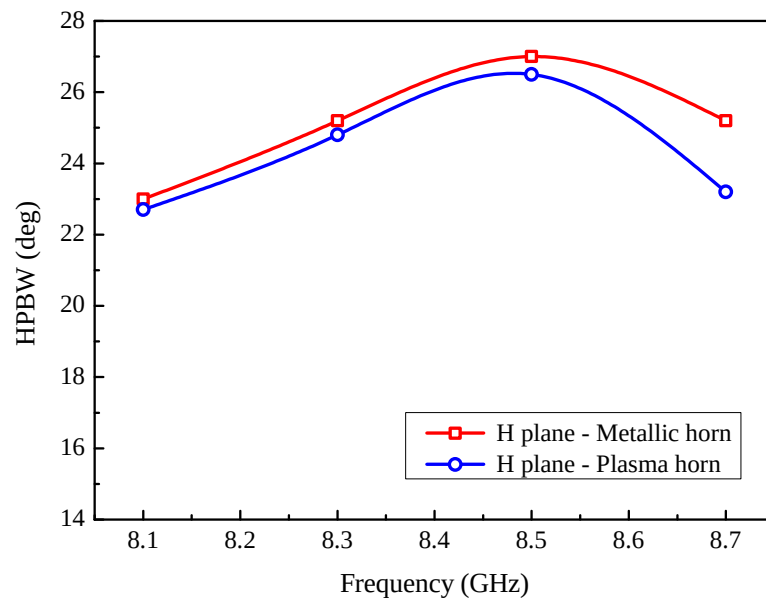


Figure 4.12: H-plane HPBW versus frequency graph of metallic horn and plasma horn.

and H-plane radiation patterns of the metallic horn and the proposed horn at different frequencies. The results are compared with the metallic horn and the variations in the side lobe levels for E-plane and H-plane are plotted in the Figs. 4.13 and 4.14 respectively. High side lobe level is undesired as the radiated energy will be then leaked through unwanted directions. For good antenna performance, the side lobe level is considered to be less than -10 dB. The proposed horn structure is satisfied with this condition. For the present test horn, the obtained side lobe level is comparable or even less than the metallic counterpart for certain frequencies indicating its efficiency in radiation performance.

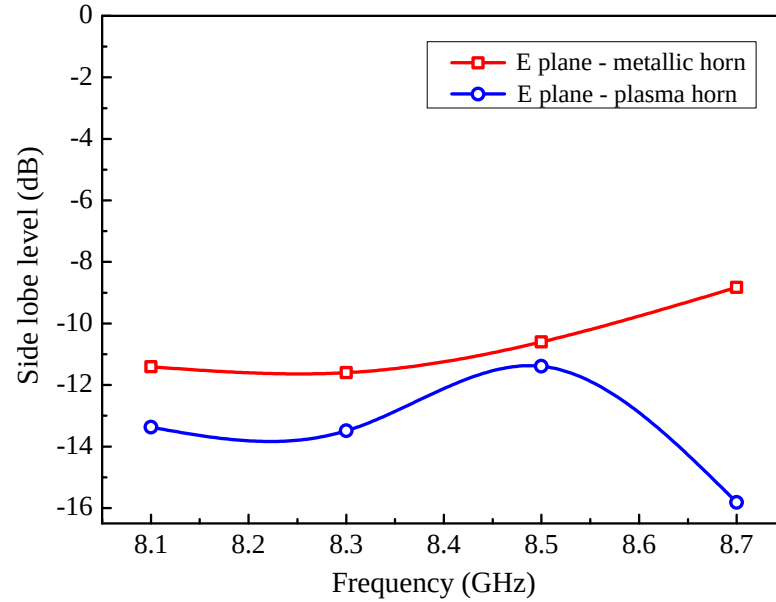


Figure 4.13: Comparison of E-plane side lobe level at different frequencies of metallic horn and plasma horn.

4.3.4 Axial gain

The gain in the axial direction is taken by the gain transfer method described in chapter 3. It is calculated with the help of the gain chart of the dual ridge wide band

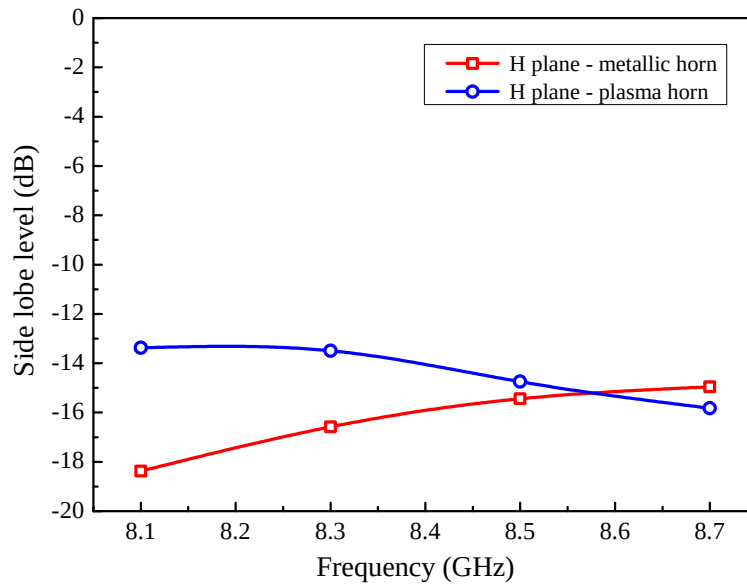


Figure 4.14: Comparison of H-plane side lobe level at different frequencies of metallic horn and plasma horn.

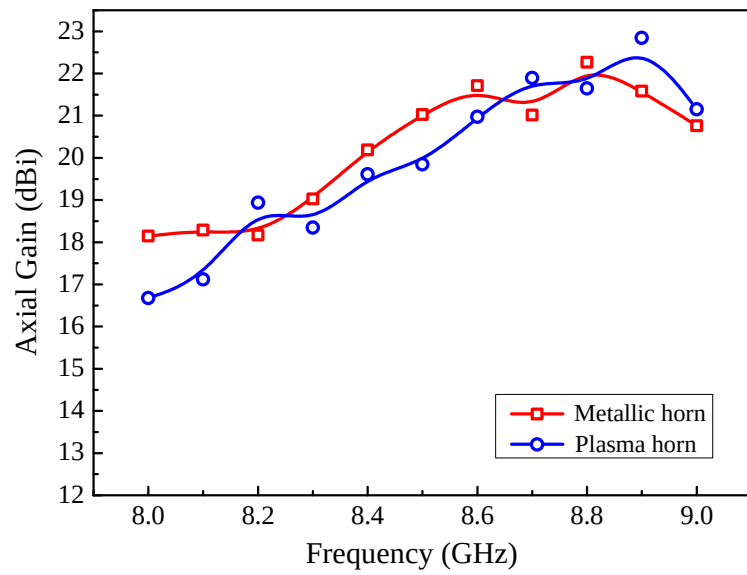


Figure 4.15: Axial gain versus frequency graph of metallic horn and plasma horn.

horn which is used as a reference antenna during the measurement. The variation of axial gain with respect to the frequency sweep is measured for both the metallic horn and the proposed horn and the resulting graph is plotted as Fig. 4.15. It shows a maximum decrease of axial gain of plasma horn upto 2 dB and that too only for certain frequencies compared to the conventional metallic horn. This result also agrees the use of this featherlight weight plasma horn in the place of heavy metallic horn without much difference in antenna gain.

4.3.5 VSWR

The VSWR is measured for the metallic horn and the plasma horn by using VNA. A graph is plotted between the VSWR and frequency and it is shown in Fig. 4.16. It shows less VSWR for most part of the frequency range. So it shows that good impedance matching is achieved at launcher section for the proposed horn antenna.

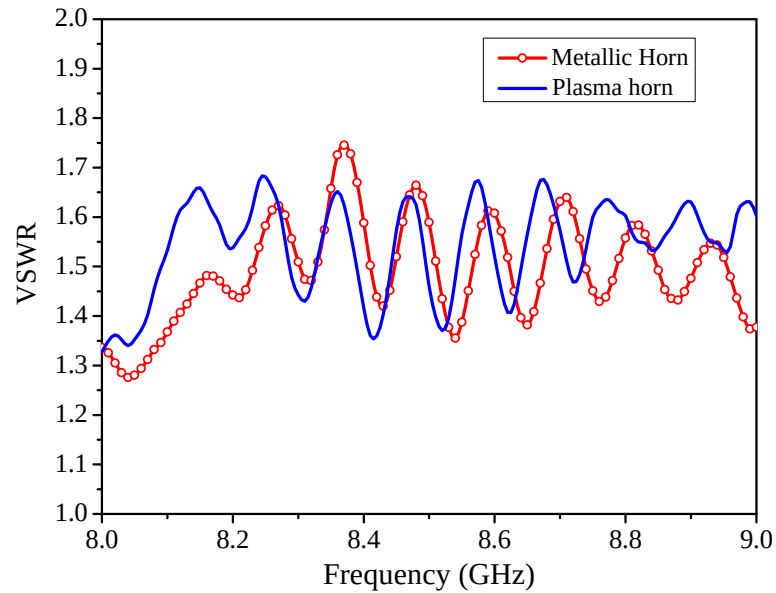


Figure 4.16: VSWR versus frequency graph of metallic horn and plasma horn.

4.4 Extension to C-band and S-band plasma horns

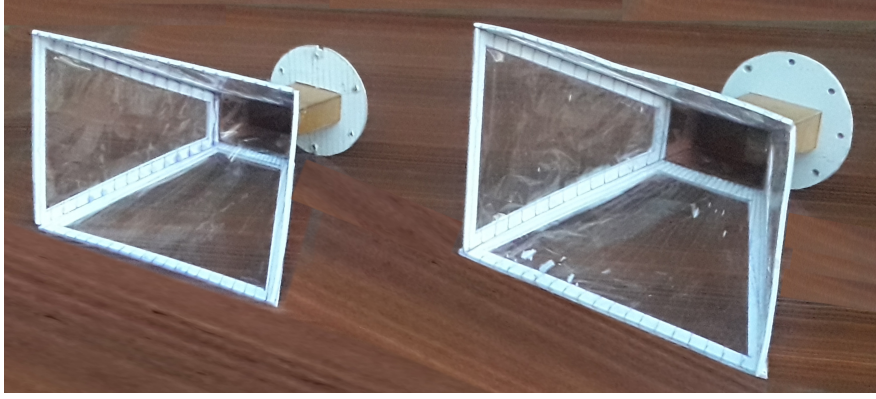


Figure 4.17: Photograph of the C-band and S-band proposed plasma horns.

The novel idea of inserting negative permittivity wire array in the side walls of the horn by replacing the metallic side walls is found to be successful in producing the almost same radiation performance of the conventional metallic horn antenna. It was tested and optimized in the frequency range of X-band from 8 GHz to 9 GHz. To extend and check this novel idea to implement in other frequency ranges, similar plasma horns are made with the same technology which works in the S-band and C-band for frequency ranges between 3.5 GHz to 8 GHz. The geometrical parameters of the wires in the wire array are designed according to the same equation 2.7 with radius of the wire $50 \mu m$ and lattice spacing $8.5 mm$ for a plasma cut off frequency 7 GHz and hence the effect of the plasma wire array as a plasma reflector below the plasma cut off frequency and its transmission behavior above the plasma cut off frequency can be verified. The following sections describe the study of antenna parameters from 3.5 GHz to 8 GHz. The photograph of the fabricated C-band and S-band plasma horns is given in Fig. 4.17.

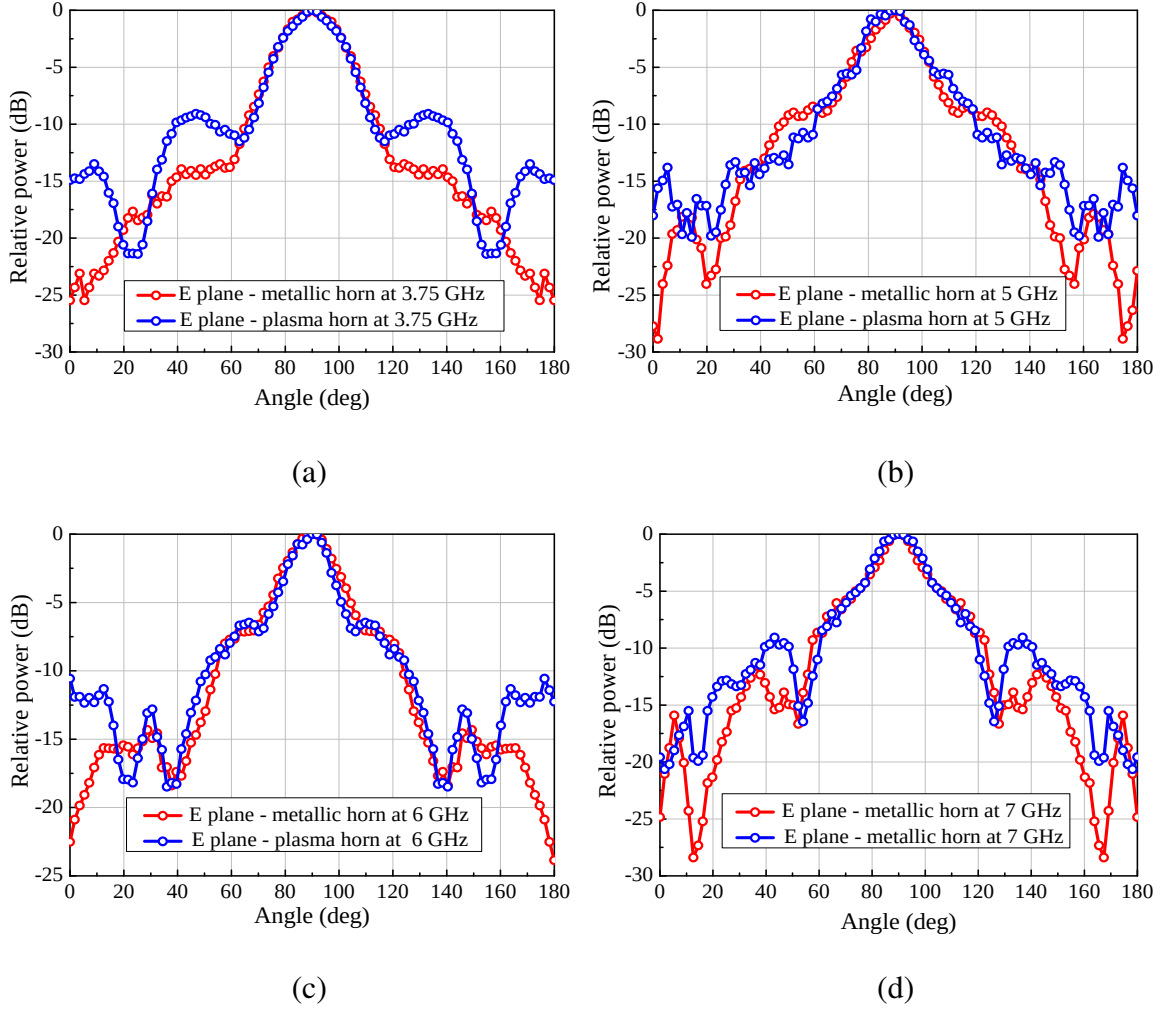


Figure 4.18: Comparison of E-plane radiation patterns of metallic and plasma horns (a) at 3.75 GHz, (b) at 5 GHz, (c) at 6 GHz and (d) at 7 GHz.

4.4.1 Radiation patterns

The E-plane and H-plane radiation patterns for four different frequencies in S-band and C-band ranges are taken and the comparison with respect to that of the conventional metallic horn are given in Figs. 4.18 and 4.19. The radiation patterns of the proposed horns are almost equivalent to its metallic counterparts. Even though

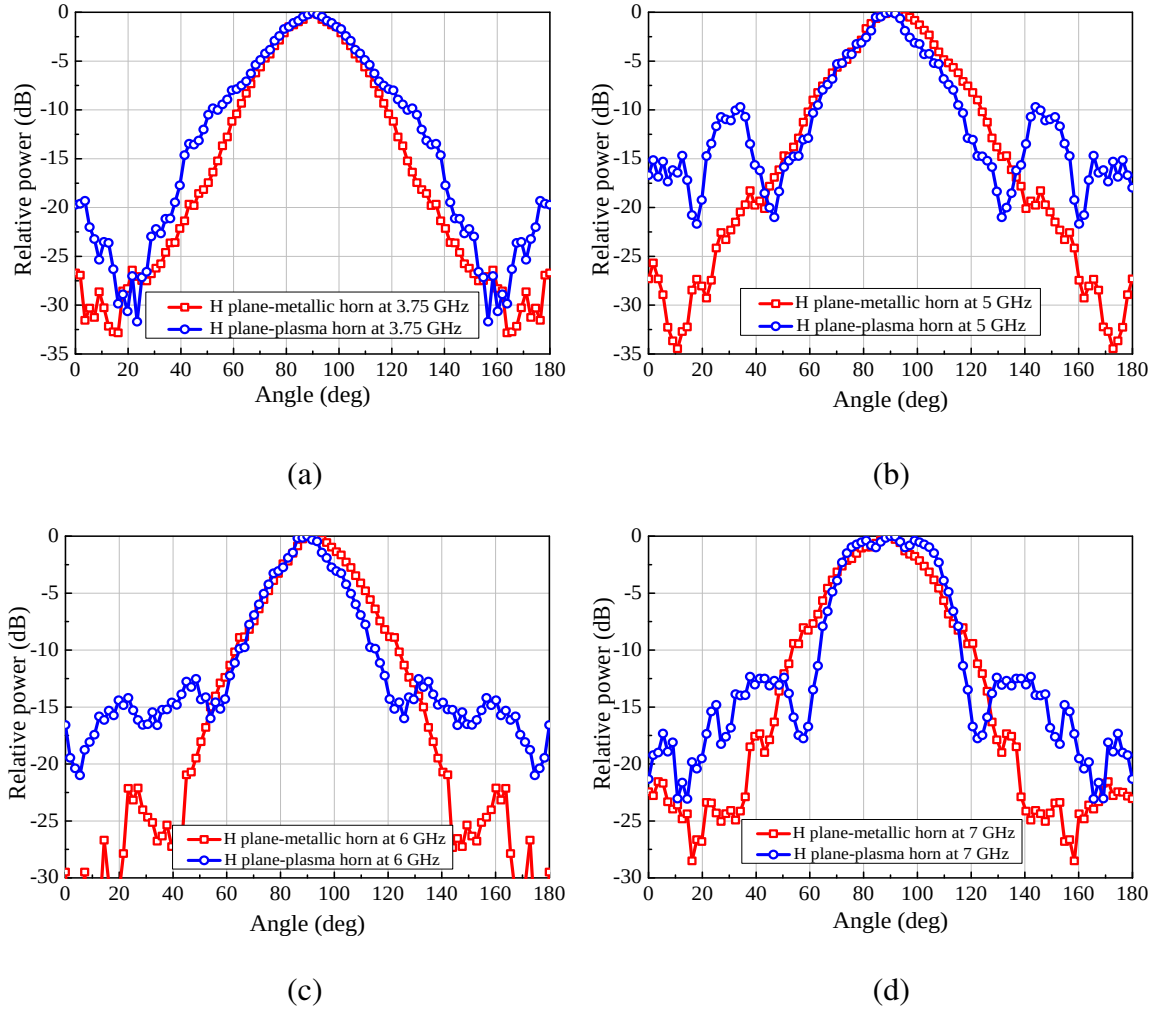


Figure 4.19: Comparison of H-plane radiation patterns of metallic and plasma horns (a) at 3.75 GHz, (b) at 5 GHz, (c) at 6 GHz and (d) at 7 GHz.

the side lobes of the plasma horn patterns are a little bit higher than that of the conventional horn patterns in certain cases, its level is lesser than -10 dB. Based on the overall radiation performance at different frequencies, the proposed plasma horn can be used in the place of conventional metal horn for a wide range of frequencies with the added advantages of weight reduction, low production cost, easy installation etc.

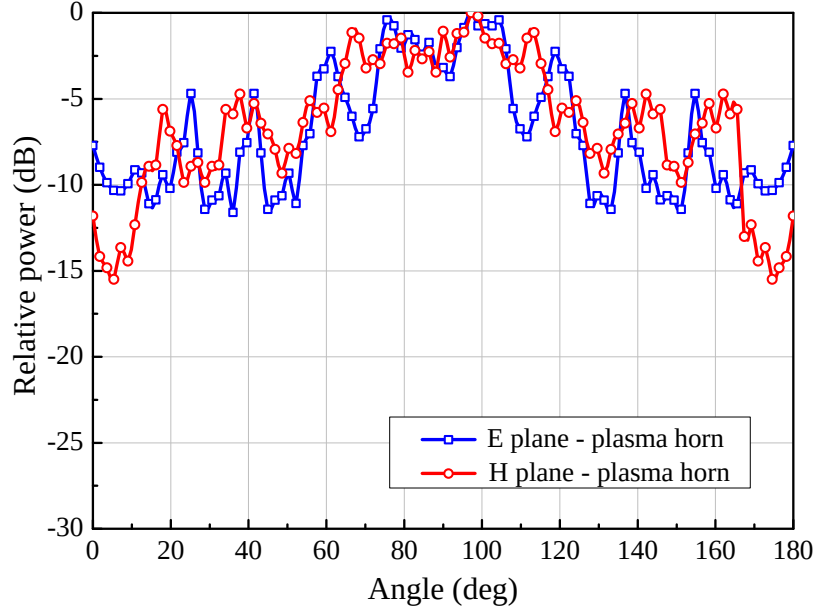


Figure 4.20: E-plane and H-plane radiation patterns of plasma horn at frequency greater than the plasma frequency.

In order to study the plasma behavior of the wire array medium of the proposed horn, the E-plane and H-plane radiation patterns at 7.8 GHz, a frequency greater than the plasma frequency (7 GHz) are also measured and the corresponding patterns are plotted as shown in the Fig. 4.20. It can be seen that both radiation patterns have become broad which is almost same as that of the launcher used. The radiated energy is distributed to the space without any directional property. It shows that the energy contained in the electromagnetic wave is transmitted through the wire medium instead of getting reflected by it, since the geometrical parameters of the wires in the array are designed in such a way that the plasma cut off frequency is at 7 GHz. As discussed earlier, the plasma wire medium acts as reflector upto the plasma frequency and above it, it acts as a transmitter. The desired radiation patterns are produced upto the plasma cut off frequency by the proposed plasma horn. Afterwards, the energy is transmitted through the wire array as unaffected by it.

4.4.2 HPBW

The HPBW for the E-plane and H-plane at different frequencies of S and C-bands for conventional metallic horn and proposed plasma horn are measured from their corresponding radiation patterns. The E-plane HPBW variation according to frequency for the proposed plasma horn is compared to that of the conventional metallic horn as shown in the Fig. 4.21. The variation of HPBWs for the proposed horn is almost similar to the metallic horn and also it is lesser than the HPBWs of metallic counterpart in most of the experimental points which indicates the merit of the plasma horn to produce narrow pattern.

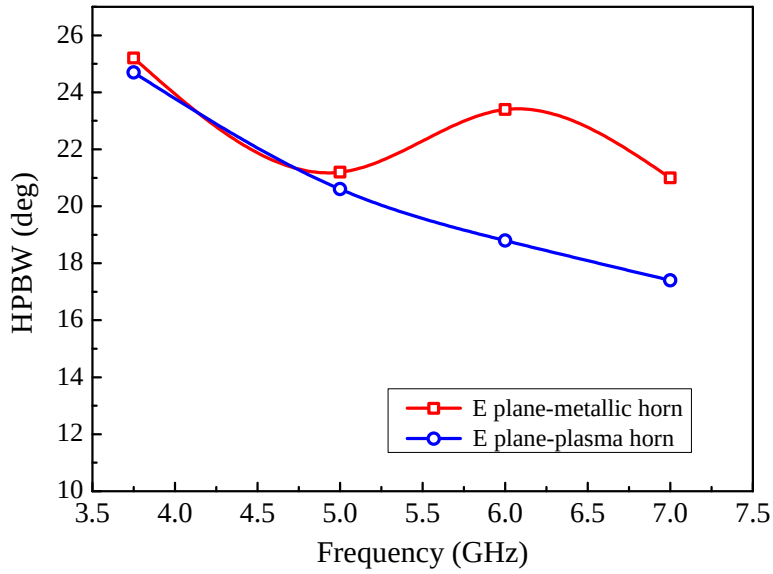


Figure 4.21: E-plane HPBW versus frequency graphs of S-band and C-band frequency ranges.

The H-plane HPBW variation with respect to the different frequencies for metallic horn and proposed plasma horn are also plotted and is given in Fig.4.22. By comparing these curves, it can be seen that the HPBW variation of the proposed horn is also similar to that of the metallic horn. Moreover, the HPBW values of the proposed horn

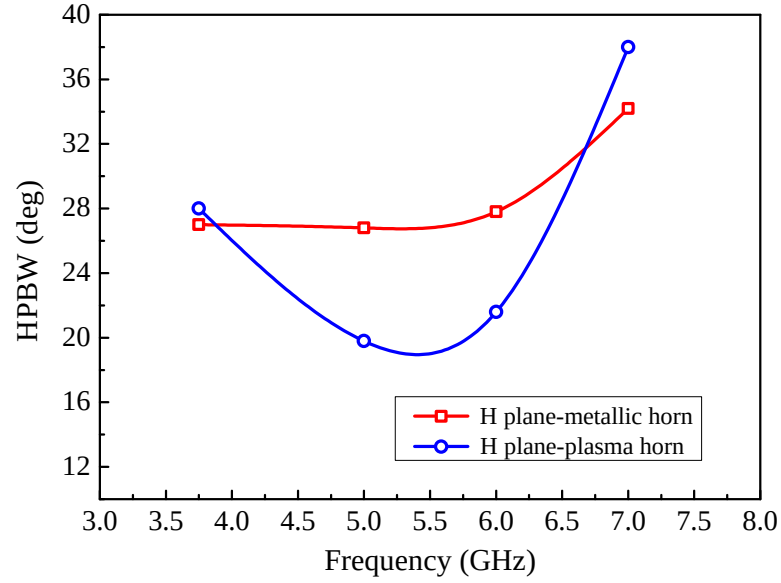


Figure 4.22: H-plane HPBW versus frequency graphs of S and C-band frequency ranges.

are lesser at most of the frequencies than the values of the metallic horn, it indicates that the main lobe is narrowed in H-plane also. So the conclusion is that the proposed horn shows almost similar HPBW variation as that of the metallic horn.

4.4.3 Side lobe level

The side lobe levels are measured from the normalized E-plane and H-plane radiation patterns for the metallic horn and the proposed horn. The side lobe levels in the E-plane patterns for both the horns at different frequencies are plotted in Fig. 4.23. The two patterns show the similar behavior and the levels are less than -10 dB. The H-plane side lobe levels of both the horns at different frequencies are plotted in Fig. 4.24. Even though the side lobe levels of the proposed horn is a little bit higher than that of the metallic horn, it may not affect the overall performance of the antenna.

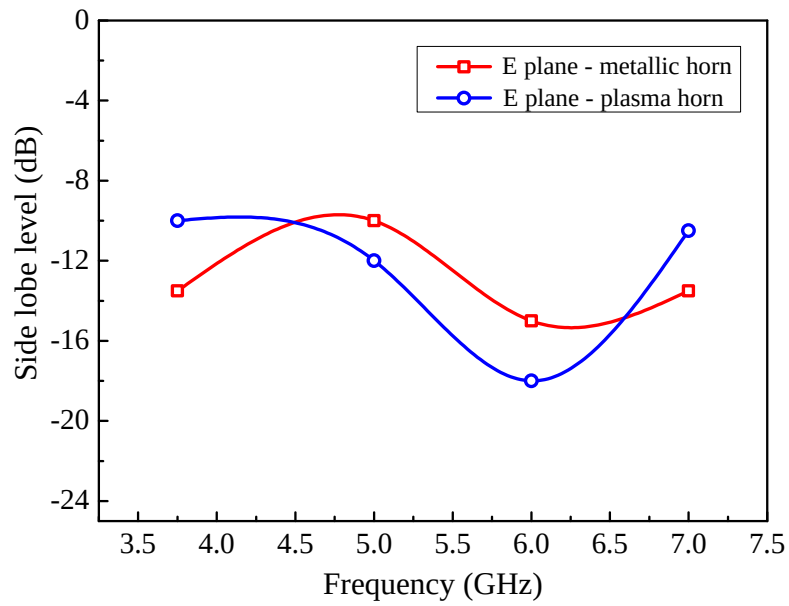


Figure 4.23: E-plane side lobe level versus frequency graph of S and C-band horns.

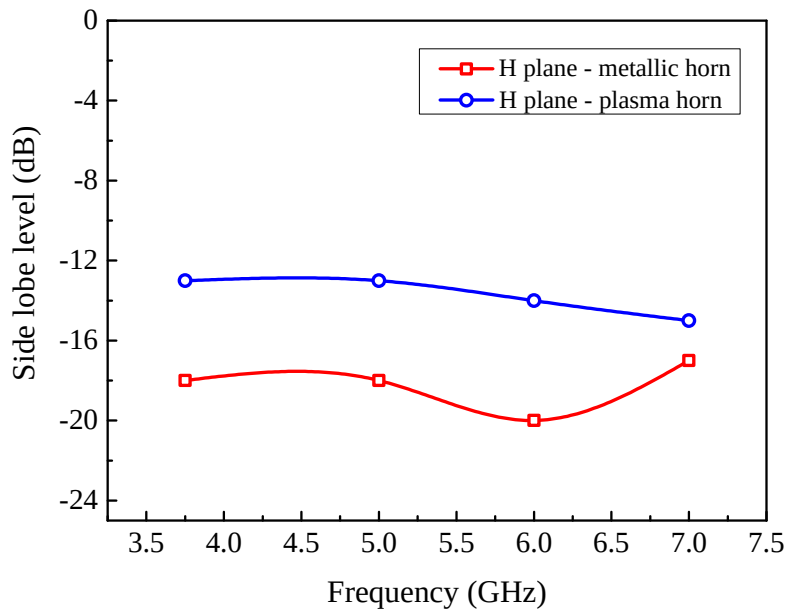


Figure 4.24: H-plane side lobe level versus frequency graph of S and C-band horns.

4.4.4 Axial gain

The gain in the axial direction is taken by gain transfer method. The variation of axial gain with respect to different frequencies for metallic horn and plasma horn is given in Fig. 4.25. The graph shows that there is no much difference between the axial gain for both horns at most of the frequencies below the plasma frequency. But a gradual decrease in gain can be observed in the case of plasma horn after 7 GHz. Since the plasma cut off frequency is designed at 7 GHz by arranging wires with appropriate dimensions in an appropriate lattice spacing in the array according to the equation 2.7, the waves of frequencies larger than the plasma cut off frequency is transmitted by the plasma wire array instead of reflection. The waves are scattered in different directions from the axial direction leaving the plasma horn transparent to the electromagnetic wave. So the study of axial gain with respect to the frequency also proves the plasma behavior of the proposed horn.

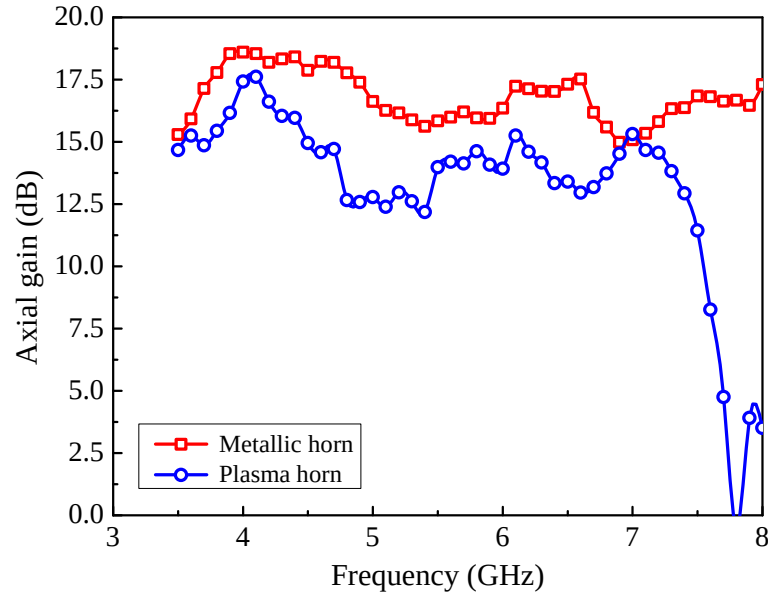


Figure 4.25: Axial gain versus frequency graph of metallic and plasma horns of S and C-bands designed for the plasma frequency 7 GHz.

4.4.5 VSWR

The VSWR is a measure of undesired reflection of the input energy from the interface of the waveguide and the horn due to mismatch. In fact, the value of the VSWR for an efficient antenna should be in between 1 and 2. The measured VSWR values with respect to the frequencies for metallic horn and plasma horn are plotted in the Fig. 4.26. It can be seen that the VSWR values of the proposed horn is also in the desired range which indicates the good impedance match between the horn and the waveguide.

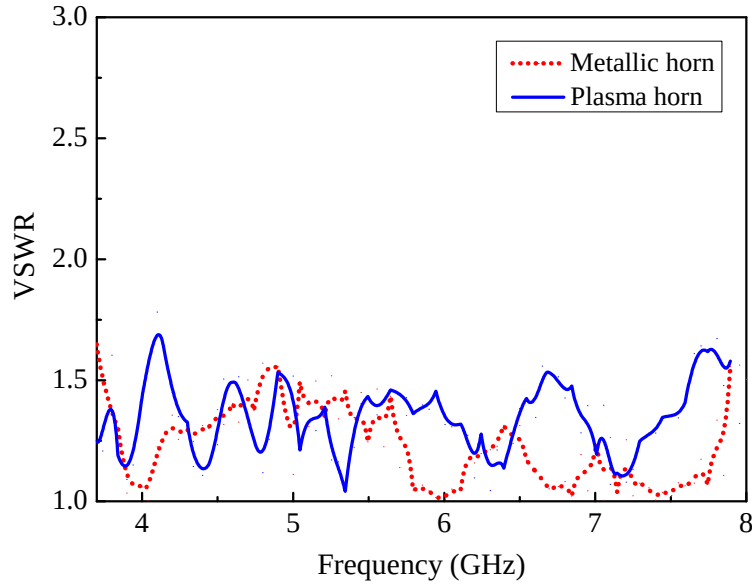


Figure 4.26: VSWR versus frequency graph of S and C-band horns.

4.5 Multilayer X-band plasma horn

In the previous sections, the radiation performance of a proposed novel artificial featherlight single layer plasma horn antenna is investigated. From the observations and analysis, it is verified that the proposed horn is capable of producing equivalent

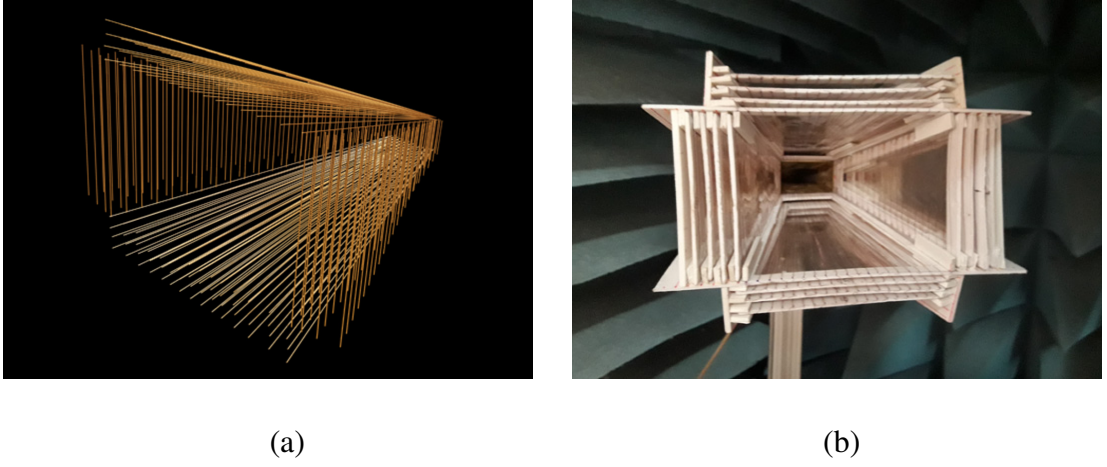


Figure 4.27: (a) Schematic presentation of the multilayer horn and (b) photograph of the multilayer horn.

radiation performance of a conventional metallic horn antenna. It is also identified that the plasma behavior of the one dimensional wire array fixed as the side walls of the proposed horn is the cornerstone of the equivalent radiation performance of the plasma horn.

In view of the fact that very often, a plasma medium is materialized with the help of more than one layer, the studies are carried out to check the effect of introduction of more layers to form the side walls. The structure can be called as multilayer plasma horn and the schematic diagram is as shown in Fig. 4.27 (a). The photograph of the multilayer horn is also presented as Fig. 4.27 (b). A frame is fabricated using a low loss foamex substrate in which grooves are provided near the side walls to insert or remove each sheet easily. In the present arrangement upto three more layers can be added to the side walls of the existing plasma horn.

Mainly three different multilayer horns are formed to study the effects of adding more plasma sheets to the side walls. The schematic presentation of the multilayer test

horns are given in Fig. 4.28 along with the single layer plasma horn. The multilayer structures are given as

1. Multilayer horn having one plasma layer each at E-walls and four layers each at H-walls,
2. Multilayer horn having one plasma layer each at H-walls and four layers each at E-walls and
3. Multilayer horn having four plasma layers each at both walls.

With the purpose of studying various parameters, the plasma layers are added one by one on each side walls. All the possible types of multilayer horns are formed and their radiation performances are studied. The results of these measurements did not show so much changes in the overall radiation performances. In the following subsections, the measurement of antenna parameters of the multilayer horn is discussed.

4.5.1 Radiation patterns

Since the radiation pattern gives the information about the energy distribution from the aperture to the space, the variation in the radiation patterns of the multilayer plasma horn with respect to the increase of plasma layers at the side walls for different frequencies have to be analyzed. Changes happened to other associated parameters like HPBW and side lobe level also need to be investigated.

The E-plane and H-plane radiation patterns of all possible combinations of layers on E and H-walls of multilayer plasma horn are taken. Out of these measurements, the radiation patterns obtained for a typical case at 8.3 GHz for three different combinations of plasma layers are plotted for getting a visualization of the effect of layers on the radiation pattern. All variations of parameters like HPBW, side lobe levels and

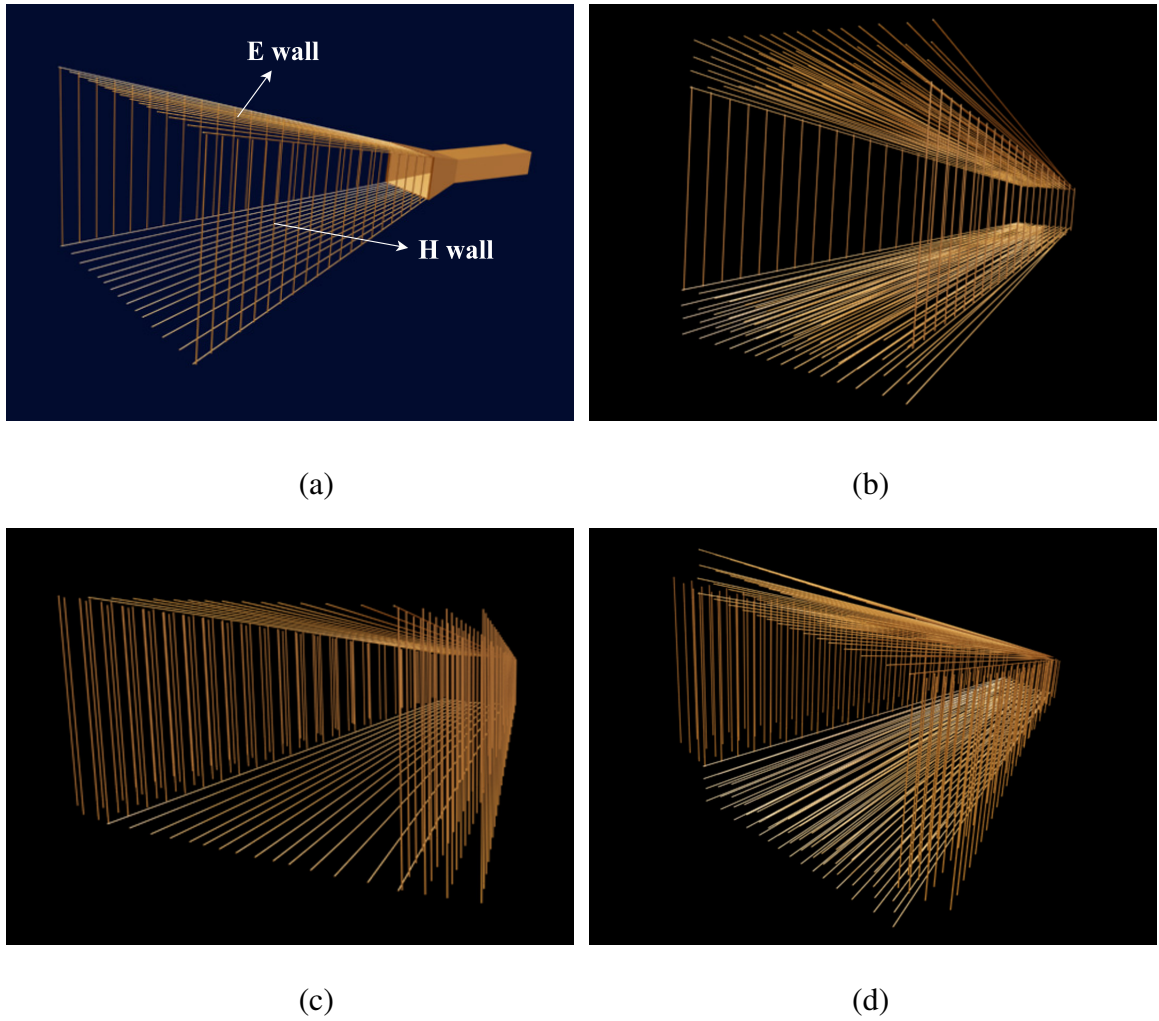


Figure 4.28: Schematic presentation of plasma horn with (a) one layer in each E-wall and H-wall, (b) one layer in each H-wall and four layers in each E-wall, (c) one layer in each E-wall and four layers in each H-wall and (d) four layers in each E-wall and H-wall.

axial gain with increase in number of layers and with respect to different frequencies are represented in tabular form. Slight variations are observed in certain cases for both types of radiation patterns with respect to the number of additional layers and frequency.

The E-plane and H-plane radiation patterns at 8.3 GHz of the single layer plasma horn and multilayer plasma horn with three more additional layers at E-walls are plotted in Figs. 4.29 and 4.30 respectively. The radiation patterns keep the same shape as that of the single layer plasma horn but slight variations in beamwidths are observed. The E-plane beamwidth is slightly widened while H-plane beamwidth is slightly narrowed.

Radiation patterns at 8.3 GHz for E-plane and H-plane of the single layer plasma horn and the multilayer plasma horn with three more additional layers at H-walls are plotted in Figs. 4.31 and 4.32 respectively. In this case also the radiation pattern of the multilayer plasma horn is almost same as that of the single layer plasma horn. However the beamwidths of the E-plane pattern and H-plane pattern are narrowed in the case of multilayer plasma horn compared to the other.

Similarly, the E-plane and H-plane radiation patterns at 8.3 GHz for the single layer plasma horn and multilayer plasma horn with three more additional layers at both E-walls and H-walls are plotted in Figs. 4.33 and 4.34. In this case the beamwidths for the E-plane patterns of both the horns remains the same while beamwidths of H-plane pattern of the multilayer horn shows a narrowing effect.

The antenna parameters like HPBW and side lobe levels of the multilayer horn for E-plane and H-plane radiation patterns are studied for different frequencies. The results obtained for the different combinations of the multilayer plasma horns are tabulated. The variations of HPBWs and side lobe levels with respect to different frequencies of multilayer horn having more number of plasma layers at H-walls but one plasma layer at E-walls are tabulated in Table 4.1. Noticeable variations in HPBWs and side lobe levels are not observed in most of the cases.

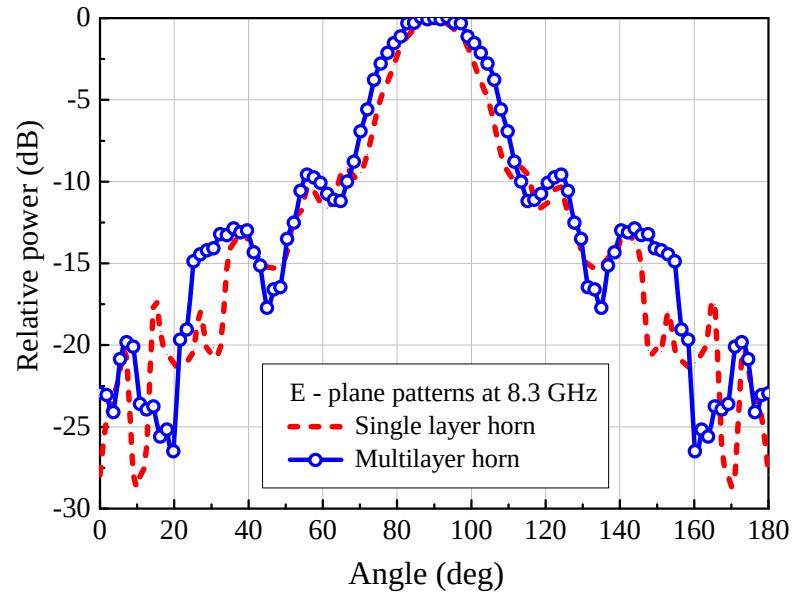


Figure 4.29: E-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each E-wall and one plasma layer in each H-wall.

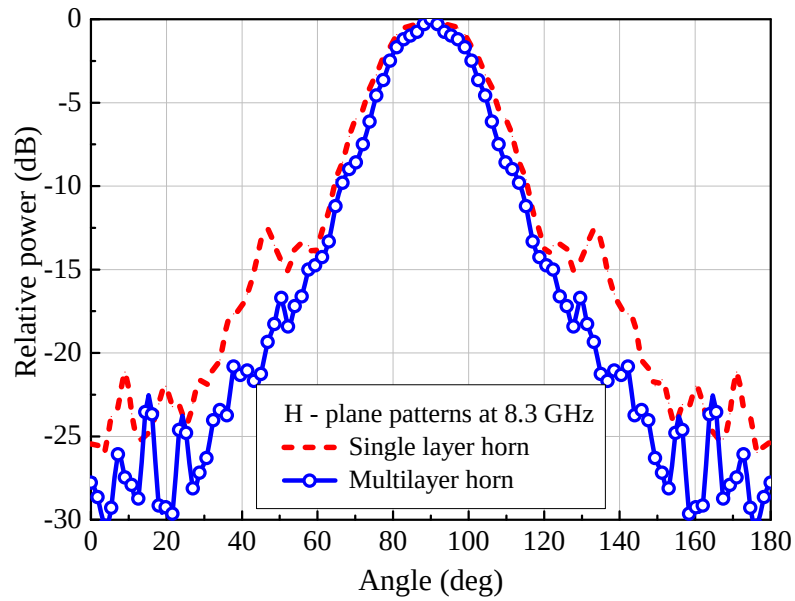


Figure 4.30: H-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each E-wall and one plasma layer in each H-wall.

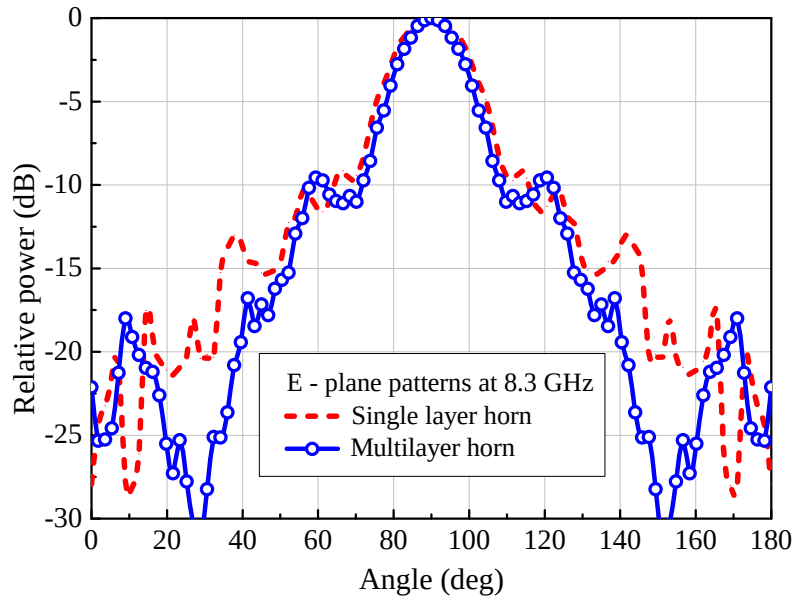


Figure 4.31: E-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each H-wall and one plasma layer in each E-wall.

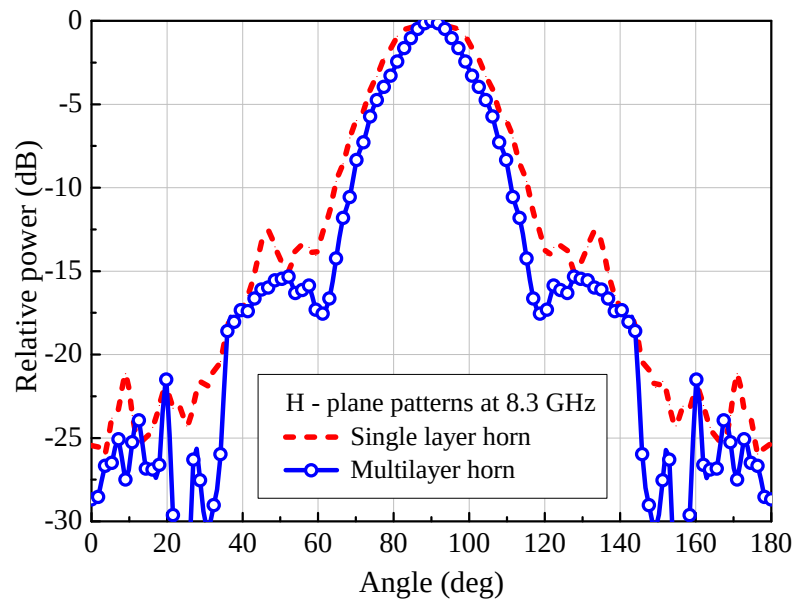


Figure 4.32: H-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each H-wall and one plasma layer in each E-wall.

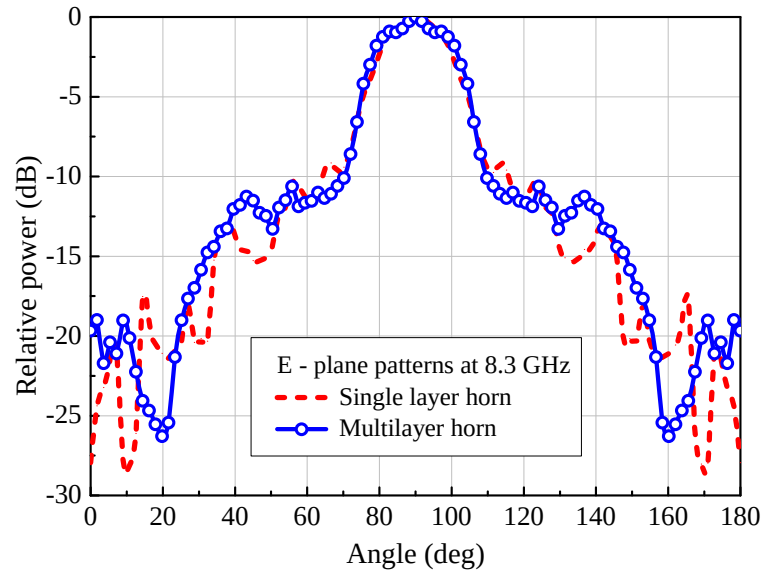


Figure 4.33: E-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each H-wall and in each E-wall.

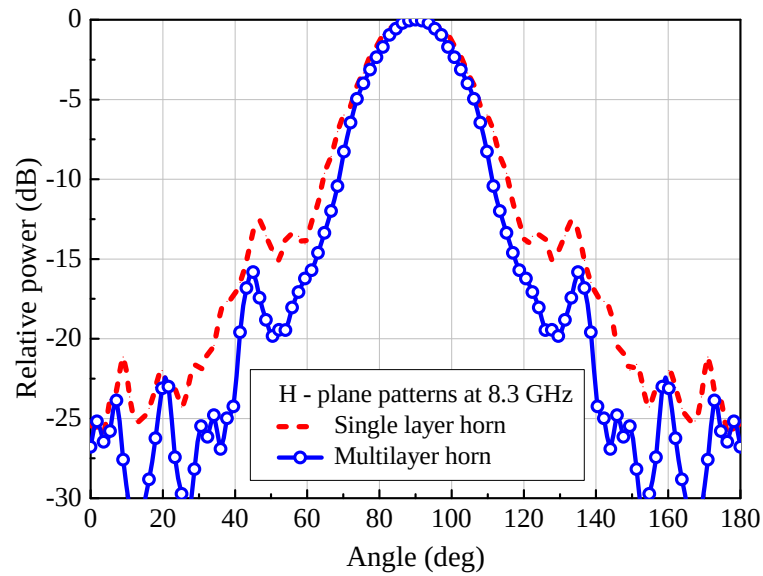


Figure 4.34: H-plane radiation patterns at 8.3 GHz for single layer plasma horn and multilayer plasma horn with four plasma layers in each H-wall and in each E-wall.

Table 4.1: HPBW and side lobe level for E-plane and H-plane patterns of different combinations of multilayer horn with single layer in each E-wall.

Frequency excited (GHz)	No. of layers in		E-plane		H-plane	
	E-wall	H-wall	HPBW (deg)	Side lobe level (dB)	HPBW (deg)	Side lobe level (dB)
8.1	1	1	25.2	-10.5	19.5	-13.5
	1	2	21.6	-10.5	30	-13.5
	1	3	20	-9	13.4	-14
	1	4	23.6	-9.5	18	-17.5
8.3	1	1	22	-11	28.8	-13.5
	1	2	20	-11.5	23	-14.5
	1	3	25.2	-9.5	20	-16
	1	4	28.8	-9.5	21.6	-16
8.5	1	1	22.8	-10.5	27	-16.5
	1	2	20	-11.5	20.5	-13.5
	1	3	18	-10.5	19.8	-14.5
	1	4	20	-10.5	21.6	-15
8.7	1	1	25.2	-10	23.5	-16.5
	1	2	23.5	-10.5	25.2	-15
	1	3	21.6	-10.5	19.3	-15
	1	4	21.6	-10.5	22	-15

The variations of HPBW and side lobe levels of multilayer horn having more number of plasma layers at E-wall but one layer at H-wall at different frequencies are tabulated in Table 4.2. Here also the increased number of plasma layers at H-walls made no significant difference on the radiation properties.

Table 4.2: HPBW and side lobe level for E-plane and H-plane patterns of different combinations of multilayer horn with single layer in each H-wall.

Frequency excited (GHz)	No. of layers in		E-plane		H-plane	
	E-wall	H-wall	HPBW (deg)	Side lobe level (dB)	HPBW (deg)	Side lobe level (dB)
8.1	1	1	25.2	-10.5	19.5	-13.5
	2	1	21.6	-9.5	23.4	-14
	3	1	18	-9.5	19.9	-14
	4	1	14.4	-10.5	26	-16
8.3	1	1	22	-11	28.8	-13.5
	2	1	16.3	-9.5	21.6	-16
	3	1	21.6	-10.5	31	-16
	4	1	18	-9.5	23	-17
8.5	1	1	22.8	-10.5	27	-16.5
	2	1	23	-11	28.8	-13
	3	1	21.6	-10	26.5	-14
	4	1	21.6	-10.5	27	-17
8.7	1	1	25.2	-10	23.5	-16.5
	2	1	27	-11.5	27	-16
	3	1	18	-10.5	16	-16.5
	4	1	19	-9.5	23	-15.5

For the simultaneously increasing number of plasma layers at both the walls, the variations of HPBWs and side lobe levels with respect to frequency are tabulated in Table 4.3. This formation of the multilayer horn also exhibited almost the same values as that of the previous cases.

Table 4.3: HPBW and side lobe level for E-plane and H-plane patterns of different combinations of multilayer horn with same number of layers in E-walls and H-walls.

Frequency excited (GHz)	No. of layers in		E-plane		H-plane	
	E-wall	H-wall	HPBW (deg)	Side lobe level (dB)	HPBW (deg)	Side lobe level (dB)
8.1	1	1	25.2	-10.5	19.5	-13.5
	2	2	20	-11	21.6	-13.5
	3	3	28.8	-10.5	30.7	-14.5
	4	4	21.6	-10	25.2	-13
8.3	1	1	22	-11	28.8	-13.5
	2	2	18	-11	28	-18
	3	3	14.4	-10.5	18	-15.5
	4	4	25.2	-11.5	25.2	-16
8.5	1	1	22.8	-10.5	27	-16.5
	2	2	20	-11	36	-12.5
	3	3	23.4	-10	20	-15.5
	4	4	18	-10.5	31.8	-13
8.7	1	1	25.2	-10	23.5	-16.5
	2	2	26.2	-10.5	21.6	-15.5
	3	3	21.6	-10	18	-16.5
	4	4	19.8	-9.5	23	-16

4.5.2 When to use multilayer?

The cause of not having much additional advantages with the increased number of plasma layers may be addressed as follows, using the concept of skin depth. In the case of metals such as copper with high electron density, the skin depth for experimental

frequency band will be around only a few micrometers. For the case of a horn with metallic walls, the thickness required will be only of the above said range. But for the case of a single layer plasma wall, the electrons confined within the wire may be thought of distributed within a slab of thickness equivalent to the diameter of the wire which may result in a reduced effective electron density value. Even in such cases, the skin depth may not exceed the equivalent thickness of the single layer plasma whereby the entire energy may be reflected by the single layer itself. This may be the possible explanation of the nearly perfect behavior of the radiation pattern obtained by using the single layer sheet.

In situations where skin depth exceeds the diameter of the wire medium, the other layers may have significance for dealing with the leaked part of the energy. This argument shows that if wires of very thin diameter are chosen to make the side walls, there may be a need of multilayers for the more effective performance of the antenna.

4.5.3 Axial gain

The variations of gain in the axial direction of the multilayer plasma horns in certain combinations of layers of side walls are studied with respect to different frequencies. The gain variations with increasing plasma layers one by one at the place of E-walls of the multilayer plasma horn by keeping only one layer at the H-walls for different frequencies are given in Fig. 4.35. It is noticed that at certain frequencies, there is enhancement of axial gain value when more plasma layers are added at E-walls. The gain variations with increasing plasma layers at the place of H-walls of the multilayer plasma horn at different frequencies are also taken and plotted in Fig. 4.36. Almost the same behavior seen, when more E-layers are added, is observed in this case also.

The multilayer horn with increasing plasma layers at both of the walls of the

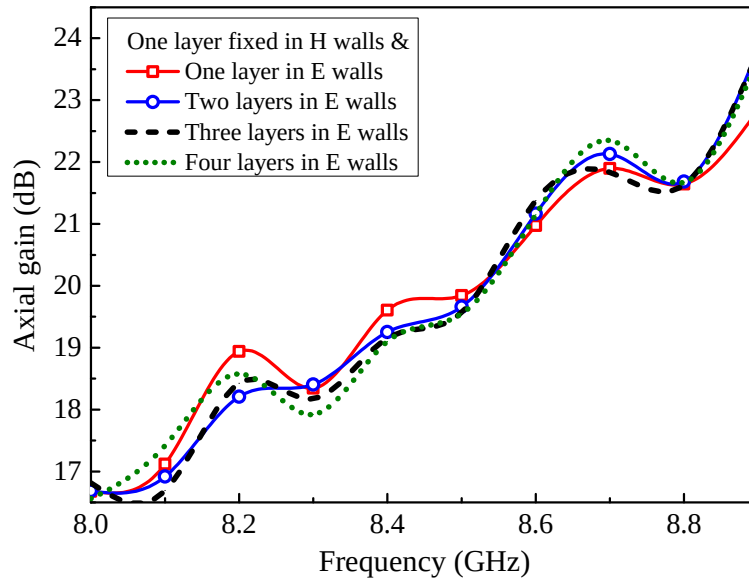


Figure 4.35: Axial gain for multilayer horn antenna at different frequencies with increase in plasma layers in E-walls, by keeping single layer in H-walls.

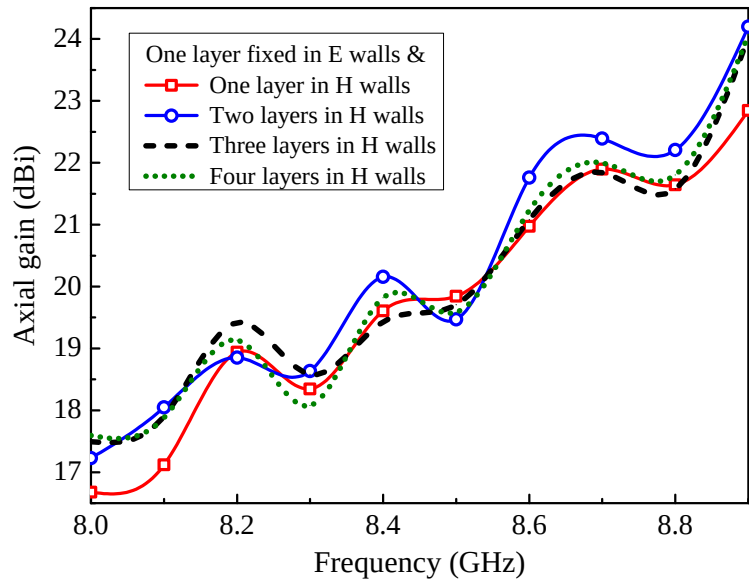


Figure 4.36: Axial gain for multilayer horn antenna at different frequencies with increase in plasma layers in H-walls, by keeping single layer in E-walls.

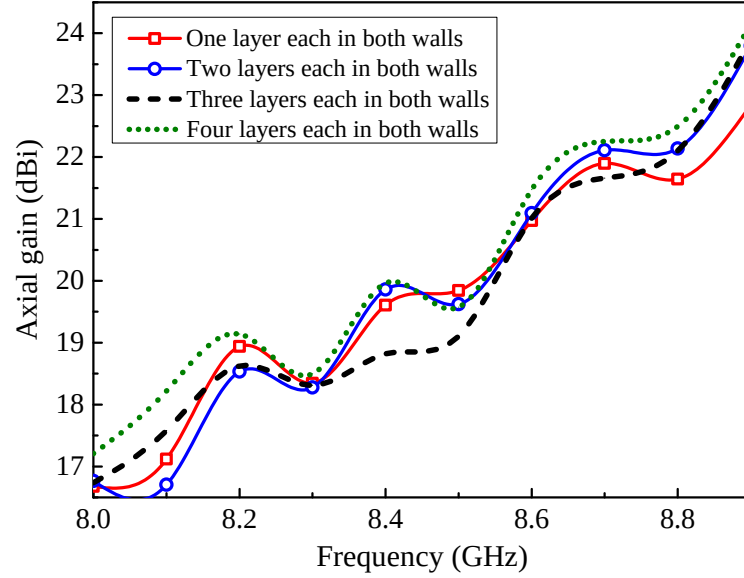


Figure 4.37: Axial gain for multilayer horn antenna at different frequencies with increase in plasma layers in both E-walls and H-walls.

plasma horn are tested for the axial gain variation with respect to the frequency. The corresponding measurements are plotted in Fig. 4.37. An increasing trend for the axial gain with respect to the increase in the number of layers can be observed at different frequencies.

4.5.4 VSWR

The VSWR for multilayer plasma horn with increasing plasma layers in E-walls at different frequencies are plotted in Fig. 4.38. Similarly the plots between the VSWR and frequency for multilayer plasma horn with increasing H-walls and that for increasing plasma layers at both walls are given in Fig. 4.39 and Fig. 4.40 respectively.

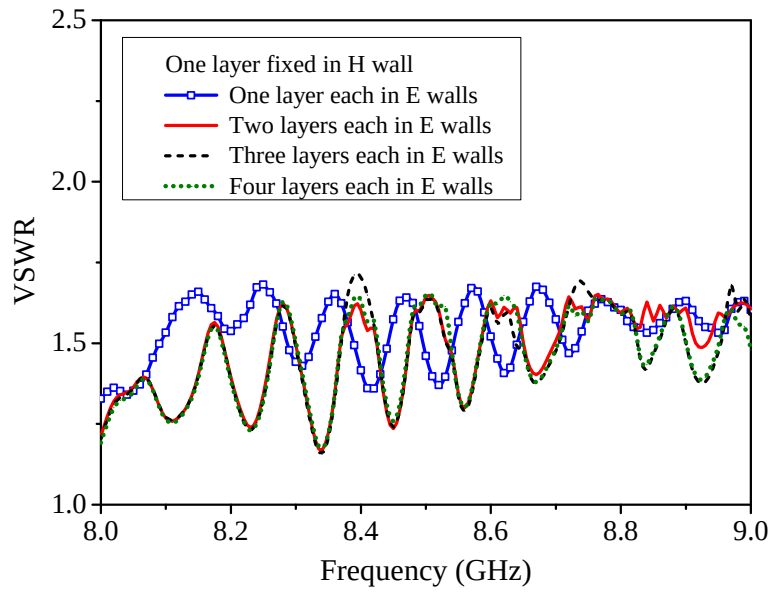


Figure 4.38: VSWR for multilayer horn antenna at different frequencies with increase in plasma layers in E-walls, by keeping single layer in H-walls.

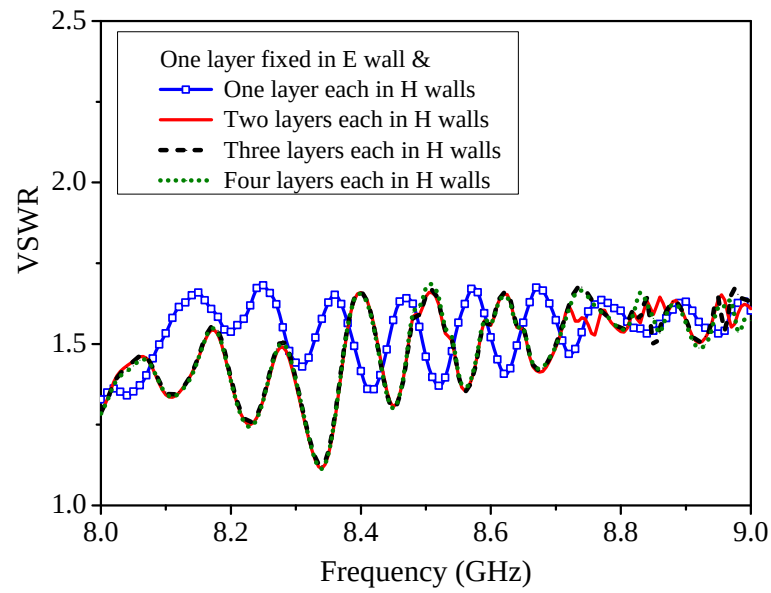


Figure 4.39: VSWR for multilayer horn antenna at different frequencies with increase in plasma layers in H-walls, by keeping single layer in E-walls.

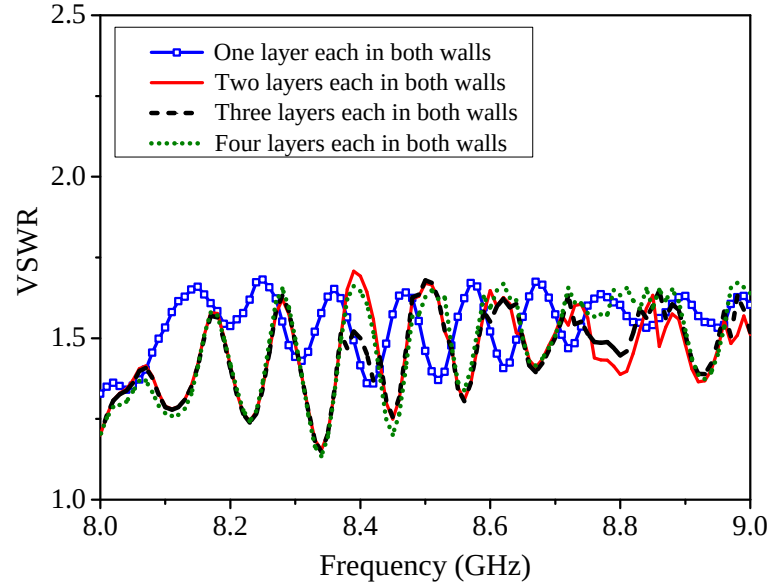


Figure 4.40: VSWR for multilayer horn antenna at different frequencies with increase in plasma layers in both E-walls and H-walls.

4.6 Conclusion

By exploring meta inspired properties, a novel proposal is made whereby the conventional metallic horn may be replaced by an equally effective artificial plasma horn antenna. The proposed featherlight artificial plasma horn has produced equivalent radiation performance of a conventional metallic horn. It is fabricated by replacing the metallic side walls of the conventional X-band pyramidal horn by the optimized thin wire arrays. From the studies of antenna parameters of the proposed horn, it can be understood that it performed similar results compared to that of metallic horn.

When the conventional metallic horns working with large collecting aperture may have disadvantages like huge antenna weight, high production cost, installation difficulties, infrastructure cost for mounting the antenna etc., the proposed novel meta-material inspired artificial plasma horn antenna may overcome such difficulties due to

its light weight and easiness of fabrication. Since the side walls of the metallic horns are replaced with the wire arrays containing thin wires, the antenna weight can be reduced much more. Hence the installation difficulties and high cost of infrastructure for mounting the horn can overcome. Moreover it avoids the collecting funnel nature of the conventional metallic horn during the windy and rainy seasons.

The idea is extended to the other bands of microwave ranges i.e. from 3.5 GHz to 8 GHz using S-band and C-band plasma pyramidal horns. It is observed that the radiation performance of the fabricated plasma horns are in good agreement with the corresponding conventional metallic horns. The experiments were also repeated by increasing the number of metamaterial plasma layers as the side walls of the proposed horn with the view of performance enhancement. The situations where such conditions may be useful are also explained in terms of effective electron density and skin depth of interacting wave.

CHAPTER 5

Results and Analysis of Metamaterial Inspired Negative Permeability Patch Antennas

5.1 Introduction

This section explains the results and its analysis of the proposed metamaterial inspired negative permeability monopole patch antennas. The fabricated antennas are tested and the antenna parameters like return loss, bandwidth, antenna gain and radiation patterns are analyzed. The single circular-SRR loaded monopole patch antenna proposed for frequency tuning is fabricated and its tuning capacity is tested for a specific microwave range. The BCSRR based monopole patch antenna for multiband operation is fabricated and its radiation properties are investigated ¹. The BCSRR

¹This work has been published in AIP Conference Proceedings, vol. 2162, no. 1, p. 020068, *AIP Publishing*, doi:10.1063/1.5130278, 2019.

based frequency tunable monopole patch antenna is also fabricated and its tuning capacity is verified over a wide frequency range ². The monopole patch antenna is designed to get a radiating frequency in the vicinity of 5 GHz which is not tunable. The presence of metamaterial inspired elements in the reactive near field of the monopole patch antenna gives an additional radiating frequency which can be tunable.

5.2 Single circular SRR loaded monopole patch antenna

The single circular SRR loaded monopole patch antenna consists of a monopole patch as the feed radiator and a single circular SRR as a metamaterial inspired resonating element. The monopole patch antenna is fabricated on a FR4 dielectric substrate and the SRR is made using a copper sheet by etching method with geometrical dimensions as given in chapter 3 section 3.5. The photograph of the experimental antenna showing the positioning of the SRR in the reactive near field of the monopole patch by a mechanical arrangement is shown in Fig. 5.1. The following antenna parameters are studied and analyzed.

5.2.1 Return loss

The experimental and the simulated S_{11} characteristics of the monopole patch antenna without SRR is given in Fig. 5.2. The simulation is done by Ansoft High Frequency Structure Simulator software. Both the characteristics curves obtained by experimental method and simulation method show good similarity. The monopole resonance frequency is fixed around 5 GHz by taking the length of the resonating patch fixed.

It can be used in the Wi-Max band applications. For the purpose of getting another

²This work has been published in *IEEE*, doi:10.1109/MetaMaterials.2019.8900946

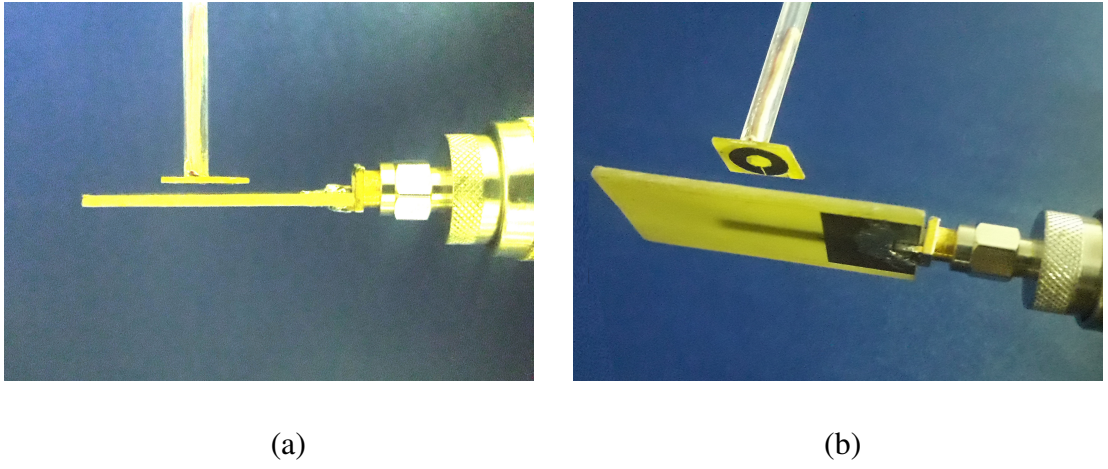


Figure 5.1: Photograph showing the positioning of the SRR with tuning facility in the reactive near field of monopole patch antenna (a) side view and (b) bottom view.

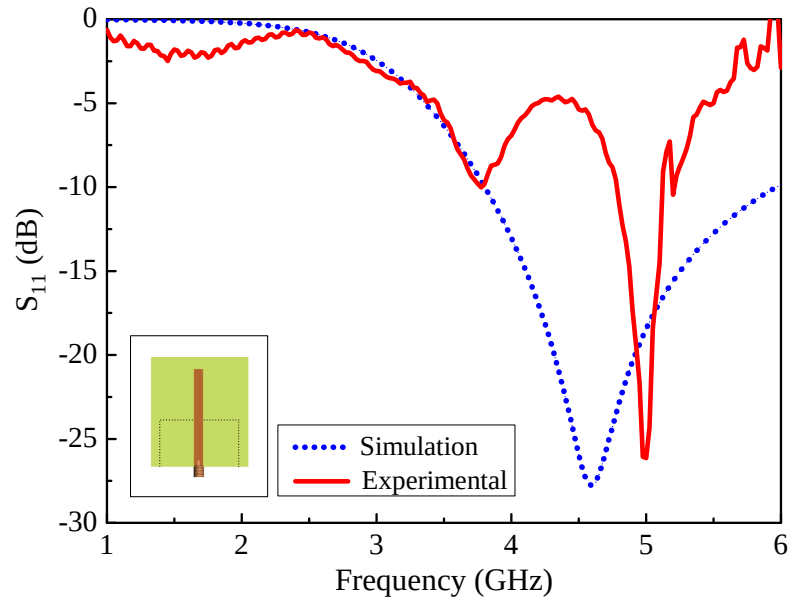


Figure 5.2: Experimental and simulated S_{11} characteristics of monopole patch antenna.

resonant radiation with a different frequency along with that of the monopole radiator, a single ring SRR of circular shape is loaded in the reactive near field of the monopole

as depicted in the Fig. 5.1. The SRR absorbs the energy required for its excitation from the wide band field available between the ground plane and termination region of the transmission line near the feed region of the monopole patch antenna. The SRR is positioned at the required place by means of a mechanical arrangement. The interplanar distance between the planes of the SRR and the monopole patch (d) can be precisely changed by means of a micrometer provided with this mechanical arrangement for tuning the radiation frequency of the SRR resonator. As the interplanar distance between the monopole plane and the SRR plane is varied, the inductive and capacitive reactances of the ring resonator changes and it causes the resonant frequency of the SRR to change accordingly with a provision of the additional benefit of tuning of radiation frequency. The S_{11} characteristics of the SRR loaded monopole patch antenna are analyzed for different interplanar distances d by both experimental and simulation methods.

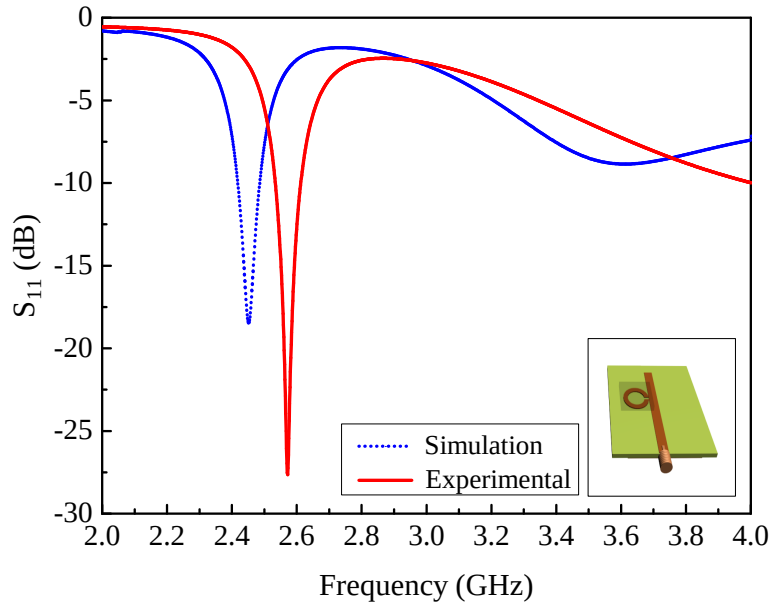


Figure 5.3: Experimental and simulated S_{11} versus frequency for the single circular SRR loaded monopole patch antenna showing the SRR resonance region.

Fig. 5.3 is a typical plot which gives a comparison of the experimental and simulated curves of S_{11} versus frequency at a specific interplanar distance of $d = 0.2$ mm. Except for a slight difference in the resonance frequency between the experimental and simulated results, both curves are in good agreement. The experimental S_{11} characteristics curves obtained with different values of d for the SRR loaded monopole patch antenna are given in Fig. 5.4. The monopole resonance absorption obtained in the vicinity of 5 GHz is not included in the Fig. 5.4, because the tuning frequency range can be shown with a better resolution in the figure. As the value of d is varied from 0.01 to 0.9 mm, the resonant frequency corresponding to the excitation from the SRR unit of the proposed monopole patch antenna changes from around 2.35 GHz to around 2.99 GHz.

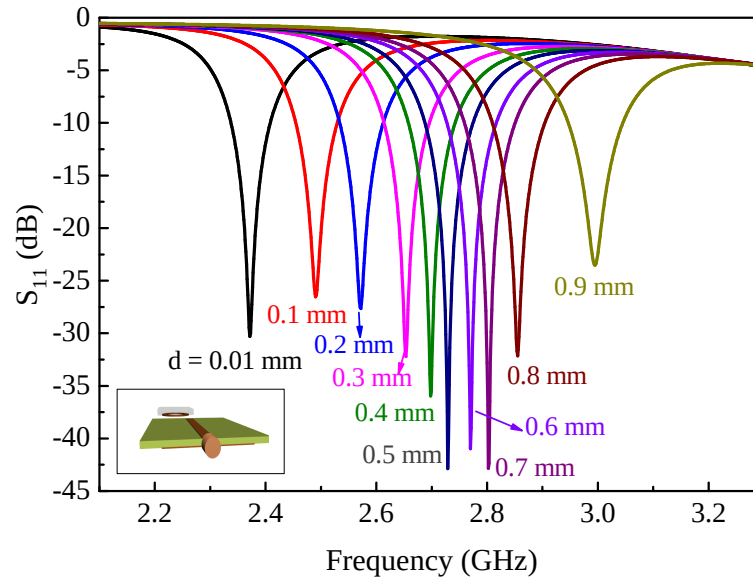


Figure 5.4: Experimental S_{11} versus frequency curves of single circular-SRR loaded monopole patch antenna for different interplanar distances d .

Fig. 5.5 depicts the variation of resonant frequency with respect to the changes in interplanar distances obtained by experimental and simulation methods. The frequency

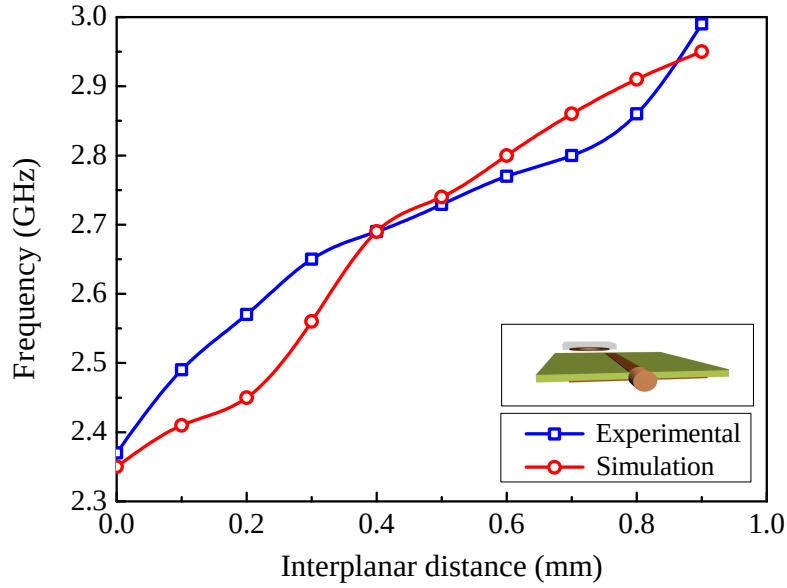


Figure 5.5: Experimental and simulation graphs of frequency versus interplanar distance ' d ' of the single circular SRR loaded monopole patch antenna.

standards for potential wireless communication applications like bluetooth, Wi-Fi and lower band of Wi-Max are included in this range.

The VSWR values for the monopole patch antenna against different frequencies are also taken and it gave a value just above 1 at the frequency range of 4 GHz to 5.5 GHz and for other frequency ranges, the value became more than 2. In addition to this, low VSWR values are obtained for SRR loaded monopole patch antenna at the frequency ranges of 2.2 GHz to 2.6 GHz also.

5.2.2 Impedance bandwidth

The single circular SRR gives an additional radiation depending on the geometrical dimensions of the ring which can be tuned with respect to the changes in interplanar distance. The 2:1 VSWR impedance bandwidths (the frequency range for which the

VSWR values less than 2) at the different tuned resonant frequencies can be measured from the VSWR versus frequency graph. The impedance bandwidth can also be evaluated in terms of percentage and is calculated from the S_{11} characteristics by measuring the frequency difference between the two identical points having S_{11} values at -10 dB. It is called as impedance bandwidth expressed in percentage and is calculated by using the equation given in the chapter 3 section 3.3.7 as

$$\text{Impedance bandwidth (in \%)} = \frac{f_H - f_L}{f_c} \times 100 \%$$

The -10 dB impedance bandwidths with respect to the different interplanar spacing (d) are measured from the experimental and simulated S_{11} characteristics and they are tabulated in Table 5.1. The experimental and simulated values of impedance bandwidth versus different interplanar distances are plotted in Fig. 5.6. Both results give reasonable similarity except for very small values of spacing (< 0.2 mm).

Table 5.1: Impedance bandwidth values of the SRR induced absorption notch of the single circular SRR loaded monopole patch antenna at various interplanar distances.

Inter planar distance d (mm)	Resonant frequency		Impedance bandwidth	
	Experimental (GHz)	Simulation (GHz)	Experimental (%)	Simulation (%)
0.01	2.37	2.35	2.95	4.13
0.1	2.49	2.40	2.97	2.08
0.2	2.57	2.44	3.04	3.07
0.3	2.65	2.56	3.09	3.87
0.4	2.69	2.69	3.16	3.64
0.5	2.73	2.74	3.3	4.16
0.6	2.77	2.80	3.29	4.04
0.7	2.80	2.86	3.25	4.06
0.8	2.86	2.91	3.32	4.19
0.9	2.99	2.95	3.38	3.86

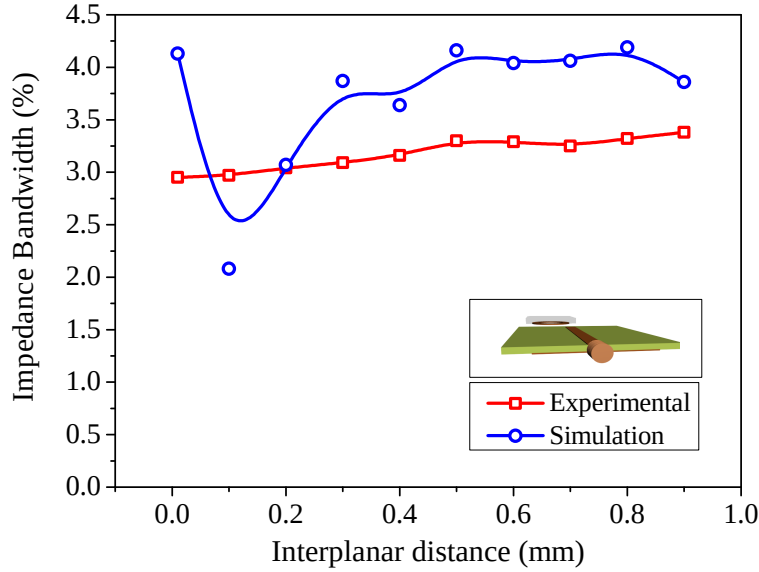


Figure 5.6: Experimental and simulated curves of impedance bandwidth versus interplanar distance (d) of single circular SRR loaded monopole patch antenna.

5.2.3 Antenna gain

The antenna gain of the single circular SRR loaded monopole patch antenna is measured by gain transfer method as explained in the chapter 3 section 3.3. The gain is taken in that direction which gives a maximum value for it. The variation of antenna gain with respect to different frequencies is measured for monopole patch antenna without the single SRR. It is plotted in Fig. 5.7. Since the monopole patch antenna is designed to radiate in the vicinity of frequency 5 GHz, it radiates with a proper gain in the range of 4 GHz to 5 GHz and has a peak value of around 5 dBi.

The variation of antenna gain with respect to different frequencies for SRR loaded monopole patch antenna is given in Fig. 5.8. The single SRR is placed for an interplanar distance of $d = 0.1$ mm. The gain-frequency curve shows two maxima for two frequency ranges and these ranges corresponds to two radiating frequencies i.e. one

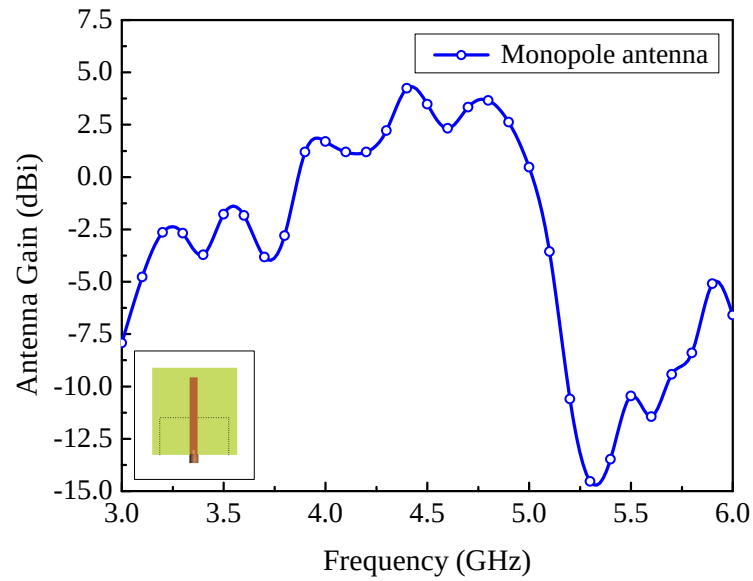


Figure 5.7: Antenna gain versus frequency graph of the monopole patch antenna.

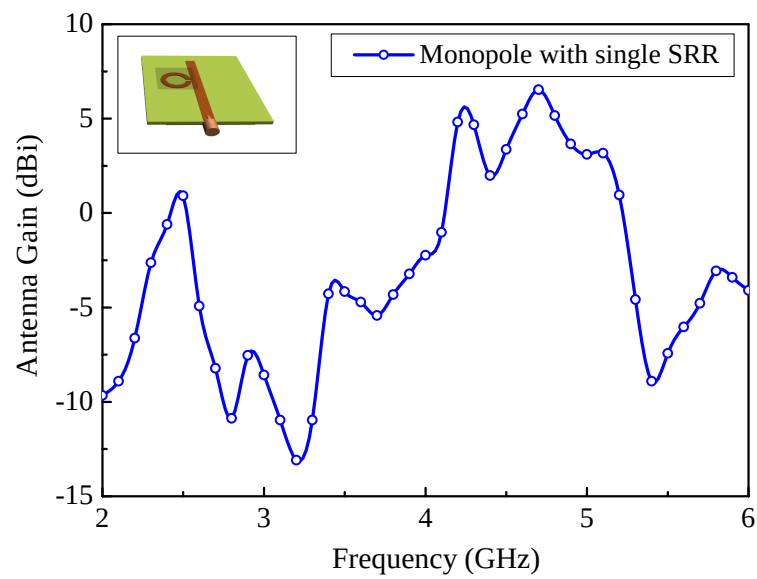


Figure 5.8: Antenna gain versus frequency graph of the single circular SRR loaded monopole patch antenna.

around 2.45 GHz due to SRR (which is tunable with respect to spacing) and the another that of the monopole radiation in the vicinity of 5 GHz. The gain of the antenna corresponding to monopole radiation is slightly increased in this case compared to the monopole alone and at the radiating frequency due to SRR, the antenna provides a gain of around 2 dBi.

5.2.4 Radiation patterns



Figure 5.9: Photograph of the experimental set up for the radiation pattern measurement of monopole antenna.

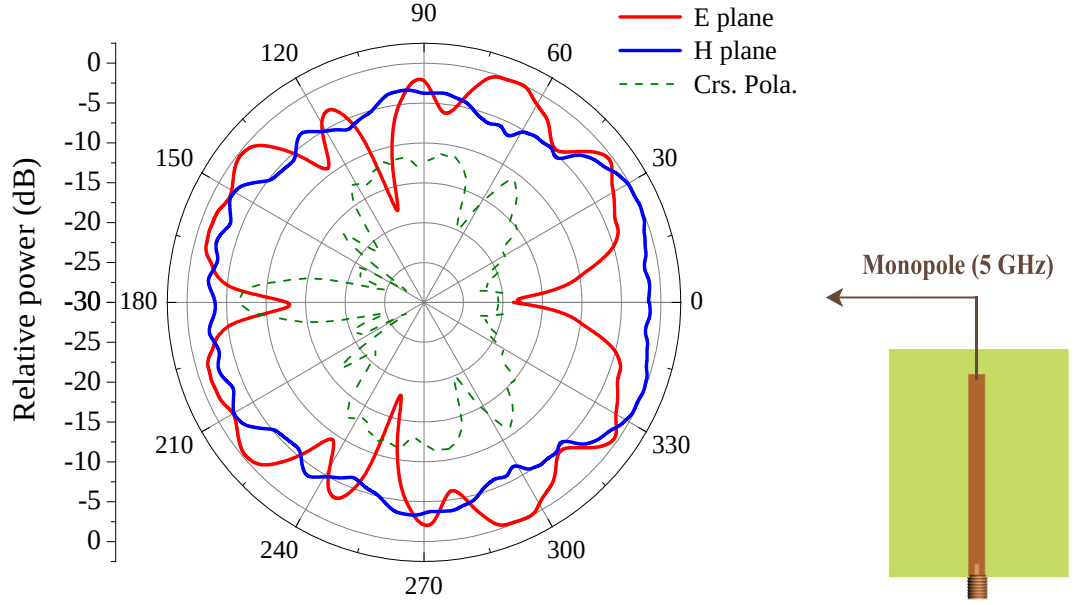


Figure 5.10: Radiation patterns of the monopole patch antenna fabricated on FR4 dielectric substrate at 5 GHz.

A photograph of the experimental arrangement used for the radiation pattern measurement is given in as Fig. 5.9. The antenna under test (AUT) is set in the receiving mode and a wide band pyramidal horn is used as the source. The 2D experimental co-polar and cross-polar radiation patterns along E-plane and H-plane of monopole patch antenna with FR4 dielectric substrate is drawn and it is given in the Fig. 5.10. The patterns are drawn near the monopole resonance at a frequency of 5 GHz. The H-plane radiation pattern shows a nearly uniform nature in all directions. The E-plane patterns show a directional behavior. The cross polarization levels are very low.

The co-polarization and cross-polarization radiation patterns along E-plane and H-plane for single circular SRR loaded monopole patch antenna with FR4 dielectric

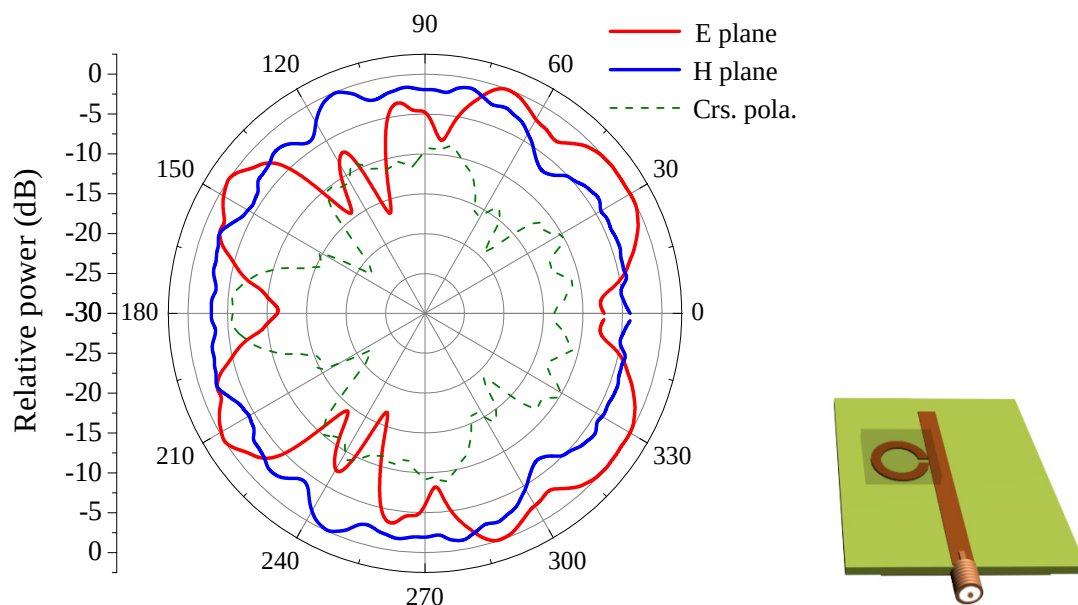


Figure 5.11: Radiation patterns of the single circular SRR loaded monopole patch antenna fabricated on FR4 dielectric substrate at 5 GHz.

substrate at a frequency of 5 GHz and at an interplanar distance of 0.1 mm are taken and given in Fig. 5.11. The E-plane and H-plane radiation patterns at 5 GHz are not much affected by the insertion of single SRR unit. The increase of the cross polar level is negligible considering the co-polar levels.

The E-plane and H-plane co-polarization and cross-polarization patterns of single circular SRR loaded monopole patch antenna with FR4 dielectric substrate at a frequency of 2.45 GHz for an interplanar distance of 0.1 mm are given in Fig. 5.12. The E-plane radiation pattern becomes almost uniform nature and H- plane becomes narrowed compared to the radiation pattern of 5 GHz. The increase of cross polar level is negligibly small.

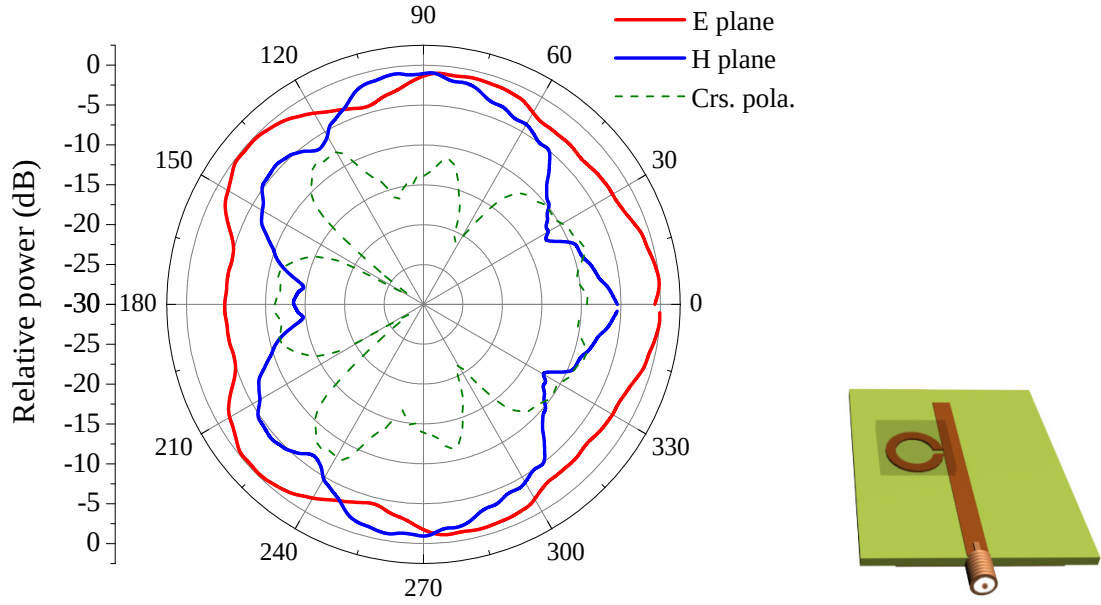


Figure 5.12: Radiation patterns of the single circular SRR loaded monopole patch antenna fabricated on FR4 dielectric substrate at 2.45 GHz.

5.3 BCSRR loaded multiband monopole patch antenna

In some situations and for specific devices, it is necessary to have a multiband antenna which can operate at multiple frequencies simultaneously. The proposed BCSRR loaded monopole antenna is such an antenna which can radiate different frequencies in addition to the monopole radiation. Depending upon the material permittivity and thickness of the substrate used for the fabrication of the BCSRR, the effective capacitance of the resonator changes which will result in the corresponding variation of the resonant frequency. Here two BCSRR units with same dielectric of different thicknesses are used to create two resonant frequencies and these frequencies are radiated along with the radiation of the monopole patch antenna. The photograph of the monopole

patch antenna loaded with two BCSRR units is given in Fig. 5.13. The simultaneous radiation of multiple frequencies is an advantage in wireless communication devices as the number of antennas installed for different applications in a single device can be reduced by replacing it with the proposed antenna.

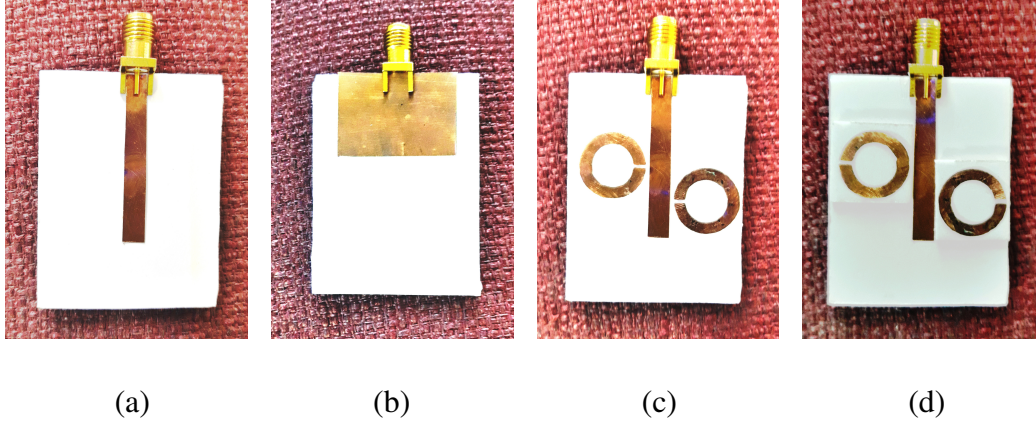


Figure 5.13: Photograph of (a) top view of monopole patch antenna with foamex substrate, (b) bottom view of the antenna, (c) top view of the antenna with the bottom rings of BCSRR and (d) top view of the BCSRR loaded multiband monopole patch antenna.

5.3.1 Return loss

The experimentally measured and the simulated S_{11} characteristics of the BCSRR loaded monopole patch antenna structure versus frequency are depicted in Fig. 5.14. The peaked notch at the vicinity of 5 GHz is due to the monopole patch radiation while the additional two notches at 2.45 GHz and at 2.75 GHz are due to BCSRR units. Since the two BCSRR units have different dielectric thicknesses, say, 1.45 mm (BCSRR-1 for 2.45 GHz) and 1.65 mm (BCSRR-2 for 2.75 GHz), the values of the effective capacitance and inductance will be different for each unit resulting in the formation of two notches at different frequencies.

The VSWR measurements are taken for the monopole patch antenna without BCSRR units at different frequencies and the measured values are less than 2 in the frequency range of 4 GHz to 5 GHz. The VSWR values for multiband BCSRR loaded monopole patch antenna are also measured at different frequencies and the observed values are well below the maximum acceptable VSWR for the frequency ranges 4 GHz to 5 GHz and at the vicinity of 2.45 GHz and 2.75 GHz.

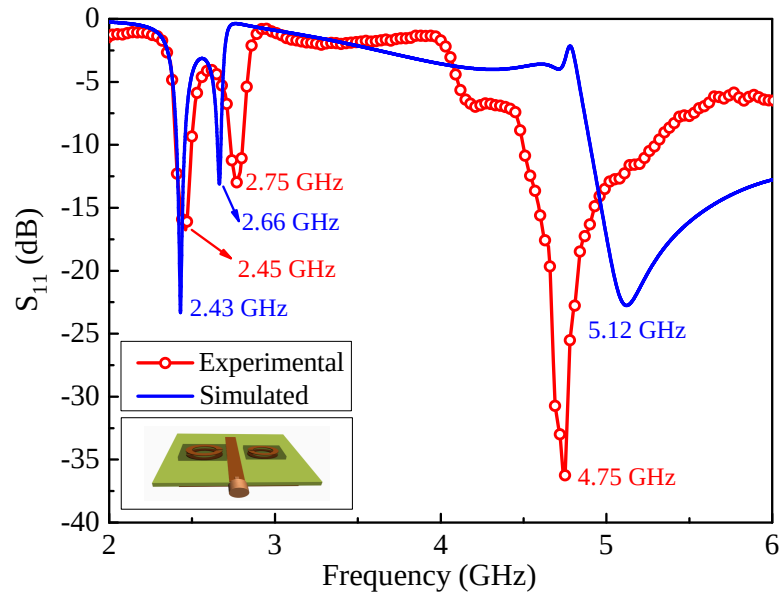


Figure 5.14: Experimental and simulated S_{11} characteristics versus frequency of the BCSRR loaded monopole patch antenna.

The geometrical parameters of the rings and thicknesses of the dielectric used are so selected that the additional frequencies are at the frequencies for potential applications such as Wi-Fi, bluetooth, Wi-Max etc. The frequency of 2.45 GHz is internationally selected for bluetooth and Wi-Fi applications. The frequency 2.75 GHz can be used for lower Wi-Max band applications while 5 GHz frequency can be used for upper Wi-Max band applications. The selected frequencies can be designed to other required values by altering the geometrical dimensions of the rings and the dielectric constant of the

substrate. As the size of the rings increases, the notch moves to the lower frequency range as the effective inductance and capacitance increases whereas the thickness of the dielectric substrate increases, the notch moves to the higher frequency side.

In fact, the magnetic resonant frequency of the BCSRR depends on the self inductance of the rings, mutual inductance between the two rings, mutual capacitance between the rings and the capacitance of the two splits. The mutual inductance between the two rings is relatively small compared to the self inductance of the two rings and the capacitance of the splits is also small compared to the mutual capacitance between the rings. So the notch due to the BCSRR coupling is mainly due to the changes in the ring dimensions, which in turn changes its self inductance, as well as the mutual capacitance between the rings. Thus multiband operation is achieved by coupling two BCSRR units having selected parameters with the monopole patch. More notches at different frequencies can be procured by inserting more number of BCSRR units corresponding to the maximum field positions near the monopole patch. Thus different antennas for different applications in a single device can be replaced with the single proposed antenna. Here, care should be taken to obtain maximum radiation power by specifically placing the BCSRR units at points where S_{11} shows maximum response.

5.3.2 Impedance bandwidth

The impedance bandwidths obtained at the two resonating frequencies and at the monopole patch radiation are narrow as expected for metamaterial inspired negative permeability structures. The bandwidths corresponding to the simulated results are also similar to the experimental values. The experimental and simulated impedance bandwidth values in percentage obtained to BCSRR-1 are 4.49 % and 2.55 % while for BCSRR-2, the values are 2.91 % and 1.25 % respectively.

5.3.3 Antenna gain

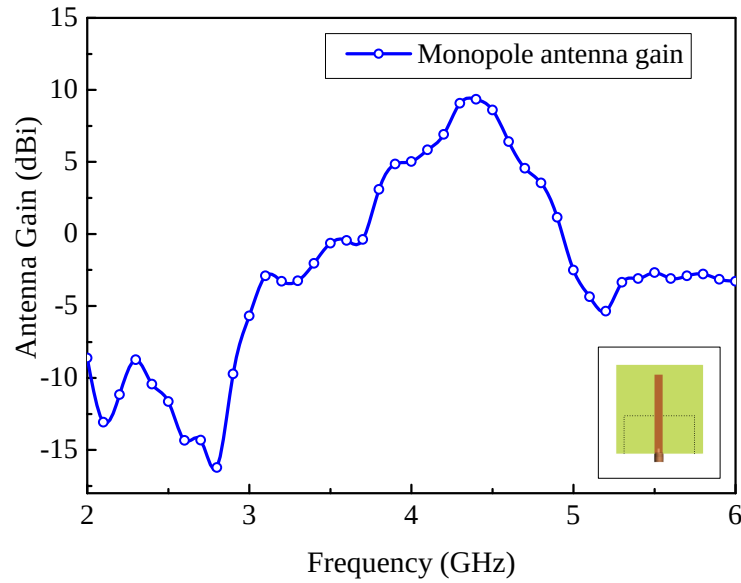


Figure 5.15: Antenna gain versus frequency graph of the monopole patch antenna fabricated on low loss dielectric substrate.

The antenna gain versus different frequencies for the monopole patch antenna with a low loss dielectric substrate of foamex sheet is measured by the gain transfer method. It is given in the Fig. 5.15. The gain is measured in the peaked direction and it shows a maximum gain of 10 dBi at 4.5 GHz.

The antenna gain of multiband BCSRR loaded monopole patch antenna with a low loss foamex dielectric substrate is measured. The gain is measured in the peaked direction and it is taken for different frequencies. It is shown in Fig. 5.16. The curve shows that the proposed antenna has good antenna gain of approximately 6 dBi in the frequency range of 4.5 GHz to 5 GHz and gain around 2.5 dBi at 2.45 GHz and 2.75 GHz. The antenna gain in the range of 4.5 to 5 GHz corresponds to the monopole patch antenna and its gain bandwidth is decreased compared to the monopole patch

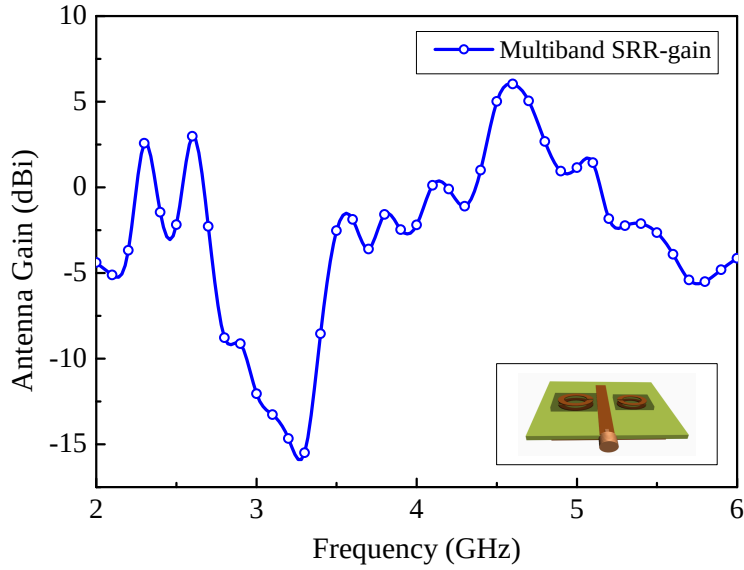


Figure 5.16: Antenna gain versus frequency graph of the multiband SRR loaded monopole patch antenna fabricated on low loss dielectric substrate.

antenna without BCSRR units. The other two gain ranges correspond to the radiating frequencies of BCSRR units.

5.3.4 Radiation patterns

The E-plane and H-plane co-polar radiation patterns along with the cross-polarization patterns of the monopole patch antenna with low loss dielectric substrate is taken at a frequency of 4.5 GHz and it is demonstrated in Fig. 5.17. It has almost same radiation patterns of the monopole patch antenna with FR4 dielectric substrate.

The E-plane and H-plane co-polar radiation patterns of the multiband BCSRR loaded proposed antenna are drawn at a frequency of 4.5 GHz and it is shown in Fig. 5.18. The E-plane pattern has the directional behavior as seen in the previous cases while the H-plane pattern changes from the uniform behavior. The cross polarization level is slightly increased in this case.

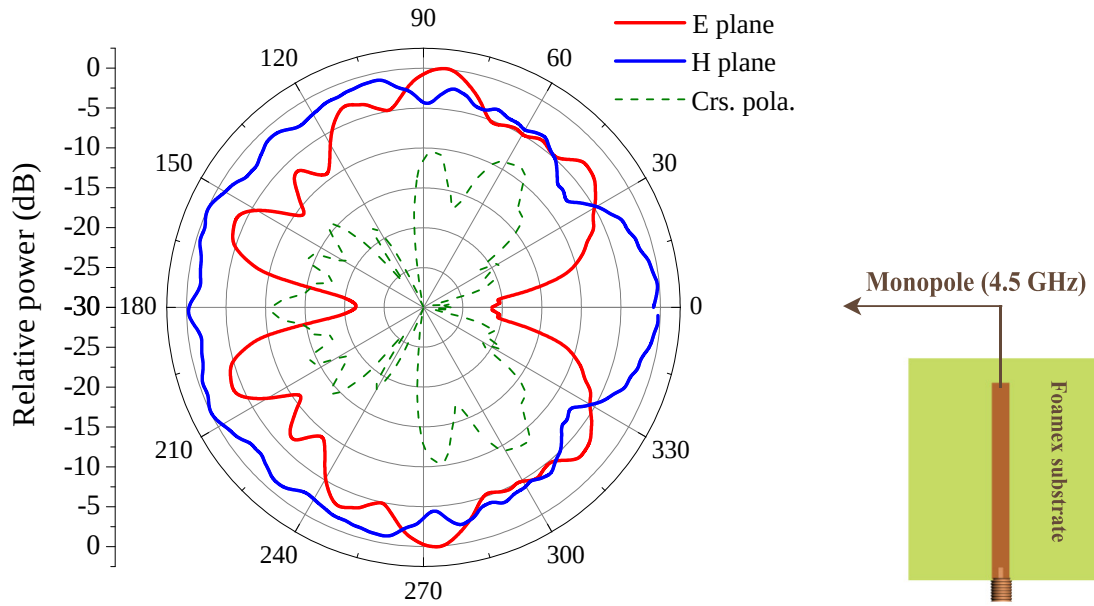


Figure 5.17: Radiation patterns of the monopole patch antenna fabricated on low loss dielectric substrate at 4.5 GHz.

The radiation patterns along the E-plane and H-plane of the multiband BCSRR loaded proposed antenna for a frequency of 2.45 GHz are taken and it is demonstrated in Fig. 5.19. The cross polarization pattern is also depicted in the figure. The E-plane radiation pattern is almost lost its directional behavior while the H-plane pattern became almost bi-directional behavior instead of uniform pattern. The cross polar levels are negligibly small.

The radiation pattern obtained for a frequency of 2.75 GHz are also shown as Fig. 5.20 along with the cross polarization pattern. The obtained patterns are almost similar to that of the patterns corresponding to 2.45 GHz.

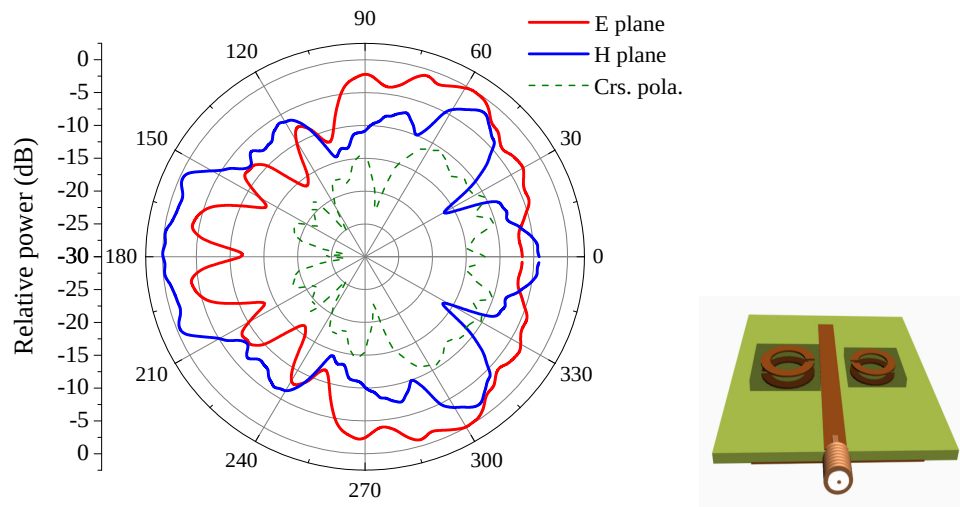


Figure 5.18: Radiation patterns of the multiband BCSRR loaded monopole patch antenna fabricated on low loss dielectric substrate at 4.5 GHz.

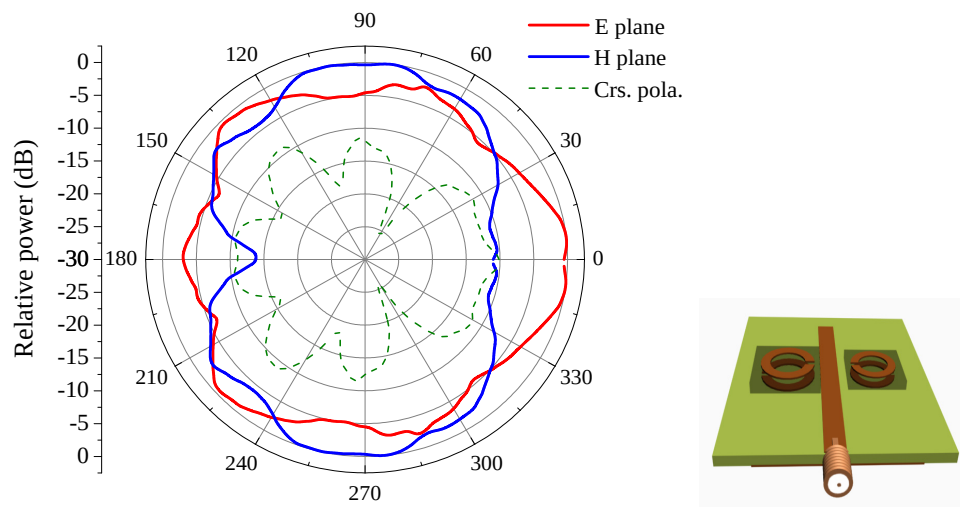


Figure 5.19: Radiation patterns of the multiband BCSRR loaded monopole patch antenna fabricated on low loss dielectric substrate at 2.45 GHz.

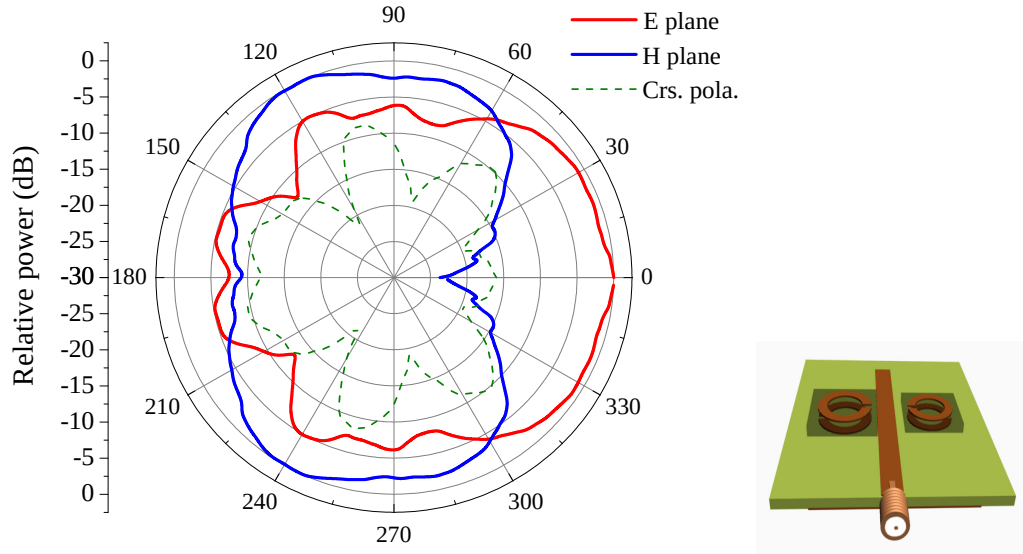


Figure 5.20: Radiation patterns of the multiband BCSRR loaded monopole patch antenna fabricated on low loss dielectric substrate at 2.75 GHz.

5.4 Frequency tunable BCSRR loaded monopole patch antenna

A detailed discussion on the results and its analysis of the frequency tunable BCSRR loaded monopole patch antenna is given in this section. The photograph of the frequency tunable BCSRR loaded monopole patch antenna is shown in the Fig. 5.21.

Since BCSRR offers more magnetic response to the incident electromagnetic wave compared to the single circular-SRR, the tunability of frequency is achieved over a wide bandwidth of almost 2 GHz. The potential wireless communication application frequency standards for ISM, GSM, bluetooth, Wi-Fi, Wi-Max and Wi-LAN can be included in this bandwidth by the proper designing of the BCSRR geometrical parameters.

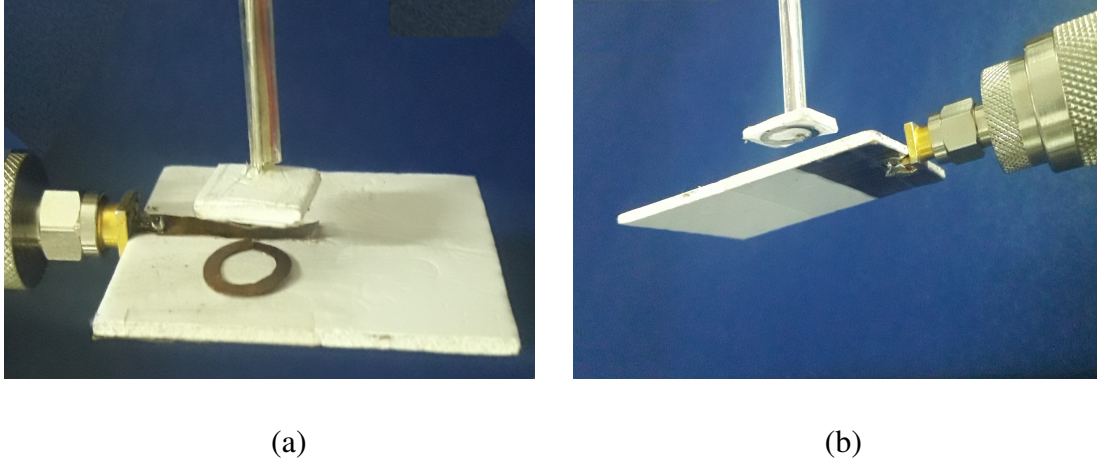


Figure 5.21: Photograph showing the BCSRR loaded monopole patch antenna with tuning facility (a) top view and (b) bottom view.

5.4.1 Return loss

The experimental and simulation S_{11} characteristics of the BCSRR loaded monopole antenna versus frequency at a typical interplanar distance $d = 0.3$ mm is depicted in the Fig. 5.22. The notch at the vicinity of 5 GHz is due to the monopole which is not tunable while the additional notch near 2.5 GHz is due to the coupling between monopole and BCSRR which is tunable. It is evident that the experimental and simulation results are in good agreement.

The S_{11} characteristics versus frequency of the frequency tunable BCSRR loaded monopole patch antenna for different interplanar distances between the rings of the BCSRR resonator are plotted in Fig. 5.23. The resonance obtained by monopole patch which is around 5 GHz is excluded in the figure to provide better resolution for the frequency changes obtained by varying the spacing between the rings of the BCSRR. The geometrical parameters of the rings are so selected that the tuning range

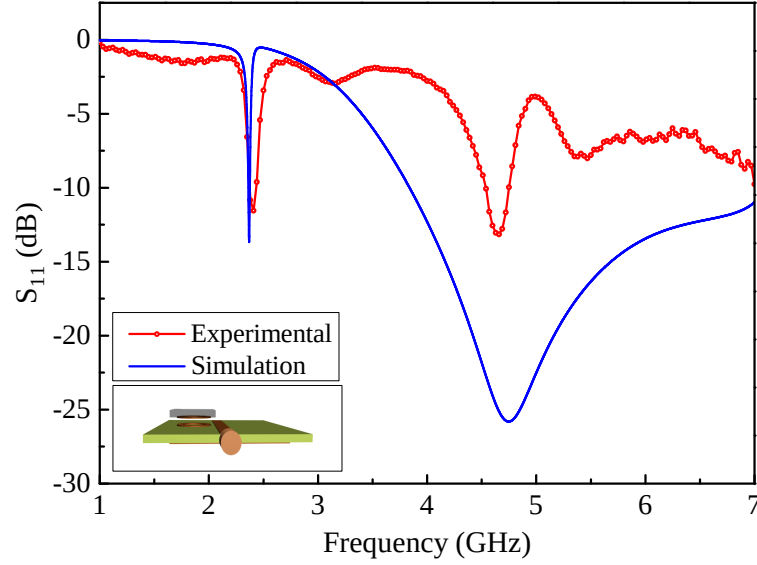


Figure 5.22: Experimental and simulation S_{11} versus frequency graph of the tunable BCSRR loaded monopole patch antenna at an interplanar distance $d = 0.3$ mm.

includes the frequencies for applications like GSM, Wi-Fi, bluetooth, ISM, Wi-Max, WLAN etc.

By slightly changing the interplanar distance between the rings from 0.15 mm to 0.85 mm, the radiating frequency is tuned from 1.6 GHz to 3.3 GHz. The variation in magnetic resonant frequency of BCSRR is mainly due to the changes in the interplanar distance between the rings which in turn changes the mutual capacitance between the rings. Thus a tunable radiating frequency is achieved in the proposed antenna by coupling the BCSRR with the monopole patch.

Fig. 5.24 gives the variation of the BCSRR related resonance frequency with respect to the distance between the two rings of the BCSRR. This tunable frequency range (1.6 GHz to 3.3 GHz) may also be shifted to other frequency regions by changing the geometrical dimensions of the rings. This novel design may be useful for frequency

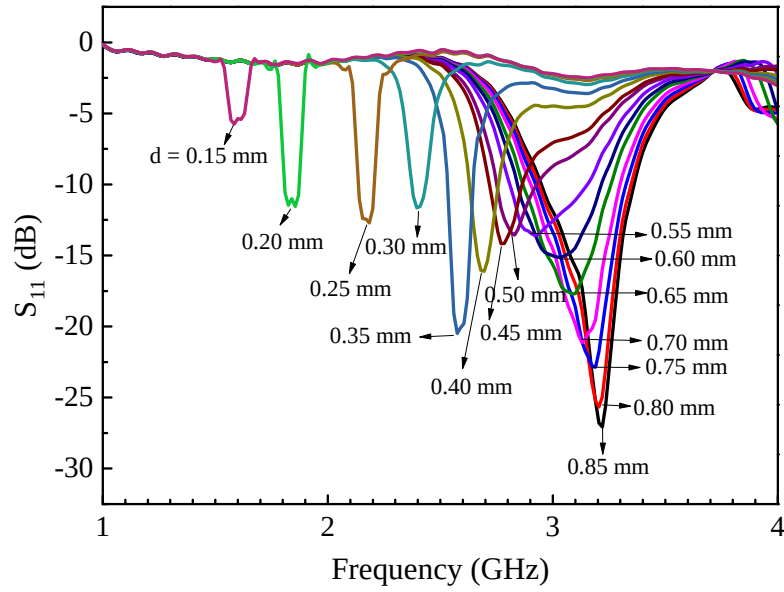


Figure 5.23: S_{11} versus frequency graph of the BCSRR loaded monopole patch antenna.

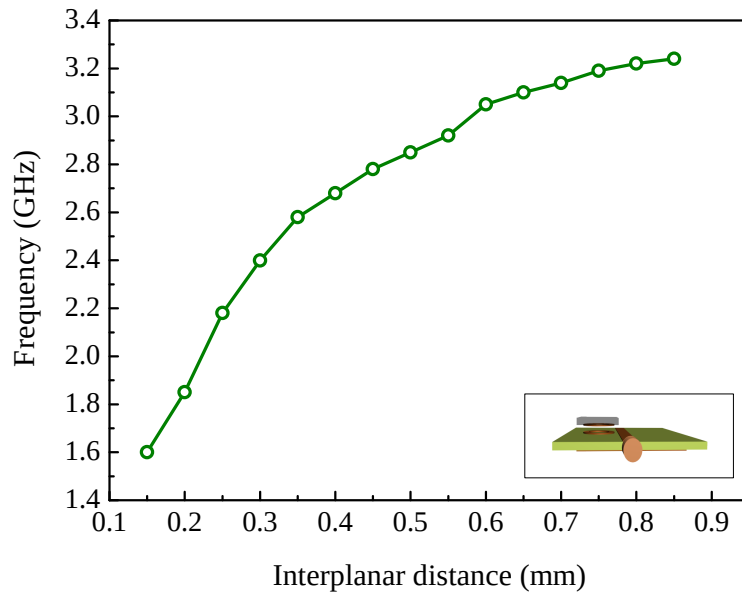


Figure 5.24: Frequency versus interplanar distance graph of the BCSRR loaded monopole patch antenna.

tuning applications where more than one frequency can be selected by the single proposed antenna.

5.4.2 Impedance bandwidth

Table 5.2: Impedance bandwidth values of the frequency tunable BCSRR loaded monopole patch antenna at various interplanar distances.

Inter planar distance	Resonant frequency	Impedance bandwidth
d	Experimental	Experimental
(mm)	(GHz)	(%)
0.20	1.84	3.59
0.25	2.175	3.40
0.30	2.403	2.66
0.35	2.584	4.37
0.40	2.687	4.95
0.45	2.78	5.36
0.50	2.83	6.54
0.55	2.918	11.96
0.60	3.02	12.52
0.65	3.08	12.50
0.70	3.13	12.52
0.75	3.18	12.58
0.80	3.2	12.72
0.85	3.21	12.93

The impedance bandwidth is calculated for different interplanar distances corresponding to different resonant frequencies for the frequency tunable BCSRR loaded antenna. The results are given in Table 5.2 along with the experimental bandwidths. It is observed that the impedance bandwidth is higher than that of the single SRR loaded monopole patch antenna and this may be due to the additional coupling effects introduced by the presence of two rings. The impedance bandwidth versus interplanar distance graphs for the experimental values are plotted and given in Fig. 5.25.

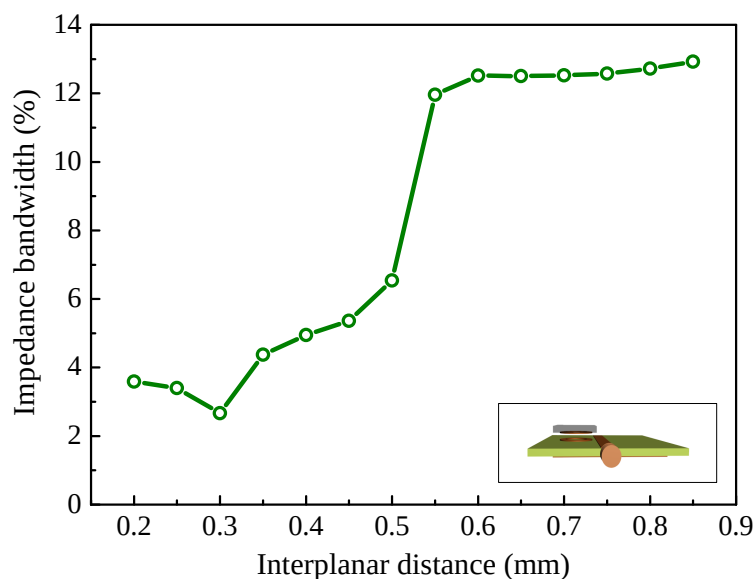


Figure 5.25: Bandwidth versus interplanar distance graph (experimental) of the BCSRR loaded monopole patch antenna.

5.4.3 Antenna gain

The gain of the BCSRR loaded frequency tunable antenna is measured by the gain transfer method. The obtained gain variation is demonstrated in Fig. 5.26. It shows a peaked gain around 8 dBi near 4.5 GHz and also shows proper gain in the frequency range of 4 GHz to 5 GHz due to the monopole radiation. It also shows a gain around 4 dBi corresponding to the BCSRR radiation with tunability in relation to the spacing between the rings of the BCSRR.

5.4.4 Radiation patterns

The radiation patterns along the E-plane and H-plane are plotted as shown in Fig. 5.27 for the proposed antenna at a frequency of 4.8 GHz for an interplanar distance of 0.25 mm. The cross polarization pattern is also included. The E-plane pattern shows

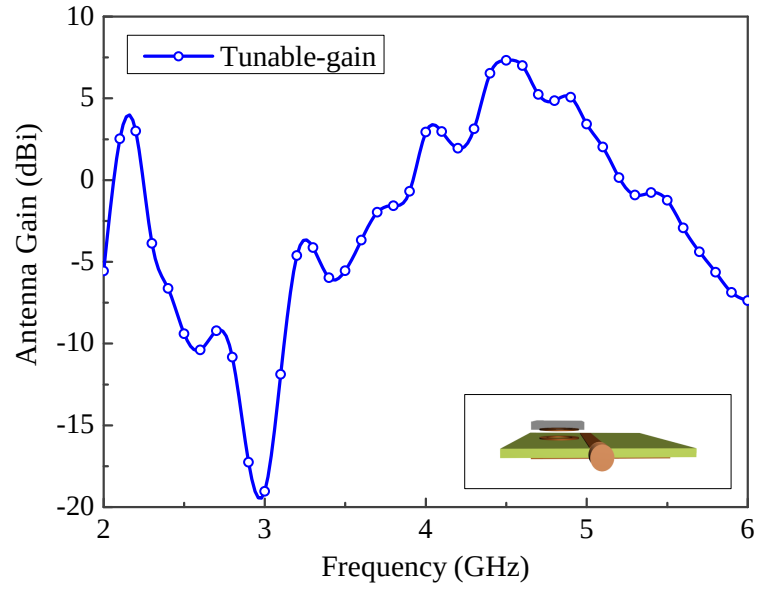


Figure 5.26: Antenna gain versus frequency graph of the frequency tunable monopole patch antenna fabricated on low loss dielectric substrate at $d = 0.25$ mm.

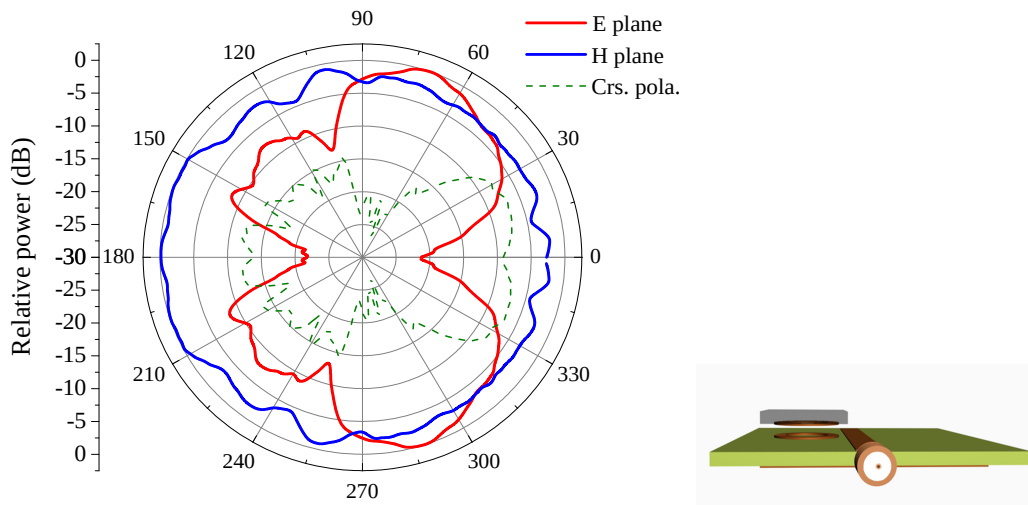


Figure 5.27: Radiation patterns of the frequency tunable BCSRR loaded monopole patch antenna fabricated on low loss dielectric substrate at 4.8 GHz.

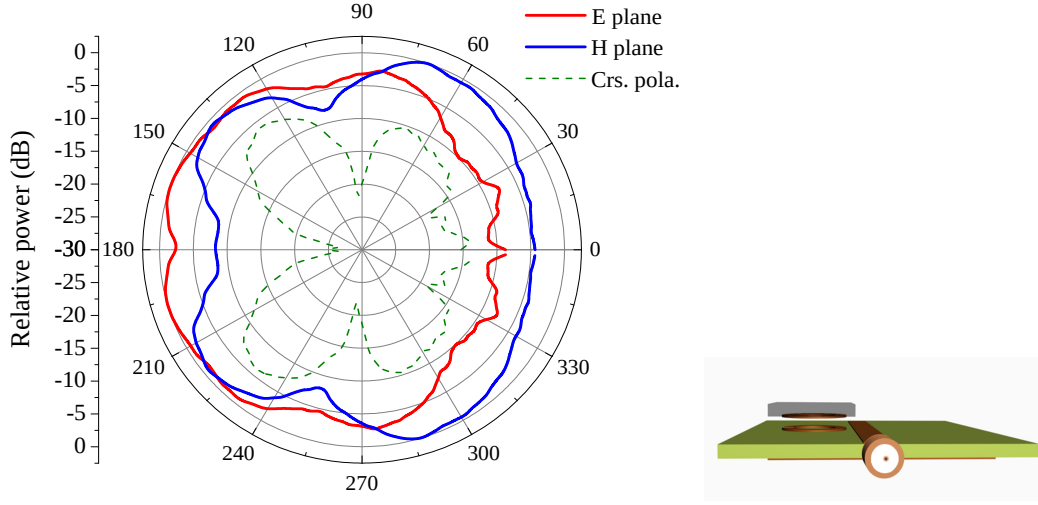


Figure 5.28: Radiation patterns of the frequency tunable BCSRR loaded monopole patch antenna fabricated on low loss dielectric substrate at 2.2 GHz.

directional behavior while H-plane pattern shows almost uniform pattern.

The E-plane and H-plane radiation patterns for the proposed antenna at a frequency of 2.2 GHz obtained for the interplanar distance of 0.25 mm are taken. The measured results are given in Fig. 5.28. The measured cross polarization levels are also included in the figure.

5.5 Conclusion

The multiband frequency operation along with frequency tunability were achieved by using negative permeability resonator structure loaded monopole patch antenna. Initially, the performance of a meta inspired single circular SRR loaded monopole patch antenna is presented. It clearly proved that the proposed antenna is capable of tuning the radiating frequency in the desired range by changing the interplanar

distance between the monopole and the ring. The geometrical dimensions of the ring and also the antenna substrate are so selected that the desired range of frequency tuning is achieved. This newly designed antenna can prove its utility in the field of communication as the frequency tunability is incorporated in a single antenna where the frequency ranges of bluetooth, Wi-Fi and Wi-Max can be covered easily.

As a second investigation it is proved that multiband frequency operation is possible in monopole patch antenna by simply coupling BCSRR units to the monopole. A high return loss at 2.45 GHz and another at 2.75 GHz along with the monopole radiation around 5 GHz are produced by the fabricated prototype of the proposed antenna. The desired radiating frequencies are achieved by using dielectric substrates of different thicknesses for the BCSRR units and also by adjusting the geometrical parameters of the ring. The experimental results are validated by simulation owing to small dimensions and easy integration with other antenna components, the potential communication applications like bluetooth, Wi-Fi and Wi-Max can be achieved easily by the single proposed antenna.

Another method of frequency tuning in monopole patch antenna is achieved by coupling a specially designed single unit of BCSRR capable of changing the spacing between the rings to the monopole patch. A high reflection coefficient magnitude is observed over a 1.7 GHz tuning range. This is the first time that the frequency tuning in antenna based on adjustable BCSRR is demonstrated. Owing to small dimensions and frequency tunability, the potential communication applications like bluetooth, Wi-Fi, Wi-Max, WLAN etc. can be achieved by the single proposed antenna. It is compact, light weight and easy to design and fabricate when compared with the recently reported multiband monopole antennas. The experimental and simulated results are in good agreement which shows that the proposed antenna is a suitable candidate for potential wireless communication applications.

CHAPTER 6

Conclusions

Metamaterial inspired structures have opened a new way of using the unique and exotic properties of such materials in many systems and devices resulting in unprecedented developments in diverse fields. This chapter summarizes the results obtained with the various proposed metamaterial inspired antenna structures and also describes the relevance of the present study in the current communication scenario. It also points out the possibilities for the future work related to the meta-inspired antennas presented in this thesis.

A detailed discussion on the concept of metamaterials and its various applications in diverse fields given in the introductory part serves as an opening point to this research work in view of the enormous potentialities and possible diverse applications

blooming from this new and fast growing branch of physics. It is also discussed the various important types of microwave antennas and its potential applications in communication fields as the prime focus of the present research work is on the inclusion of metamaterial inspired structures in the microwave horn and monopole patch antennas. The meta inspired modifications are incorporated in two relevant antennas by bringing the negative permittivity and negative permeability structures into their design by which a lot of promising as well as fascinating applications are opened up. The negative permittivity inspired modifications made on pyramidal horn antenna by making use of artificial plasma medium in the form of a wire array lead to the development of a featherlight plasma horn antenna which may rediscover the potentialities of this age old horn structure by reintroducing it into the fields of astronomical data collection and communication networks.

In the same manner, the negative permeability modifications made on the popular monopole patch antenna using meta inspired split ring resonators may revolutionize the micro strip antenna related communication networks owing to its tunability and multiband operations. The proposed research work, its realization and analysis can be summarized in terms of the negative permittivity wire medium and negative permeability SRR structure modifications.

6.1 Negative permittivity inspired plasma horn antennas

- The performance of a new featherlight X-band plasma horn antenna constructed using artificial negative permittivity metamaterial medium has been presented.
- It is fabricated by replacing the metallic walls of the conventional pyramidal horn with plasma sheets made with one dimensional array of very thin copper wires.
- The results clearly show that the proposed horn is capable of producing almost

the same radiation characteristics as that of an equivalent metallic horn.

- The attractive feature of the proposed plasma horn is the considerable reduction in weight compared to its metallic counterpart.
- With proper strengthening mechanism this novel antenna is ideal for the situations like satellite communications where the antenna weight is a major concern.
- This novel idea is also verified with the S-band and the C-band plasma horn antennas where the radiation characteristics showed good similarity with the conventional metallic horn antennas.
- The detailed experiments carried out by using a thick plasma wall in the form of multilayers showed the situations and possibilities where performance enhancement can be achieved by such structures.

6.2 Negative permeability inspired monopole patch antennas

- A single circular SRR coupled to a monopole patch antenna is presented and its experimental results are analyzed.
- It is verified that the proposed antenna is frequency tunable over a bandwidth of 1 GHz from 2.3 GHz to 3.3 GHz by slightly adjusting the distance between the monopole patch and the split ring.
- It has been demonstrated that multiband frequency operation in monopole patch antenna is possible by coupling BCSRR units to the monopole.
- The fabricated prototype of the proposed antenna exhibits high return loss at 2.45 GHz and 2.75 GHz along with the monopole radiation around 5 GHz.

- The radiating frequencies can be designed to other desired values by making changes in dielectric thicknesses and in ring parameters.
- It has been demonstrated that frequency tuning in monopole patch antenna is possible by a single unit of BCSRR coupled to the monopole.
- The fabricated prototype of the proposed antenna exhibits high reflection coefficient magnitude in a 1.7 GHz tuning range from 1.6 GHz to 3.3 GHz.
- The results obtained by experimental and simulated methods are in good agreement which shows that the proposed antenna is a suitable candidate for potential wireless communication applications like ISM, GSM, bluetooth, Wi-Fi, WLAN, Wi-Max etc.

6.3 Relevance and scope of the study

The development of a metamaterial inspired artificial plasma horn having all the important radiation properties of the conventional metallic horn with the added advantage of featherlight weight and ease of fabrication has opened up new avenues in the microwave antenna research. With proper strengthening technique, this novel plasma antenna may be quite suitable in satellite communication applications owing to its light weight. This may also be useful in astronomical data collection researches which require large collective aperture without adversely affecting the environmental changes in relation to wind and rain. A pointed beam using a 2D array of such antennas for collecting signals from very weak astronomical sources can also be realized using this novel structure.

Owing to small dimensions and frequency tunability, the potential communication applications like bluetooth, Wi-Fi, Wi-Max, WLAN etc. can be achieved by the pro-

posed single circular SRR inserted monopole patch antenna or by BCSRR inserted monopole patch antenna. The latter has more frequency bandwidth compared to the former. By attaching a programmable electronic tuning to the proposed antennas makes them suitable for using in new generation communication devices like mobiles and laptops. Since these antennas are very simple to fabricate and inexpensive, they can be integrated with the wireless devices where simultaneous operation of more than one frequency is required. The communication by bluetooth, Wi-Fi, Wi-Max etc. at the same time is possible using this proposed antenna.

The novel ideas of meta inspired modifications in microwave horn and patch antennas can be extended to other types of antenna structures. The novelty of the present work is to bring the exotic and unique properties of both the negative permittivity and negative permeability structures into the class of two widely used microwave radiating systems. In this way the antenna communication technologies can be optimized and the hidden new realms in antenna research field can be explored.

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List of Publications

1. **Kizhakooden, Joe**, Jovia Jose, Nees Paul, Sikha K. Simon, Sreedevi P. Chakyar, Jolly Andrews, and V. P. Joseph., “Metamaterial inspired featherlight artificial plasma horn antenna for astronomical and communication applications”, *Microwave and Optical Technology Letters*, 61, no. 3 (2019): 777-780.
2. **Joe, K.**, J. Jovia, P. Nees, J. Andrews, and V. P. Joseph. “Frequency Tunable Monopole Patch Antenna Using Broadside Coupled Split Ring Resonator for Wireless Communication Applications.” In *2019 Thirteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)*, Rome, pp. X-200, IEEE, doi:10.1109/MetaMaterials.2019.8900946, 2019.
3. **Kizhakooden, Joe**, Jovia Jose, Nees Paul, Sreedevi P. Chakyar, Anju Sebastian, Sikha K. Simon, K. S. Umadevi, C. Bindu, Jolly Andrews, and V. P. Joseph. “Broad-side coupled split ring resonator based multiband monopole patch antenna for wireless communication applications”, In *AIP Conference Proceedings*, vol. 2162, no. 1, p. 020068, AIP Publishing, doi:10.1063/1.5130278, 2019.

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6. Jose, Jovia; K. Simon, Sikha; **Kizhakooden, Joe**; Sebastian, Anju ; Chakyar, Sreedevi
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8. Paul, Nees, Sreedevi P. Chakyar, K. S. Umadevi, Simon K. Sikha, **Joe Kizhakooden**,
Jolly Andrews, and V. P. Joseph. “Humidity Sensitive Flexible Microwave Absorb-
ing Sheet Using Polyaniline–Polytetrafluoroethylene Composite”, Arabian Journal for
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9. Jose, Jovia, Sikha K. Simon, Anju Sebastian, Sreedevi P. Chakyar, **Joe Kizhakooden**,
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12. Bindu, C., Sreedevi P. Chakyar, Anju Sebastian, Sikha K. Simon, Jovia Jose, Nees Paul, K. S. Umadevi, **Joe Kizhakooden**, Jolly Andrews, and V. P. Joseph. “Enhancing the resolution in imaging using folded metamaterial split ring resonator structure at microwave frequencies.” In AIP Conference Proceedings, vol. 2162, no. 1, p. 020067, AIP Publishing, 2019, doi:10.1063/1.5130277.

Conference Presentations

1. **Joe Kizhakooden**, Jovia Jose, Nees Paul, Jolly Andrews, and Joseph V P; “Frequency Tunable Monopole Patch Antenna Using Broadside Coupled Split Ring Resonator for Wireless Communication Applications”; Metamaterials 2019, Rome, 13th International Congress on Artificial Materials for Novel Wave Phenomena, 16- 19 Sept. 2019.
2. **Joe Kizhakooden**, Jovia Jose, Nees Paul, Sreedevi P Chakyar, Anju Sebastian, Sikha K Simon, Umadevi K S, Bindu C, Jolly Andrews and Joseph V P , “Broadside coupled split ring resonator based multiband monopole patch antenna for wireless communication applications”; International Conference on Advanced Materials, 12 – 14 June 2019 at Nirmalagiri College, Kannur, Kerala, India.
3. **Joe Kizhakooden**, Jovia Jose, Nees Paul, Sreedevi P Chakyar, Sikha K Simon, Anju Sebastian, Jolly Andrews and V P Joseph; “ Optimization of structural parameters of negative permittivity plasma horn antenna”, National Seminar on ‘Materials, Methods, Sensors for Electromagnetic Applications’, Department of Physics, Christ College (Autonomous), Irinjalakuda, Thrissur, Kerala, India held on 24th and 25th January 2019.

4. **Joe Kizhakooden**, Jovia Jose, Nees Paul, Sikha K Simon, Sreedevi P Chakyar, Anju Sebastian, Jolly Andrews, V P Joseph; ‘Metamaterial inspired monopole antenna for frequency tunable applications’ – in DST-SERB sponsored International Conference on Advanced Functional Materials (ICAFM 2018) at St. Berchmans College, Changanassery, Kottayam, Kerala, India on 9th October 2018.

Selected Publications

RESEARCH ARTICLE

Metamaterial inspired featherlight artificial plasma horn antenna for astronomical and communication applications

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Abstract

In this article, we introduce a novel type of horn antenna constructed using artificial plasma sheets. This metamaterial inspired negative permittivity antenna fabricated using thin metallic wires in a specialized manner is observed to have same radiation performance of an equivalent conventional metallic horn structure. This novel plasma antenna can replace the conventional one in all microwave applications. The featherlight weight and the ability to remove the problems related with wind resistance and rain accumulation of this new structure may result in a rethinking of the use of horn antennas in astronomical data collection.

KEYWORDS

artificial plasma medium, horn antenna, metamaterials, radiation pattern, satellite application

1 | INTRODUCTION

From its introduction by J. C. Bose, horn antennas were extremely popular in all fields of microwave application including astronomical research due to its moderate bandwidth, high gain, good power handling capability and ease of fabrication. Modified versions of horn antennas are extensively used as the primary feed in parabolic reflectors and as a universal standard for calibration and gain measurements.^{1,2} To make the pyramidal horn more compact, many approaches that include dielectric loading^{3–5} and lens-correction⁶ have been considered. Further approaches like loading by metal baffles⁷ have also been considered for modifying its radiation characteristics. However, these modifications make the structure heavy and expensive which cause them not suitable for many applications like space research.

In recent years, researchers have attempted to give modifications to horn antennas by making use of metamaterial inclusions of negative permeability medium (split ring resonator) and negative permittivity wire medium (artificial plasma). The effects of incorporating a wire medium inside horn antennas have been investigated by simulation and experimental studies.⁸ In this article, we present a novel type of horn antenna constructed by replacing the metallic walls of a conventional horn structure with artificial plasma sheets. Usually negative permittivity metamaterial sheets are constructed using periodic array of thin metallic wires in a 3D manner. But even a single layer of periodic wires can be considered as artificial plasma (sheet of thickness equal to the diameter of the wire) with effective medium parameters.⁹ Here the plasma sheets are specially oriented for maintaining the field distribution inside the new horn as in a conventional metallic horn structure.

2 | ANTENNA FABRICATION

The schematic diagram of the proposed plasma horn antenna is presented in Figure 1. Plasma structure constructed using thin copper wires is attached to the wave guide via a pyramidal launcher of length 2 cm. The axial length of the horn is 14 cm and the flare angles in E and H planes are 30° and 40°, respectively. Plasma medium for constructing the sidewalls of the horn structure is made of a single layer of thin metallic wires of radius 250 μm arranged with a periodicity of 5 mm in the H walls and an angular spacing of 2° with respect to the apex of the horn in the E walls. The

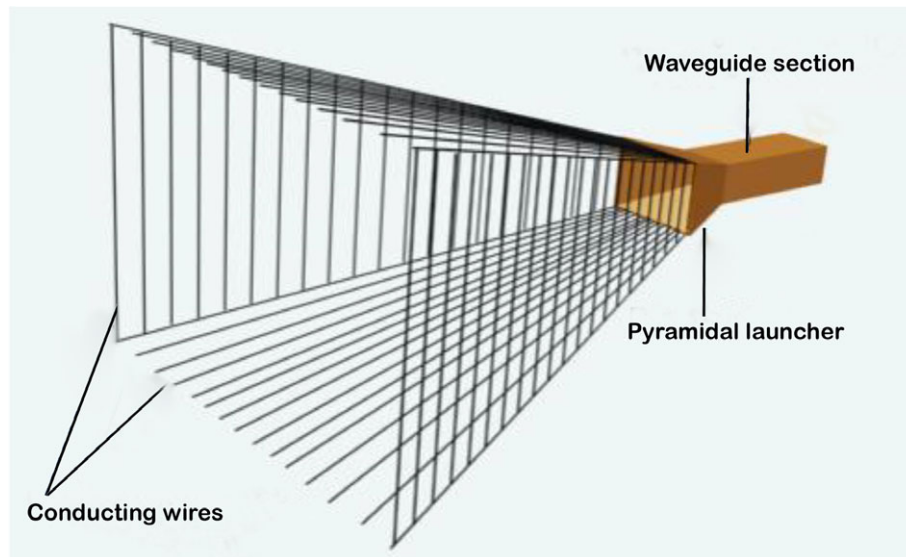


FIGURE 1 Schematic presentation of proposed plasma horn antenna [Colour figure can be viewed at wileyonlinelibrary.com]

effective plasma frequency of this artificial medium is obtained from the equation.⁹

$$f_p = c \left[a \sqrt{2\pi \left(\ln \frac{a}{\pi d} + 0.5275 \right)} \right]^{-1}$$

where f_p , plasma frequency; c , velocity of light in free space; a = spacing between the wires and d = diameter of the wire. With the present values of a and d , the plasma frequency will be 18.44 GHz. Below this frequency the medium acts as a perfect reflector and hence the horn constructed using this artificial plasma sheet shows the same properties as that of the metallic horn antenna.

Though the copper wires used for making plasma sheet can be arranged in different orientations for constructing the E and H walls of the plasma antenna, for getting radiation properties similar to the conventional metallic horn antenna, they need to be arranged in the following manner. For the H walls, the direction of the copper wires of the plasma sheet should be parallel to the E vector of the radiating field (TE_{10} mode) so that the boundary condition for E (tangential component) behaves similar to that of its metallic counterpart. With respect to E walls, the direction of the wires should be parallel to the propagating wave vector $\mathbf{k}$ in order to guide the electromagnetic wave properly through the horn structure. For other possible orientations of copper wires in the

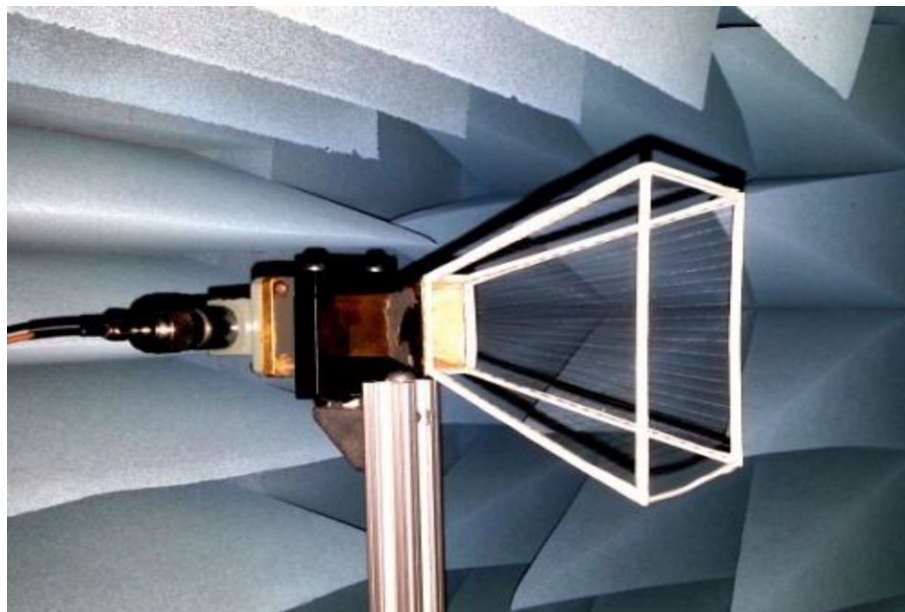


FIGURE 2 Photograph of plasma horn antenna arranged inside anechoic test box [Colour figure can be viewed at wileyonlinelibrary.com]

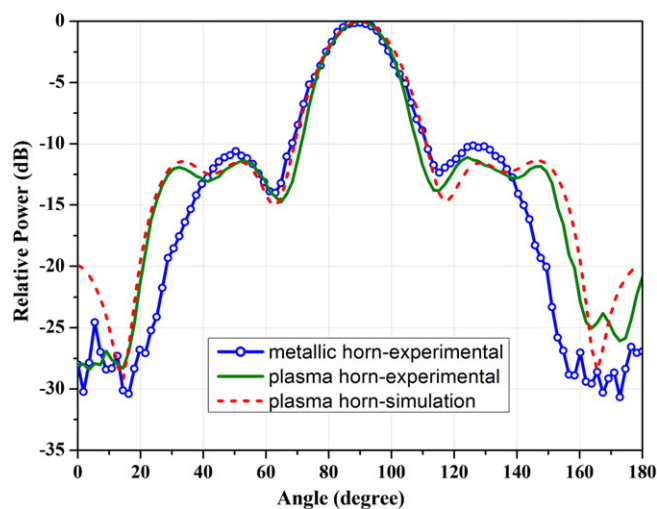


FIGURE 3 E plane radiation pattern of test horn and corresponding metallic horn [Colour figure can be viewed at wileyonlinelibrary.com]

plasma sheet, the boundary conditions are not satisfied perfectly as for the conventional horn antenna.

3 | MEASUREMENTS AND RESULTS

The E and H-plane radiation patterns of the plasma horn (X band) are drawn using a vector network analyzer by arranging it inside an anechoic test box as depicted in Figure 2. A pyramidal frame made up of low loss dielectric strips of thickness 2 mm and width 3 mm is used for loading the metallic wires.

E-plane radiation pattern of the antenna under test (AUT) for frequency 8.5 GHz is shown in Figure 3. The result obtained by simulation is also plotted in the figure which is found to be in excellent agreement with the experimental one. The radiation pattern of an equivalent metallic horn is included in the figure for comparison purpose. The patterns of the metallic horn and the plasma antenna are remarkably similar except for small deviations in side lobe width which may be due to slight leakage of the power through the plasma medium. But their half power beam widths are found to be in excellent agreement.

Figure 4 depicts the H-plane radiation pattern obtained for the AUT (8.5 GHz) along with the simulation result and that obtained for the metallic counterpart. The similarity of the radiation patterns of the plasma horn with an equivalent metallic horn clearly verifies the possibility of replacing the conventional one with this new light weight antenna. Increase in voltage standing wave ratio compared with its equivalent metallic horn is negligible due to the presence of the launcher, which reduces the mismatch between metallic waveguide and the plasma horn. A slight decrease in axial gain ($\lesssim 2$ dB)

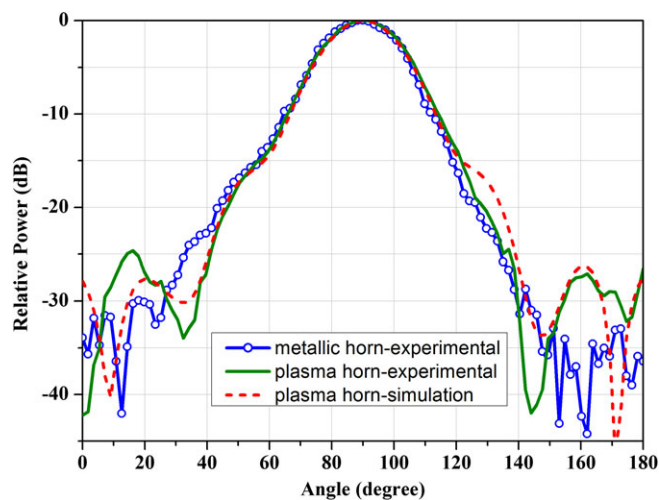


FIGURE 4 H plane radiation pattern of test horn and corresponding metallic horn [Colour figure can be viewed at wileyonlinelibrary.com]

is observed which may not be a major concern while considering its manifold positive advantages.

It is observed that plasma sheets fabricated using metallic wires of smaller radius shows same results whereas if the radius is increased beyond 1 mm, the pattern shows deviations from the expected one. Plasma sheets fabricated with wires of different radii between 20 μm and 1 mm are used for constructing various test horns and the radiation patterns obtained are found to be identical.

4 | CONCLUSION

The performance of a new featherlight plasma horn antenna constructed using artificial negative permittivity metamaterial medium has been presented. It is fabricated by replacing the metallic walls of the conventional pyramidal horn with plasma sheets made with array of very thin copper wires. The results clearly show that the proposed horn is capable of producing almost the same radiation characteristics as that of an equivalent metallic horn. The attractive feature of the proposed plasma horn is the considerable reduction in weight compared to its metallic counterpart. With proper strengthening mechanism this novel antenna is ideal for the situations like satellite communications where the antenna weight is a major concern. Since it is easy to fabricate the proposed plasma antenna with large collecting aperture, it can also be employed in astronomical data collection purposes by installing them in the form of a 2D array to obtain a pointed radiation beam. Since the structural deformities due to wind and rain and the installation difficulties of this antenna are comparably lower than the other antennas presently employed in the field, our antenna may find a wide variety of applications associated with various microwave technologies.

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How to cite this article: Kizhakooden J, Jose J, Paul N, et al. Metamaterial inspired featherlight artificial plasma horn antenna for astronomical and communication applications. *Microw Opt Technol Lett*. 2019;61:777–780. <https://doi.org/10.1002/mop.31633>

Broadside coupled split ring resonator based multiband monopole patch antenna for wireless communication applications

Cite as: AIP Conference Proceedings **2162**, 020068 (2019); <https://doi.org/10.1063/1.5130278>
Published Online: 29 October 2019

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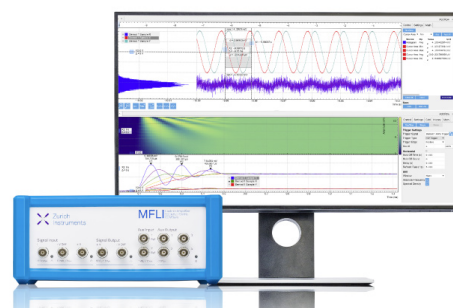
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Broadside Coupled Split Ring Resonator Based Multiband Monopole Patch Antenna for Wireless Communication Applications

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Abstract: The present work reports the development of a multiband monopole patch antenna by utilizing Broadside Coupled Split Ring Resonator (BCSRR) units. This antenna makes use of the resonant property of metamaterial BCSRR units for multiband frequency designing. Since the magnetic resonant frequency of the BCSRR depends on the effective capacitance and inductance of its rings, the geometrical parameters of the rings like inter planar distance between them, inner and outer radii, split widths and the dielectric material between the rings play important role in designing the radiating frequency bands of the proposed antenna. The desired frequencies for potential applications like Bluetooth, Wi-Fi and Wi-Max are thus achieved by proper designing of the BCSRR units. In this work, it is demonstrated that two additional frequencies can be radiated along with the monopole radiation by coupling two BCSRR units to the monopole. The fabricated antenna exhibits high return loss at 2.45 GHz and 2.75 GHz along with the monopole radiation around 5 GHz. The number of operating frequencies can be increased by adding more BCSRR units at various positions near to the monopole patch. The proposed antenna is compact, light weight and easy to design and fabricate when compared with the recently reported multiband monopole antennas. The good agreement between the experimental and simulated results shows that the proposed antenna is a suitable candidate for potential wireless applications. The different antennas for different applications in a single device can be replaced with the single proposed antenna.

INTRODUCTION

Multiband operation of antennas have lead to tremendous applications in the field of electronic wireless communication due to its properties like light weight, compactness, ease of fabrication and easy integration with other microwave components [1]. Electromagnetic metamaterial based multiband antennas have recently attracted great attention due to their capability of altering the radiation performance owing to their negative values of permittivity and permeability [2]. Frequency reconfigurable antennas using various designs and techniques are also noticeable strides in this field [3]. Recent developments in multiband operation of antennas using a radiating patch with electromagnetic metamaterial components have gained a great attention in the wireless communication field. Various techniques like inducing slots in radiating element [4], re-fashion in ground plane [5], fractal geometry techniques [6] etc. are introduced for further development of antennas using radiating patch. Most of these structures require complex antenna designs and fabrications. In this work, an easy designing and fabricating method based on

Broadside Coupled Split Ring Resonator (BCSRR) loaded monopole patch antenna for multiband operations is presented.

BCSRR is a metamaterial component which exhibits negative permeability. It is a modified form of Split Ring Resonator where the two rings are fabricated on the opposite sides of the dielectric substrate. The proposed monopole patch antenna makes use of the BCSRR properties for multiband frequency designing. The magnetic resonant frequency of the BCSRR structure depends on the effective capacitance and inductance of the rings determined by the geometrical parameters like the inner and the outer radii, the split widths, inter planar distance between the rings and dielectric constant of the substrate. These parameters are designed so as to get desired frequencies for potential applications like Bluetooth, Wi-Fi and Wi-Max. In this work, it is demonstrated that two additional frequencies can be radiated along with the monopole radiation by coupling two BCSRR units to the monopole. The fabricated antenna exhibits high return loss at 2.45 GHz and 2.75 GHz along with the monopole radiation which is designed to get a radiating frequency in the vicinity of 5 GHz. The number of operating frequencies can be increased by adding more BCSRR units at various positions near to the monopole patch. The experimental and simulated results are in good agreement which shows that the proposed antenna is a suitable candidate for potential wireless applications.

BCSRR LOADED MONOPOLE PATCH ANTENNA

The layout of the BCSRR loaded monopole patch antenna is given in Fig.1. Instead of using the conventional double sided PCBs, we have employed thin copper sheets and low loss dielectric substrate for the fabrication. The monopole patch (27.5 mm x 4.5 mm) and the ground plane (40 mm x 15 mm) are made using copper sheet of thickness 20 μm . The dielectric substrate used is a low loss PVC foam sheet of thickness 1.45 mm having relative permittivity 1.2 and dielectric loss tangent 0.001. The surface area of the substrate is 53 mm x 40 mm. The BCSRR unit is constructed distinctly from the conventional manufacturing methods. The two rings are separately etched photo chemically from thin sheets of copper with thickness 20 μm . The outer and inner radii of the rings are designed as 6 mm and 4.5 mm respectively and the slit width is 0.5 mm. Then they are fixed on the opposite sides of a low loss PVC foam substrate of thickness 1.65 mm and the combination is fixed very near (0.3 mm) and side by side to the monopole patch with the slit of the bottom ring facing the patch and the center of the ring coming at a distance of 17 mm from the feed end. Similarly another BCSRR unit of same dimensions but with substrate thickness 1.55 mm is constructed and placed on the other side of the monopole patch such that the center of the ring is at a distance of 11 mm from the feed end.

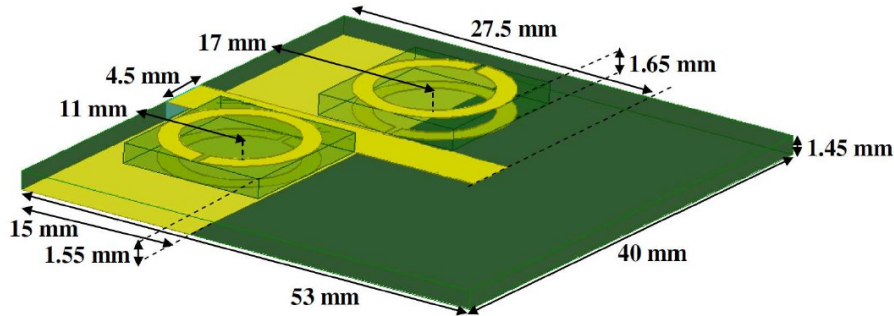


FIGURE 1. The schematic representation of the proposed BCSRR loaded monopole patch antenna.

RESULTS AND DISCUSSIONS

The measured and the simulated S_{11} characteristics of the BCSRR loaded monopole antenna structure versus frequency using Vector Network Analyzer (VNA) and simulation software are depicted in Fig.2. The peaked notch at the vicinity of 5 GHz is due to the monopole patch while the additional notches at 2.45 GHz and at 2.75 GHz are due to the coupling between monopole and BCSRR units. Since the two BCSRR units have different dielectric thicknesses, the values of the effective capacitance and inductance will be different for each unit resulting in the formation of two notches at different frequencies. The geometrical parameters of the rings and thicknesses of the

dielectric inserted are so selected that the additional frequencies are at the frequencies for potential applications such as Wi-Fi, Bluetooth, Wi-Max etc. The frequency of 2.45 GHz is internationally selected for Bluetooth and Wi-Fi applications. The frequency 2.75 GHz can be used for lower Wi-Max band applications while 5 GHz frequency can be used for upper Wi-Max band applications. The selected frequencies can be designed to other required values by altering the geometrical dimensions of the rings and the dielectric constant of the substrate. As the size of the rings increases, the notch moves to the lower frequency range as the effective inductance and capacitance increases whereas the thickness of the dielectric substrate increases, the notch moves to the higher frequency side.

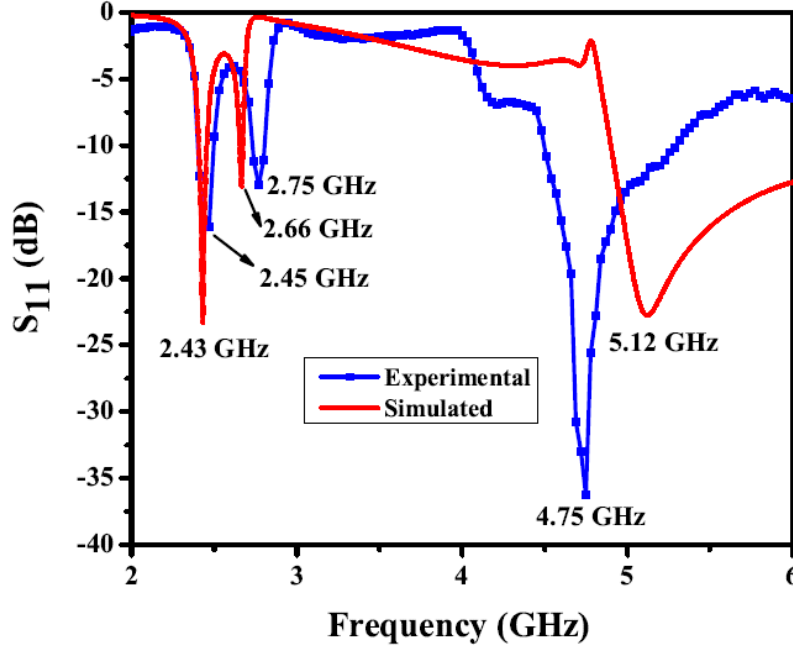


FIGURE 2. The experimental and simulated S_{11} characteristics versus frequency of the proposed BCSRR loaded monopole patch antenna.

In fact, the magnetic resonant frequency of the BCSRR depends on the self inductance of the rings, mutual inductance between the two rings, mutual capacitance between the rings and the capacitance of the two splits. The mutual inductance between the two rings is relatively small compared to the self inductance of the two rings and the capacitance of the splits is also small compared to the mutual capacitance between the rings. So the notch due to the BCSRR coupling is mainly due to the changes in the ring dimensions, which in turn changes its self inductance, as well as the mutual capacitance between the rings. Thus multiband operation is achieved by coupling two BCSRR units having selected parameters with the monopole patch. More notches at different frequencies can be procured by inserting more number of BCSRR units corresponding to the maximum field positions of the monopole patch. Thus different antennas for different applications in a single device can be replaced with the single proposed antenna.

CONCLUSION

It has been demonstrated that multiband frequency operation in monopole patch antenna is possible by coupling BCSRR units to the monopole. The fabricated prototype of the proposed antenna exhibits high return loss at 2.45 GHz and 2.75 GHz along with the monopole radiation around 5 GHz. The radiating frequencies can be designed to other desired values by making changes in dielectric thicknesses and in ring parameters. The multiband frequency operation in antenna based on BCSRR is manifested for the first time and the experimental results are validated by simulation. Owing to small dimensions and easy integration with other antenna components, the potential communication applications like Bluetooth, Wi-Fi and Wi-Max can be achieved easily by the single proposed antenna. Thus compared with the reported multiband monopole antennas, the proposed BCSRR based multiband monopole patch antenna is quite easy to design and fabricate.

ACKNOWLEDGMENTS

Jovia Jose would like to thank University Grants Commission (UGC), Government of India for the financial support given under Faculty Development Program (FDP). Sreedevi P. Chakyar acknowledges UGC, Govt. of India for the financial support given under UGC Junior Research Fellowship (UGC JRF). Sikha K Simon also gratefully acknowledges UGC, Govt. of India for the financial support under Moulana Azad National Fellowship (MANF JRF).

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Frequency Tunable Monopole Patch Antenna Using Broadside Coupled Split Ring Resonator for Wireless Communication Applications

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Abstract – This paper presents metamaterial based monopole patch antenna capable of tuning the radiating frequency over a wide bandwidth. The proposed novel antenna structure makes use of the metamaterial properties of Broadside Coupled Split Ring Resonator (BCSRR) for frequency tuning. The magnetic resonant frequency of the proposed antenna can be tuned by slightly adjusting the interplanar distance between the rings of the BCSRR so that the coupling due to effective capacitance and inductance between them can be changed. The desired range of frequency tuning for potential applications like Global System for Mobiles (GSM), Bluetooth, Wi-Fi, Wi-Max, WLAN etc. is achieved by proper designing of the geometrical parameters of BCSRR. The different antennas for different applications in a single device can be replaced with the proposed novel metamaterial based antenna structure.

I. INTRODUCTION

Tremendous advancements in the field of electronic wireless communication industry pose the necessity of developing antennas capable of frequency tuning. Recent developments in multiband operation of antennas using a radiating patch with electromagnetic metamaterial components [1] have gained a great attention in the wireless communication field due to its capability of altering the radiation performance having negative values of permittivity and permeability [2]. Frequency reconfigurable antennas using various designs and techniques are also noticeable achievements in this field. Even though these antennas have properties like light weight, compactness, ease of fabrication and easy integration with other microwave components, the property of tuning the frequency continuously in a wide range is not achieved.

Broadside Coupled Split Ring Resonator (BCSRR) is a metamaterial component which exhibits negative permeability [3, 4, 5]. The proposed monopole patch antenna makes use of the BCSRR properties for frequency tuning. Since the magnetic resonant frequency of the BCSRR depends on its effective capacitance and inductance of the rings, the geometrical parameters of the BCSRR rings like inner and outer radii, split width and interplanar distance between them play important role in designing the frequency tuning range. The fabricated antenna exhibits high reflection coefficient magnitude in a 1.7 GHz tuning range which includes frequencies for potential applications like Global System for Mobiles (GSM), Bluetooth, Wi-Fi, Wi-Max etc.

II. BCSRR LOADED MONOPOLE PATCH ANTENNA

The layout of BCSRR loaded monopole patch antenna is given in Fig.1. The BCSRR is fabricated distinctly from the conventional manner where the two rings are separately etched photo chemically from thin sheets of copper with thickness 20 μm . One of the two rings of the BCSRR is fixed on the dielectric substrate of the antenna very near (0.3 mm) and side by side to the monopole patch as the slit faces the patch and the center of the ring is at a distance of 16 mm from the feed end. The second ring fixed on another piece of a dielectric substrate is arranged near the first ring co-axially such that the interplanar distance between the rings (d) can be varied continuously for frequency tuning. In this work a mechanically tunable antenna is designed since the mechanical realization of tunability is comparatively easy to procure. The monopole radiating patch and the ground plane are also made

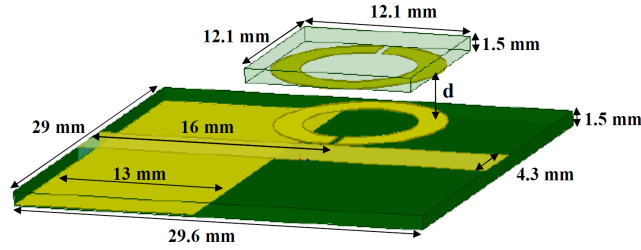


Fig. 1: The layout of BCSRR loaded monopole patch antenna.

from copper sheets of thickness $20 \mu\text{m}$. The dielectric substrate used is a PVC foam sheet (thickness 1.5 mm) of relative permittivity 1.2 and dielectric loss tangent 0.001. The structural dimensions of the rings are inner radius 4 mm, outer radius 6 mm and split width 0.5 mm.

III. RESULTS AND DISCUSSIONS

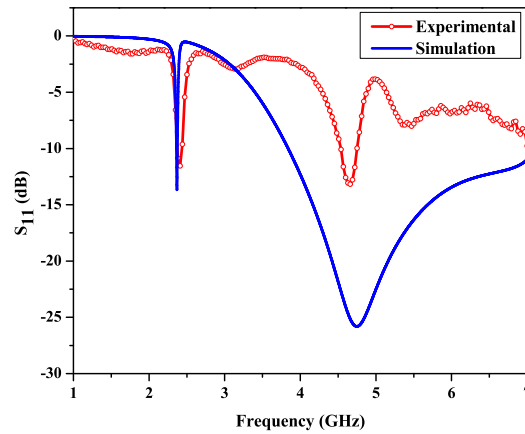


Fig. 2: S_{11} characteristics of the BCSRR loaded monopole for a typical spacing $d = 0.3$ mm.

The experimental and simulation S_{11} characteristics of the BCSRR loaded monopole antenna versus frequency at an interplanar distance of $d = 0.3$ mm is depicted in Fig.2. The notch at the vicinity of 5 GHz is due to the monopole which is not tunable while the additional notch near 2.5 GHz is due to the coupling between monopole and BCSRR which is tunable. The S_{11} characteristics versus frequency for different interplanar distances between the rings are plotted in Fig.3. The geometrical parameters of the rings are so selected that the range of frequency tuning includes the frequencies for applications like GSM, Wi-Fi, Bluetooth, Wi-Max, WLAN etc. It can be seen that a frequency tuning of range 1.7 GHz - 3.4 GHz is possible by adjusting the interplanar distance between the rings from 0.15 mm to 0.85 mm. The magnetic resonant frequency of the BCSRR depends on the self inductance of the rings, mutual inductance between the two rings, mutual capacitance between the rings and the capacitance of the two splits. The mutual inductance between the two rings is relatively small compared to the self inductance of the two rings and the capacitance of the splits is also small compared to the mutual capacitance between the rings. So the variation in magnetic resonant frequency of BCSRR is mainly due to the changes in the interplanar distance between the rings which in turn changes the self inductance of the rings as well as the mutual capacitance between the rings. Thus a tunable radiating frequency is achieved in the proposed antenna by coupling the BCSRR with the monopole patch.

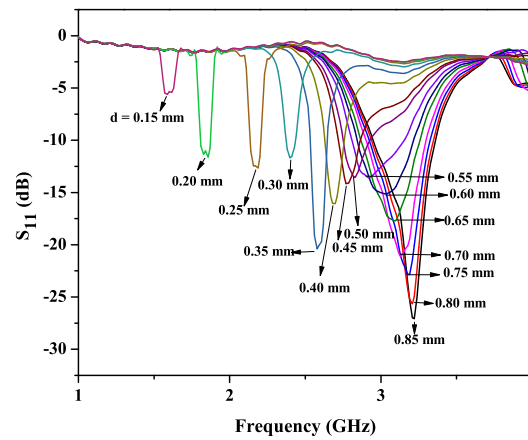


Fig. 3: The S_{11} characteristics of the BCSRR loaded monopole patch antenna at different interplanar distances, d .

The geometrical parameters of the monopole patch have been estimated to provide an additional resonant frequency in the vicinity of 5 GHz which is not tunable. It can be used in the upper Wi-Max band. The tunable frequency range (1.7 GHz to 3.4 GHz) may also be shifted to other frequency regions by changing the geometrical dimensions of the rings. This novel design may be useful for applications where more than one frequency radiation can be achieved using single antenna.

IV. CONCLUSION

It has been demonstrated that frequency tuning in monopole patch antenna is possible by a single unit of BCSRR coupled to the monopole. The fabricated prototype of the proposed antenna exhibits high reflection coefficient magnitude in a 1.7 GHz tuning range. This is the first time that the frequency tuning in antenna based on adjustable BCSRR is demonstrated. Owing to small dimensions and frequency tunability, the potential communication applications like Bluetooth, Wi-Fi, Wi-Max, WLAN etc. can be achieved by the single proposed antenna. The proposed antenna is compact, light weight and easy to design and fabricate when compared with the recently reported multi-band monopole antennas. The experimental and simulated results are in good agreement which shows that the proposed antenna is a suitable candidate for potential wireless communication applications.

ACKNOWLEDGEMENT

The authors would like to thank Government of India for the financial support given through UGC Faculty Development Program (FDP).

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