Implementation of Dual Window Tapered Annular-Ring Electromagnetic Bandgap Filter Structures with Varying Aspect Ratio

A thesis submitted in the partial fulfillment of the requirement for the award of degree of

Master of Engineering
In
Wireless Communication

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CERTIFICATE

I, Priyanka Grover, hereby certify that the work which is being presented in this thesis entitled **"Implementation of Dual Window Tapered Annular-Ring Electromagnetic Bandgap Filter Structures with Varying Aspect Ratio"** by me in partial fulfillment of the requirements for the award of degree of Master of Engineering in Wireless Communication Engineering from Thapar University (Deemed University), Patiala, is an authentic record of my own work carried out under the supervision of Dr. Rajesh Khanna.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of any other degree.

Date: 30/6/14

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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My greatest thanks are to all who wished me success especially my parents. Above all I render my gratitude to the Almighty who bestowed self-confidence, ability and strength in me to complete this work for not letting me down. I do not find enough words with which I can express my feelings of thanks to my dear friends for their help, inspiration and moral support which went a long way in successful competition of the present study.

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ABSTRACT

Filtering of undesired frequencies can be done by using shunt stubs and stepped impedance lines. These techniques are typically narrow band and require large circuit area. In order to solve the problem of conventional filters, one possible way to reject a band of frequencies is to use Electromagnetic Bandgap (EBG) Structure.

Periodic structures that allow circulation of electromagnetic waves in a specific frequency band for certain angles of incidence and polarization senses are known as electromagnetic band-gap (EBG) structures. The peculiar feature of 2-D EBG structures is the presence of the stopband where electromagnetic waves are prohibited to propagate. It has been widely used as the dielectric material of high frequency circuits such as patch antennas to suppress the interfering waves between two closely placed antennas.2-D EBG structures shows good compatibility with microstrip circuits which make them work efficiently as bandstop filters. In EBG structures a stopband occurs when the periodic elements like circles are etched in the ground along with modulated microstrip line at an upper face of substrate. The behavior of EBG materials can be improved with the proper choice of tapering coefficient in correspondence with aspect ratio control factor. In this thesis, non uniform dual window tapered annular ring EBG structures are designed in order to observe any improvement over the conventional uniform circular-patterned EBGs. The main aim of this thesis is to design a compact EBG based microstrip structure with large bandwidth and stopband attenuation with small ripple level in both the lower and higher passband. In this thesis, the concept of PBG/EBG structure is presented along with the applications and advantages. With this EBG configuration; the proposed structure displays an ultrawide stopband with high attenuation within a small circuit area.The non uniform dual window tapered annular ring EBG structures with aspect ratio 0.4 and 0.25 for outer and inner circles respectively has been designed using the Computer Simulation Technology (CST)-2010 studio suite software and this simulated annular ring EBG Structure has been fabricated using Printed Circuit Board (PCB) technology and in order to have more precise practical results this fabricated design is tested on Agilent Vector Network Analyzer (VNA) of model no : N9917A ,with frequency range 4GHz-16GHz, comparison between the measured results and simulated results are also discussed. A brief summary of the contributions regarding the present work and suggestions for future research work conclude the thesis.

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ABBREVIATIONS

AC	Alternating Currents
AMC	Artificial Magnetic Conductor
AR	Aspect Ratio
BSF	Band Stop Filter
BPF	Band-Pass Filter
BSF	Bandstop Filter
C-EBG	Compact Electromagnetic Bandgap
CAD	Computer Aided Design
CST	Computer Simulated Technology
DGS	Defected Ground Surface
DRA	Dielectric Resonator
DC	Direct Current
DNG	Double Negative
EBG	Electromagnetic Bandgap Structures
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FMS	Ferromagnetic Semiconductor
GBN	Ground Bounce Noise
HIES	High Impedance Electromagnetic Surface
HIS	High Impedance Surface
HPF	High-Pass Filter
HTS	High-Temperature Superconductors
HMIC	Hybrid Monolithic Integrated Circuit
LH	Left-Handed

LTCC	Low Temperature Confired Ceramics
LPF	Low-Pass Filter
MEMS	Micro Electronics Mechanical System
MLIN	Microstrip Line
MMIC	Monolithic Microwave Integrated Circuits
NIR	Negative Index Of Refraction
PEC	Perfect Electric Conductor
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PBG	Photonic Bandgap Structures
PC	Photonic Crystal
PCB	Printed Circuit Board
RF	Radio Frequency
SCML	Schottkey Contact Microstrip Line
SLL	Side Lobe Level
SSN	Simultaneous Switch Noise
TSA	Tapered Slot
TEM	Transverse Electric Magnetic
UC-EBG	Uniplanar Compact EBG
VNA	Voltage Network Analyzer

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Electronic filters like low-pass filters, band-stop filters, high-pass filters and band-pass filters are extensively used in communications engineering and signal processing. Filters are used for the selection or rejection of desired frequency bands required for communication engineering.

In order to evade switching among different passive filters arrangements or for specific filtering applications like adaptive spectrum filtering, it will be advantageous to make use of tuneable filters. Due to the ever increasing demand for larger bandwidth, small passband ripples with improved passband and bandstop responses for Radio Frequency (RF) and microwave devices, new design techniques are emerging throughout the world. In recent years, ancient Greek prefix, Meta (means “beyond”), has been used to explain the composite materials with distinctive characteristics that do not present in the nature [1].On this significance most of the recent technologies in the field of high frequency microwave filters and antennas with Planar Bandgap designs are considered as one of the best design techniques. Electromagnetic Bandgap Structure (EBG) is an emerging technology in the direction of improvement in the features of existing RF active and passive electronic devices.

The search for artificial complex materials, particularly for EBG which is a metamaterials, has attracted immense interest from worldwide researchers.EBG is an application of special texture to a conducting plane, which is used to change the surface properties. This new EBG surface is regarded as by exhibiting very high electromagnetic surface impedance [2]. This high-impedance EBG surfaces preludes a useful new ground plane for novel miniature low profile antenna applications like in wide-band planar antenna, band stop filter, amplifiers, reflectors, resonators and in many more GHz frequency circuits’ applications.

In recent years, EBG surfaces have been mostly accepted due to their miniature low profile circuit area, no difficulty in integration and fabrication with MMICs (monolithic microwave integrated circuits). Throughout this entire thesis work new designs of Electromagnetic Bandgaps are proposed in order to improve bandgap features of a filter .These designs are simulated on CST microwave studio and out of all the proposed designs, the design which gave the best result has been fabricated with Printed Circuit Board (PCB) technology and this fabricated design has been tested on Agilent Technologies Vector Network Analyzer (VNA) Model no. N9917A. In addition, effect of aspect ratio (AR) calculations are also described with an objective to improve passband and stopband performances of a microwave filter for the application in the field of efficient wireless technologies.

1.2 OVERVIEW

A filter allows a certain range of frequencies to pass while attenuating the others thereby forming a pass-band and a stop-band [3]. Ideally for a bandstop filter there should be large stop band with small in-band insertion loss and optimum large out-of-band attenuation loss with the improved pass band performances within a miniature circuit area [4]. Miniature Low profile antenna design methodology forms exceptionally striking answers for emerging wireless trends in mobile technology. Authors in [5] describe plenty references for the existing modern Electromagnetic Band-Gap (EBG) high impedance surface structures. The main aim of these designs is to uncouple the cause of the adjoining ground plane from the conducting element or antenna itself. It has been observed when an electric dipole antenna is positioned in a parallel proximity to perfect electric conductor (PEC) ground plane than reverse image current flows as shown in Figure 1.1 which this leads to the severe degradation in antenna performance [6]. Hence in order to reduce the interaction between PEC ground plane and antenna, a high impedance surface structure known has electromagnetic band-gap (EBG) structure which has a features such as reflection in-phase and suppression of surface wave have been designed [6].

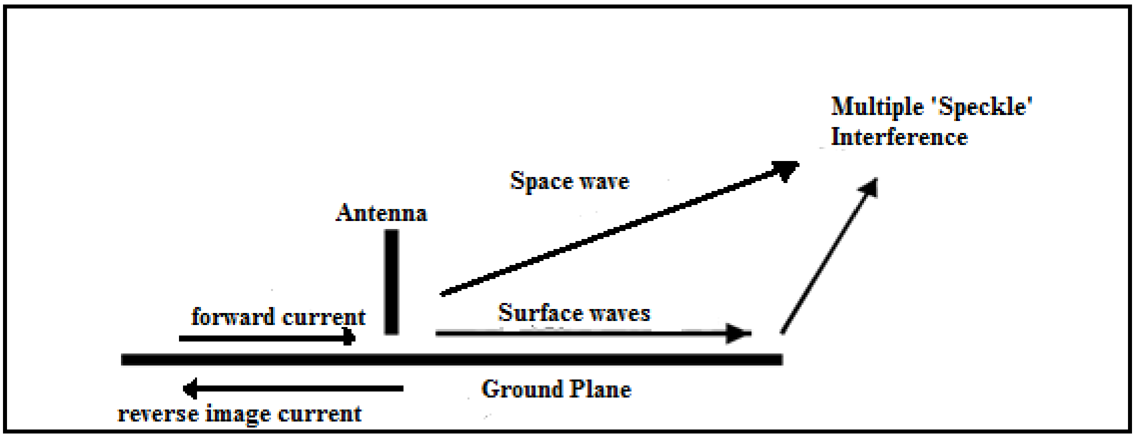

Figure1.1. Multipath speckle interfering surface waves on a ground plane [8]

Therefore EBG is such kind of periodic structures that allows circulation of EM waves in a specific band of frequency for definite angles of incidence and polarization trends are known as Electromagnetic Band-Gap (EBG) structures [7]. 2-D EBG structures shows good compatibility with microstrip circuits which make them work efficiently as bandstop filters [7]. A stopband occurs in the 2-D EBG microstrip structure when the periodic elements like circles are etched in the ground along with modulated microstrip line at upper face of substrate [7]. The behaviour of EBG materials can be improved with the proper choice of tapering parameters such as Kaiser Coefficient and Chebyshev Coefficient in correspondence with their aspect ratio control factor.

In this thesis work, EBG units in the form of non uniform dual window tapered annular-ring structures have been designed in order to observe any improvement over the conventional uniform circular-patterned EBGs. The main aim of this thesis work is to design a filter with wide stopband and reduced ripples in the pass band along with reduced surface waves during transmission as shown in Figure 1.2 EBG ground overcomes the end fire surface waves radiation which leads to removal of surface current during EM wave propagation .

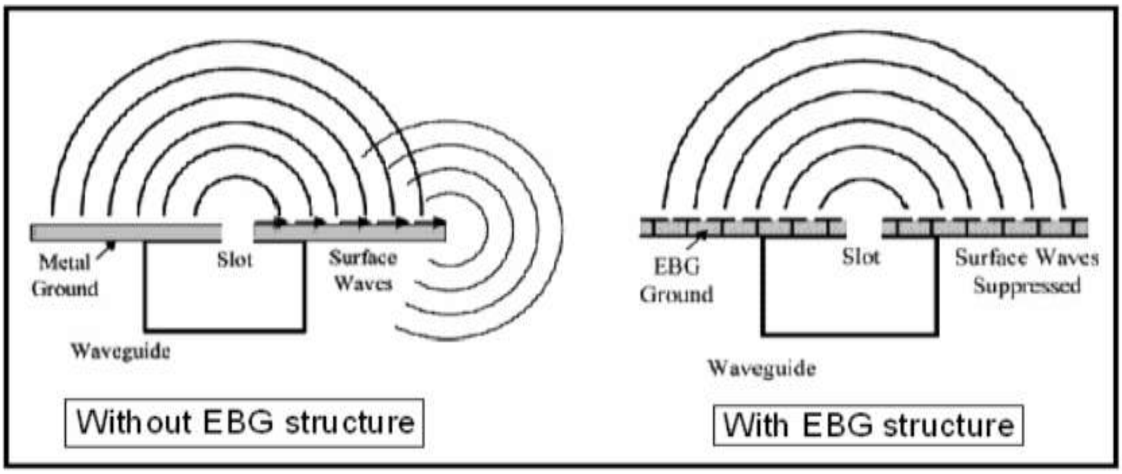

Figure1.2 The blocking of propagation surface wave by EBG structure [9]

Chebyshev and Kaiser Polynomials—as applied to antenna array synthesis, are used to taper the radius of the etched circular patterned EBG units on the ground plane. While the uniform distribution of the circular-patterned EBG is deteoriated with high passband ripples near the cut-off frequency, the non-uniform EBGs structures in correspondence with aspect ratio control factor is adopted in the forms of dual window i.e. Kaiser and Chebyshev tapered designs, which yields better results performances by suppressing passband ripples and producing distinct wide stopband up to several gigahertz.

1.3 THESIS OBJECTIVES

The objectives of this thesis are:

- Design of a uniform 2-D EBG Bandstop Filter Structure
- Design of a non-uniform 2-D EBG Kaiser-Chebyshev dual window tapered Bandstop Filter structure with wide stop-bandwidth and large attenuation within the stop band.
- Design and simulation of the effect of varying aspect ratio on uniform 2-D bandstop filter structure.
- Design and simulation of the effect of varying aspect ratio on Non-Uniform Dual window Tapered 2-D Annular Ring EBG Structure with Varying Aspect Ratio.
- Fabrication and testing of the Non-Uniform Dual window Tapered Annular- Ring EBG bandstop filter structure.

1.4 THESIS ORGANISATION

To start with, in the **second chapter**, a literature review of a multiple papers has been done which gave a smooth start to this research work. A review of papers that are based on High Impedance Electromagnetic Bandgap Structures (EBG) to improve the passband and stopband performance or to design miniature low profile design of microstrip circuits is done.

In **third chapter**, theoretical background of the composite materials for ex: EBG with their unique features is presented along with their classification and their applications in microwave GHz circuits.

In **fourth chapter**, various microwave filters and their characteristics are presented along with their parameters. Also a brief introduction about an LC modelling of mushroom type EBG structure is described in this chapter.

In **fifth chapter**, the 2-D microstrip filter structures are presented in this chapter. The methodology of a simple 2-D Electromagnetic Bandgap Structure filter structure is presented by designing defected ground plane and microstrip line in another plane separated by a substrate. The defected ground plane is formed by etching single column of circles with radius ‘r’ varying proportionally to the aspect ratio ‘r/a’ This dual window tapered annular ring EBG based microstrip filter structure is proposed which provides a wide stop-bandwidth with higher attenuation within the stopband and ripples in the passband that are caused due to the reason of periodicity of the high impedance EBG surfaces, are reduced by adopting this dual window annular ring EBG structure. Moreover The Kaiser-Chebyshev dual window tapered Annular ring EBG based microstrip filter is fabricated and the measured and simulated results are compared in this chapter and in this chapter it is also shown that 2-D

Electromagnetic Band gap design exhibits better compatibility with micro strip circuits which formulate them to work well as low pass filters. Hence in this chapter, an improved performance, low profile 2-D EBG design with a U- shaped microstrip line structure is proposed to work efficiently as low pass filter structure.

In **sixth chapter**, a brief summary of the contributions regarding the present work and suggestions for future research work conclude the thesis.

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CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

In order to start the thesis, the first step is to study the papers that have been already published by other researchers. Paper related to this work are chosen and studied. With the help of literature review, it becomes easier to perform this research work smoothly. A review of a variety of microstrip structures with various window techniques like Chebyshev, Binomial, Taylor and Uniform is used for improving the passband and stopband performances of microstrip filter structure in which the ground plane is modified is presented.

2.2 LITERATURE SURVEY

Shao Ying Huang, and Yee Hui Lee [4] proposed, an improved performance, low profile 2-D EBG design with a U- shaped microstrip line structure is designed to work efficiently as low pass filter .In this paper it is shown that by employing the peculiar dual plane EBG units arrangement and the curved design of the modulated microstrip line, the projected model gives broad stopband with large stopband attenuation and a better selectivity within a miniature circuit size.

F.Yang, and Y. Rahmat-Samii [5] Implemented a mushroom-like EBG structure in the design of microstrip antenna arrays to reduce the strong mutual coupling caused by the thick and high permittivity substrate without sacrificing the compact size or bandwidth of the antenna elements. It was seen that the E-plane joined microstrip antenna arrangement on a broad and elevated permittivity substrate had a powerful mutual coupling due to the prominent surface waves. For that reason, an EBG structure was inserted among array elements to lessen the mutual coupling effect. Several microstrip antennas were fabricated to validate this observation, and an 8 dB mutual coupling reduction was observed at the resonant frequency.

Yahya Rahmat-Samii, and Harish Rajagopalan [6] designed patch antennas and EBG structures residing on high dielectric constant substrates. The proposed structure describes the operation of high dielectric constant materials that leads to pronounced surface waves and a narrow bandwidth and. This paper also focuses on the bandwidth improvement using a thick substrate; along with improvement in antenna efficiency and severe surface waves, The EBG structure illustrated in this paper has a mushroom-like configuration, which exhibits a surface-wave suppression feature.

Yee Hui Lee, and Shao Ying Huang [7] designed two 2-D novel tapered Electromagnetic Band-gap microstrip filters structures. The projected model in this paper gives an evidence of an ultra wide stopband with large attenuation within a miniature circuit size. Window tapering technique like Chebyshev distribution is applied to tailor the ripples in the upper and lower passband occurred due to the periodicity of the high impedance EBG units. This comes up with a packed in EBG structure that shows outstanding rejection and transmission and features in the Bandgaps. The proposed structure has been fabricated in this paper shows better compatibility with monolithic microwave integrated circuits technology.

Daniel Frederic Sievenpiper, L. Zhang, and R.F.J. Broas [8] in this paper a novel kind of metallic electromagnetic arrangement has been developed with elevated surface impedance features proposed EBG structure has the property to prohibit the circulation of EM waves for specific frequency bands. Unlike usual conductors, this new discussed high impedance surface does not sustain circulating surface waves and it reflects electromagnetic waves with zero phase reversal. The proposed design in this paper consists of a metal area textured with a 2-D pattern of resonant basics which work as a 2-D filter to stop the spread of electric currents. This peculiar high surface impedance material is appropriate to a range of electromagnetic problems, as well as for new type of miniature design of low-profile antennas

Harish Kumar, Manish Kumar, Mohit Kumar, Abhijeet Kumar, and Rajeev Kanth [9] designed a mushroom like EBG structure with different diameter of vias to analyze the behaviour of the EBG structure. A simple, compact EBG microstrip antenna that embraces broadband of 2.5 to 3.7 gigahertz Industrial Scientific and Medical band, Bluetooth application was proposed. In this paper it is observed that when the radius of EBG units was increased the bandgap shifted to higher frequency range. In this paper a comprehensive model is presented to accurately characterize an important class of high impedance surface electromagnetic bandgap (EBG) structures over a wide range of frequencies. The model predicts with high degree of accuracy the dispersion diagram over a wide band of frequencies. Optimization of EBG structures to meet specific engineering criteria can be performed with high efficiency, thus saving significant computation time and memory resources.

An-Shyi Liu, Yin-Chi Chen, and Ruey-Beei Wu [10] demonstrated a simple pattern of periodic holes or structures etched in ground plane beneath the strip conductor had been proposed for stopband and lowpass filter designing design procedure for the EBG structure to achieve a wide stopband, by combining tapered etched holes and multi-period EBG structure units. The structure proposed was based on a combination of non uniform tapered etched holes and multiperiod EBG structure. A large one acts as a slot patch when the radius reaches the one half wavelength and increases radiation loss at higher frequency. It was found that the stopband of multiperiod EBG structure was widened owing to the cascading of the individual stopbands.

Liang Chen, Chun Wang, Qi Zhang, and Xiangsong Yang [11] presented a novel low profile miniature wide-band high impedance electromagnetic bandgap (EBG) structures utilizing cascaded mushroom-like units with and without 'chip capacitors' loading. Direct communication process is used to determine the band-gap of the dual tapered Electromagnetic Bandgap structure. The resulting effect of loading capacitors among the nearby metal patches on the EBG properties was studied. The outcomes show that the total band-gap embraces the stop-bands produced by the two original uniform designs.

Kai Herbertz [12] investigated the use of variety of EBG structures as component of a number of different antenna design. Both one-dimensional and two-dimensional geometries comprising of dielectric slab, rods and air pockets in dielectric was studied. Antenna used is microstrip patch, dielectric resonator (DRA) and tapered slot (TSA). With microstrip patch antenna EBG structure was found to affect the back lobes somewhat but had little influence on the pattern near the horizon. With DRA the insertion of EBG alters the radiation pattern but did little to suppress the side lobes. Only the dielectric slab EBG exhibits the anticipated behaviour, which was the development of nulls at non-propagating directions. Three types of antenna and EBG were used with the objective of altering the side lobe levels of antenna but the result had not been as promising as desired.

V. G. Veselago [13] in 1968, Veselago was the first to put forward the existence of left handed materials and provide a theoretical examination [13]. In this paper an introduction to the left handed material has been given as double negative materials (DNGs). "Double Negative (DNG) materials" are special type of materials with negative index of refraction (NIR). Along with effective negative permeability and effective negative permittivity and these DNG materials also possess left-handed (LH) wave propagation.

Veselago studied a comprehensive model to accurately characterize an important class of electromagnetic bandgap (EBG) structures over a wide range of frequencies. The model predicts with high degree of accuracy the dispersion diagram over a wide band of frequencies. Optimization of EBG structures to meet specific engineering criteria can be performed with high efficiency, thus saving significant computation time and memory resources.

F.R.Yang, K.P.Ma, and Y.Qian [14] proposed Uniplanar-Compact EBG structures consist of a 2-D square prototype each part consists of a metal pad and four linking narrow branches to form a distributed LC network. A novel kind of metallic electromagnetic arrangement has been developed, which is categorized by elevated surface impedance. In this paper it has been described that planar EBGs are of special attention at microwave frequencies range, due to simplicity of fabrication. These EBGs are regularly only periodic in a 2-D plane and do not show signs of a bandgap for every angles of incidence of an E.M wave, but just for all angles in that one plane. In the collection of planar EBGs, the uniplanar compact EBG and the mushroom kind EBG are of meticulous value. It is also shown that Uniplanar Compact EBG designs can be built by implementing standard planar fabrication techniques without any alterations.

Yahya Rahmat-Samii [15] describes the periodic structures that prohibit the circulation of EM waves in a definite frequency band for definite polarization senses and definite arrival angles. This paper shows the trade off between bandwidth and suppression of surface waves on the basis of application of thick substrate .This paper describes various antenna concepts like antenna efficiency, radiation pattern, mutual coupling etc along with description of high impedance EBG structure which has a mushroom-like configuration, exhibiting a surface-wave suppression feature in order to overcome the above difficulties of mutual coupling and surface waves.

Jin-Yang Kim, and H. Lee [16] proposed a novel bandstop filter (BSF) design for wideband and miniature size circuit applications. Only3 cells of the projected structure are adequate for the measured 10 dB bandgap from 4.3 to 16.2 GHz. The projected Band Stop Filter realizes the wide stopband features by superimposing two different photonic bandgap (PBG) structures into a coupled double-plane arrangement we expect this novel BSF structure is widely used for miniature compact and wideband circuit applications, such as compact high-efficiency power amplifiers by means of harmonic tuning techniques.

X.Q.Chen, X.W.Shi, Y.C.Guo, and C.M.Xiao [18] studied the performance of PBG structures as substrates for microstrip circuits. This paper anticipated a new defected ground structure (DGS) for the microstrip line. The proposed DGS element structure can provide the bandgap attribute in some frequency bands with only one or more unit lattices. The equivalent-circuit parameters are extracted by using a simple circuit analysis method. By employing the extracted parameters and circuit analysis hypothesis the bandgap consequence for the provided defected ground unit structure can be described. The corresponding circuit for the proposed defected ground unit structure is derived by way of 3-D field analysis methods. By means of the derived and extracted equivalent circuit and parameter, the low-pass filters are planned and implemented. The investigational results show outstanding agreements with theoretical results and the validity of the modelling method for the projected defected ground unit structure.

Y.Fei-Ran, M.Kuang-Ping, Q. Yongxi, and T. Itoh [20] A novel kind of metallic electromagnetic arrangement has been developed, which is categorized by elevated surface impedance. In this paper it has been described that planar EBGs are of special attention at microwave frequencies range, due to simplicity of fabrication. These EBGs are regularly only periodic in a 2-D plane and do not show signs of a bandgap for every angles of incidence of an E.M wave, but just for all angles in that one plane. In the collection of planar EBGs, the uniplanar compact EBG and the mushroom kind EBG are of meticulous value. The Uniplanar-Compact EBG structures consist of a 2-D square prototype each part consists of a metal pad and four linking narrow branches to form a distributed LC network. It is also shown that Uniplanar Compact EBG designs can be built by implementing standard planar fabrication techniques without any alterations.

D. Sievenpiper [21] in this paper a novel kind of metallic electromagnetic arrangement has been developed with elevated surface impedance features proposed EBG structure has the property to prohibit the circulation of EM waves for specific frequency bands. Unlike usual conductors, this new discussed high impedance surface does not sustain circulating surface waves and it reflects electromagnetic waves with zero phase reversal. The proposed design in this paper consists of a metal area textured with a 2-D pattern of resonant basics which work as a 2-D filter to stop the spread of electric currents. This peculiar high surface impedance material is appropriate to a range of electromagnetic problems, as well as for new type of miniature design of low-profile antennas.

C. Jinwoo, V. Govind, and M. Swaminathan [25] in this document it is shown that the surface waves which propagate along the surface of the substrate can be suppressed by the multiple photonic band-gap structure because of its effect of forbidden band, that it can radiate most of electromagnetic waves' energy in the substrate significantly, and that it has lower return loss (S11) compared to the conventional patch antennas. When added to patch antenna we get a photonic crystal patch antenna which provide lower return loss, higher gain and a better capacity to radiate the energy in the bottom substrate. There is a frequency shift because of PBG structure because the introduction of PBG structure make the guide wave length shorter, and the size of antenna also becomes low profile which makes it compatible with mixed-signal system applications.

Y. Li, F. Mingyan, and F. Zhenghe [26] presented a simple 2-D EBG structure consisting of spiral-shapes etched in the ground plane of 50Ω microstrip transmission line. The spiral-shaped EBG structure presented superior antenna features as compared to the periodically loaded circular patch. The patch antenna was electromagnetically coupled to a microstrip with EBG ground plane having cross shaped slots. Wide stopband was obtained for the present EBG structure. Enhanced performance was observed when EBG structure was incorporated as ground plane for a rectangular microstrip antenna.

B. Lin, Q. Zheng, and N. Yuan [27] introduced different techniques for characterizing low profile reduce sized EBG structures to design EBG waveguides working in millimetre frequency band. Square and triangular lattices of holes are used. These waveguides then provide better return loss and insertion loss. A EBG waveguide can be formed by introducing a 1-dimentional defect in the periodic lattice of the EBG structure. A square lattice of dielectric rods has been used to design EBG waveguide for TE modes and a triangular lattice for TM modes. The structure was designed to achieve a stopband around 30GHz.

E.R. Brown, C.D. Parker, and E. Yablonovitch [29] proposed a Novel 1-D microstrip PBG cells. They are sections of microstrip line with unique hole patterns etched on the line. As examples, two types of Photonic bandgap cells are investigated. Simulation and experiments explain that the cell exhibits outstanding slow-wave and band-stop effects. A corresponding -circuit is used to model the Photonic bandgap cell. Numerous cells linked in series to form an outstanding band-stop filter.

L. Zhan, and Y. Rahmat-Samii [30] Describes plenty references for the existing modern Electromagnetic band-gap (EBG) high impedance surface structures. The main aim of this paper is to uncouple the cause of the adjoining ground plane from the conducting element or antenna itself. It has been observed when an electric dipole antenna is positioned in a parallel proximity to perfect electric conductor (PEC) ground plane than reverse image current flows which this leads to the severe degradation in antenna performance. Hence in order to reduce the interaction between PEC ground plane and antenna, a high impedance surface structure known has electromagnetic band-gap (EBG) structure which has a features such as reflection in-phase and suppression of surface wave have been designed.

E. Yablonovitch [33] proposed a novel PBG structure for a wide stopband lowpass filter with a new periodic lattices and demonstrated the PBG microstrip antenna with the novel PBG structure. The proposed PBG structure had a wide stopband without any increasing circuit size. The antenna had improvement in the return loss level and the bandwidth. It was also expected that the proposed structure can be applied in various microstrip circuits to improve their performance by removing harmonic components using the characteristics of wide stopband.

Vesna Radisic, Y. Qian, and T. Itoh [34] proposed a new 2-D PBG structure for microstrip lines, in which a periodic 2-D prototype consisting of holes are etched in the ground plane of microstrip line. There is no requirement of drilling through the substrate. 3 PBG circuits were designed and fabricated with dissimilar circle radii in order to decide the most favourable dimensions, as well as a Photonic bandgap circuit with the compensated perpendicular microstrip bend. Measurements illustrate that this proposed structure can exhibits deep and wide stopbands.

Ramón Gonzalo, P. D. Maagt, M. Sorolla [35] proposed a photonic bandgap structure for patch antenna which minimizes the surface wave effect. A configuration of thick substrate was utilized. These PBG patch antenna shows reduced surface modes, thus modifying the gain and far-field radiation pattern design. An antenna if placed over a high permittivity substrate dielectric substrate may couple more power into substrate mode which contributes to a loss mechanism. Surface wave diffraction plays a key role when thick substrate was used to increase the bandwidth of antenna. When PBG is used with patch antenna the resonance frequency shifts due to variation of dielectric constant. This shows that PBG offer potential application in array configuration increasing the antenna efficiency together with suppressing of mutual coupling through the substrate material

2.3 CONCLUSION

From above literature survey we can conclude that EBG structures are extensively used to improve the performance of microstrip patch antennas, numerous EBG structures have been proposed but these approaches have some limitations regarding ripples level in the passband, narrow stop bandwidth, small in band attenuation etc. Therefore to have a novel structure which full fill all the requirements, research work has been presented in following chapters, which gives a design methodology to have the optimum structure in order to have best possible design technique to overcome all the gaps in the existing designs.

CHAPTER 3

THEORETICAL BACKGROUND OF EBG STRUCTURES

3.1 INTRODUCTION

In current years, there has been increasing attention in utilizing sub-class of metamaterials i.e. Electromagnetic Band-Gap (EBG) structures as shown in Fig 3.1. The term metamaterials encompasses artificial complex planes of various periodic structures with characteristics that do not exist in nature [12].

Veselago, in 1968 was the first to put forward the existence of left handed materials and provide a theoretical examination [13]. Left Handed materials are also called double negative materials (DNGs). "Double Negative (DNG) materials" are special type of materials with negative index of refraction (NIR). Along with effective negative permeability and effective negative permittivity and these DNG materials also possess left-handed (LH) wave propagation.

Periodic structures that allow circulation of EM waves in a specific band of frequency for definite angles of incidence and polarization trends are known as Electromagnetic Band-Gap (EBG) structures. This interesting feature of EBG makes them very promising candidate to a number of applications [14]. EBG structures permit the circulation of EM waves in definite frequency bands and forbid them in other bands known as bandgap.

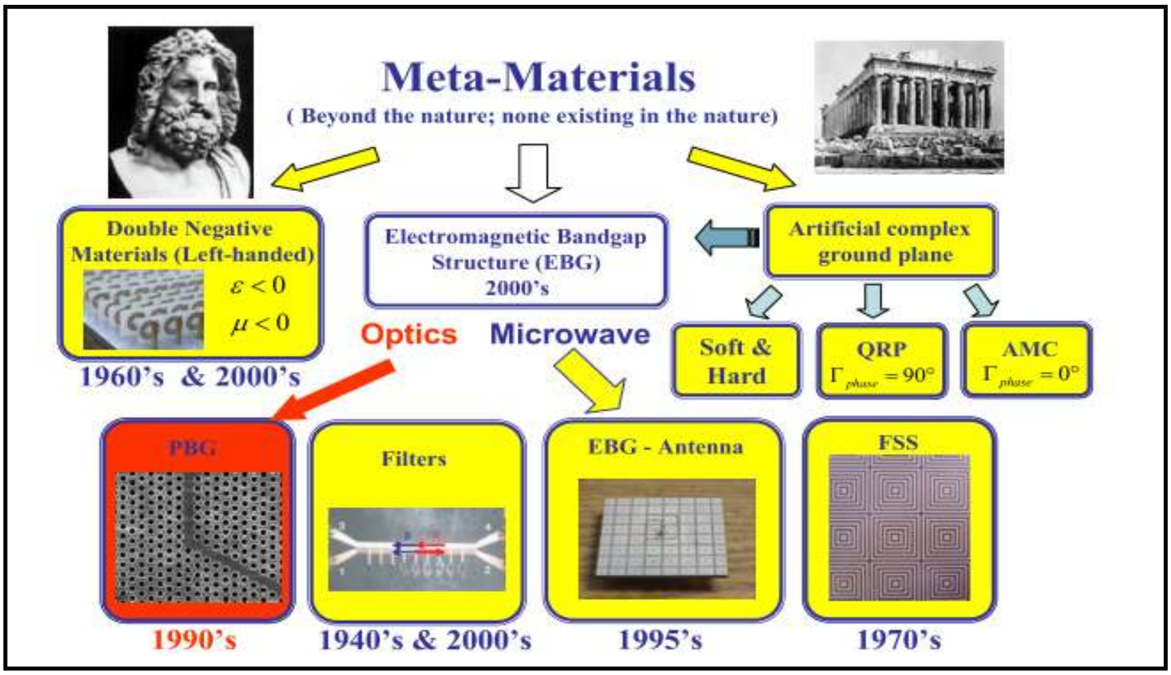


Figure3.1 Classification of Metamaterials [15]

3.2 SURFACE WAVE SUPPRESSION FEATURE OF EBG STRUCTURE

Surface waves are caused by the numerous reflections of the electromagnetic waves linking the ground plane and the air-dielectric boundary. These waves are incident on the ground plane at this angle shown, get beck from there, then meet the interface of air and dielectric which reflect them also after the zigzag motion has followed, they at last arrive at the limits of the microstrip structure where waves are diffracted and reflected by the ends giving birth to the radiations known as end-fire radiations as shown in below Fig 3.2.

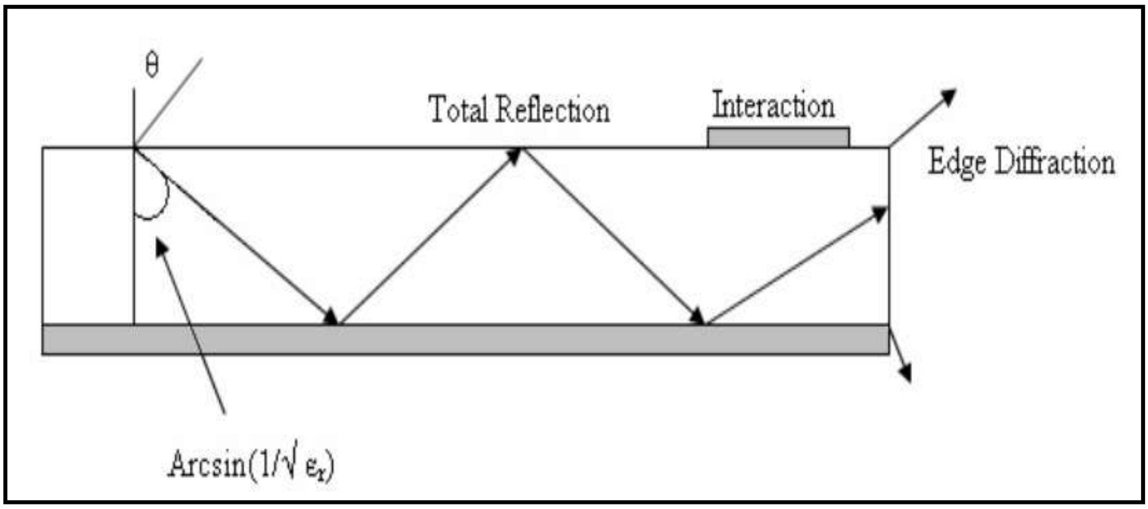


Figure 3.2 Surface Waves propagation within the dielectric material of patch antenna [17]

Surface waves are the foundation of two basic problems in any systems: First problem is the outflow of energy through leaky waves and end-fire radiation. The second problem is the false coupling among circuit components and antenna basics these problems roots an overall reduction in the structure effectiveness, bound the bandwidth, and limits the appropriate frequency range of microstrip systems [14]

EBG as an additional important class of metamaterials consist of ground planes that show evidences of peculiar reflection characteristics other than traditional Perfect Electric Conductor, and are distinctly defined as "artificial complex ground planes, EBG has been extensively adopted as the substrate material of high frequency circuits applications like in microstrip patch antennas to suppress the interfering waves between two closely placed antennas and power amplifiers to lessen the ripples within the passband.

It has been seen that when an electric dipole antenna is positioned in a parallel proximity to perfect electric conductor (PEC) ground plane than reverse image current flows this leads to the severe degradation in antenna performance. In order to reduce the interaction between PEC ground plane and antenna, electromagnetic band-gap (EBG) structures have been designed. Moreover, the EBG structures do not endure from excess losses in the upper and lower passband; on the contrary, such structures might give superior insertion and return loss standards due to their capability to lessen the surface waves. This feature of surface-wave suppression helps to improve antenna's performance such as escalating the gain of antenna and less power wasted when reducing backward direction.

3.3 EBG APPLICATIONS IN ANTENNA ENGINEERING

Diverse research activities on EBG structures are on the rise in the electromagnetic and antenna community, and a wide range of applications have been reported, such as low profile antennas, active phased arrays, TEM waveguides, and microwave filters.

3.3.1 Antenna substrates for surface wave suppressions

Surface waves are by-products in several antenna designs. Directing EM waves circulation by the side of the ground surface as a substitute of radiation into free space, the surface waves lessen the antenna effectiveness and gain. The band gap characteristic of EBG structures has originated practical applications in suppressing the surface waves in a range of antenna designs. For example, an EBG structure is adopted to enclose a microstrip antenna to boost the antenna gain and lessen the back lobe.

3.3.2 Antenna substrates for efficient low profile wire antenna designs

Another favourable purpose of EBG is to propose miniature low profile antennas with good quality radiation competence which is needed in recent wireless communication systems. The EBG surface is proficient of providing a positive image current within a definite frequency band, resulting in superior radiation efficiency.

3.3.3 Reflection transmission surfaces for high gain antennas

EBG structures are also useful in scheming antennas with a better gain in the region of or above 20 dBi. Conventionally, antennas with better gain are designed by means of either parabolic antennas or large antenna arrays. On the other hand the curved exterior of parabolic antennas makes it complicated for them to be conformal with mobile utilities, whereas large antenna arrays constantly experience loss in the feeding networks. The planar Electromagnetic Bandgap surfaces presents an another key to this difficulty For example, it is used to model a high gain resonator antenna.

Besides antenna applications, EBG structures have also found several applications in microwave circuit course designs. A representative example is microwave filter design that effectively discards the upper harmonics in the circuits.

Finally, the advantages of EBG structures can be concised into seven main points:

1. Slow-wave effect which is very important for size reduction.
2. Low cost
3. Suppression of surface waves
4. Low attenuation in the passband
5. Easy fabrication
6. Ability of these structures to introduce distinctive stopbands
7. Compatibility with standard circuit technologies

3.4. CLASSIFICATION OF ELECTROMAGNETIC BANDGAP STRUCTURES

Electromagnetic Bandgap structures can be classified as shown in Figure 3.3, on the basis of the arrangements of EBG units in ground plane or drilling of EBG units in substrate and their application as high impedance surface for the removal of surface waves.

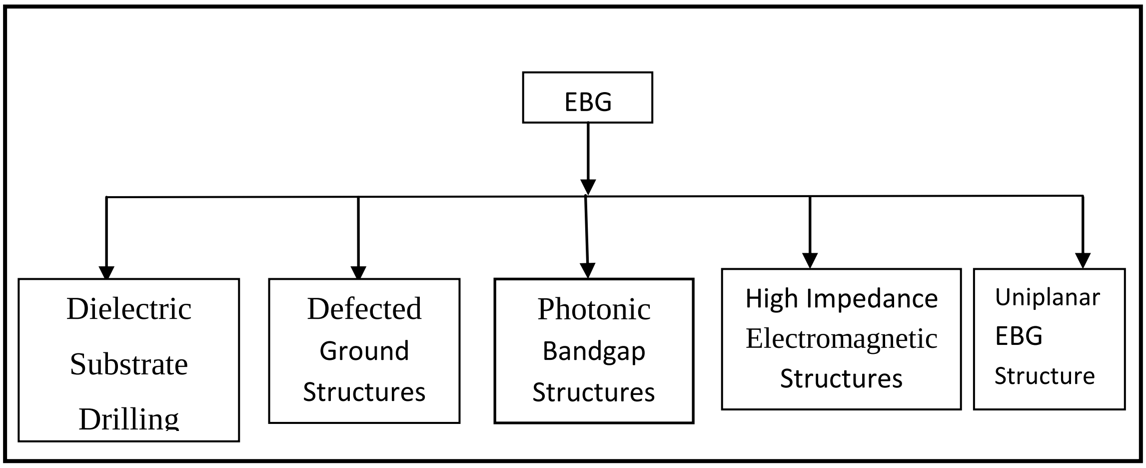


Figure3.3 Classification of EBG structures

3.4.1 Dielectric Substrate Drilling Periodic structures

An array of air holes drilled through a dielectric substrate .This structure as shown in Figure 3.4 consists of periodic arrangement of dielectric inclusion with a substrate changed from that of the host dielectric substrate. This sort of EBG structures requires the complicated work of drilling through the substrate. Moreover, these EBG structures are not easy to model and analyze.

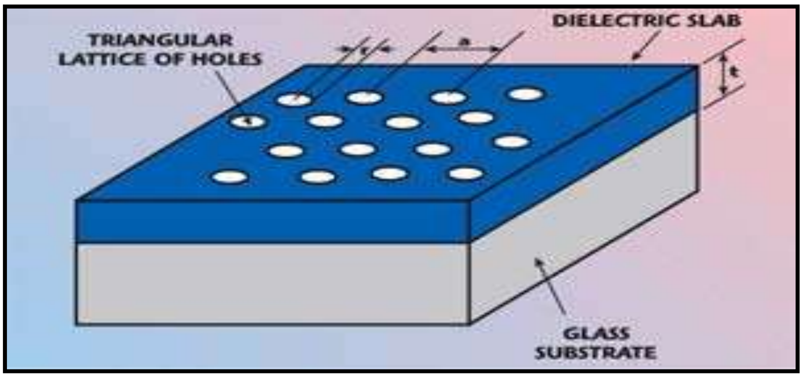


Figure3.4 EBG Structures from Periodic Dielectric Substrate Drilling [41]

3.4.2 Defected Ground Structures (DGS)

DGS has straightforward structure and potentially great applicability to design microwave circuits such as filters, amplifiers and oscillators. DGS has random shapes and is positioned on the backside metallic ground plane .It rejects certain frequency bands and hence it is called electromagnetic bandgap (EBG) structures. The DGS cell as shown in Figure 3.5 has a simple geometrical shape, such as circular. A Defected Ground Structure is an etched pattern form which is positioned on the ground flat surface DGS is realized on the underneath plane with one island located at both sides of the microstrip line on the upper plane.

DGS for the microstrip line, which has etched defects in the backside metallic ground plane, is one important concepts of microwave circuit design at the present time, Compared to photonic bandgap (PBG) its bandgap and slow-wave characteristics are better than the customary ground plane. DGSs have gained importance in filter design [18] screening most favourable passband and stopband responses and sharp selectivity and ripple elimination.

The features of the defected ground plane are:

- Increases valuable capacitance and inductance of transmission line
- Enhances effective permittivity
- Disturbs protecting fields on the ground plane
- Size reduction for the module

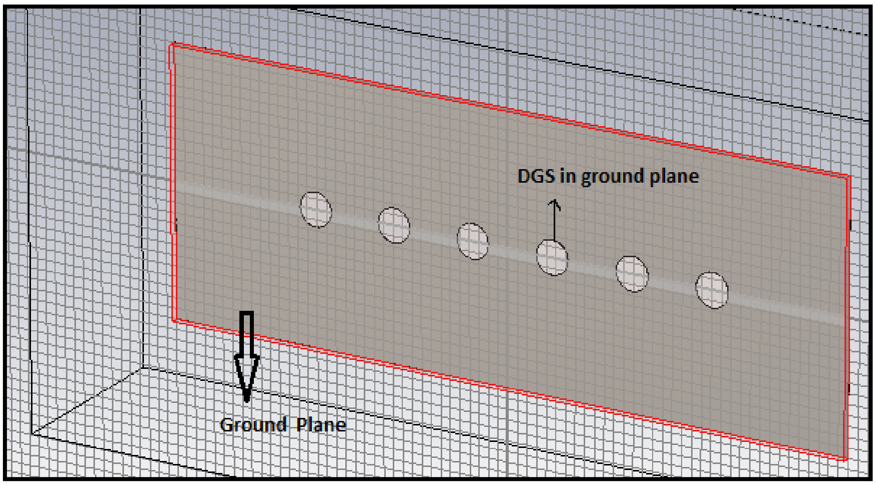


Figure3.5 Diagram of DGS

3.4.3 Photonic Bandgap (PBG) Structures

A photonic crystal essentially behaves much like a band-stop filter, eliminating the spread of power over a predetermined group of frequencies. Semiconductor material exhibits an electronic bandgap where electrons cannot exist. Photonic bandgap (PBG) structures are periodic structures that influence electromagnetic radiation in a way alike to semiconductor procedure manipulating electrons.

Similarly, a photonic crystal that contains a photonic bandgap does not allow the propagation of electromagnetic radiation with specific frequencies in the bandgap [19]. This observable fact results from the destructive Bragg diffraction interference due to the periodic boundary conditions of PBG structures. This property has a significant importance in many microwave and optical applications to improve their efficiency.

However, once a defect is preluded such that it disrupts the periodicity in the crystal, a region to confine or catch electromagnetic power is recognized this ability to lock up and direct electromagnetic energy has numerous practical applications at microwave frequencies as couplers, filters and particularly antennas. This straightforward notion of inserting defects in a photonic crystal arrangement preludes a new tactic in the devise of microstrip (patch) antennas. The proposal is to plan a 2-Dimensional photonic crystal substrate, where the patch becomes the defect in the crystal configuration .The property of avoidance of surface waves improves the working bandwidth and directivity, while reducing side-lobes and coupling.

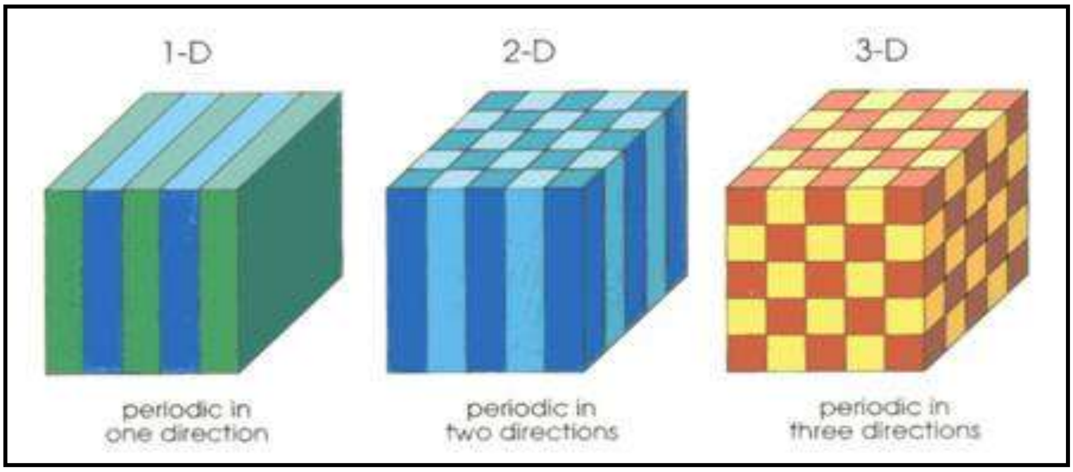


Figure3.6 Example of PBG 1-D, 2-D and 3-D [41]

3.4.4 High Impedance Electromagnetic Surface (HIES)

A novel kind of metallic electromagnetic arrangement has been developed. It is categorized by elevated surface impedance. Even though it is prepared of constant metal and conducting Direct Current (DC), it does not perform Alternating Currents (AC) within a prohibited frequency band. Unlike usual conductors, this new surface does not sustain circulating waves at the surface and it give back EM waves with zero phase reversal.

The design consists of a metal area textured with a 2-D pattern of resonant basics which work as a 2-D filter to stop the spread of currents.

The surface can be described by means of a lumped factor circuit model, which precisely predicts many of its electromagnetic features. This peculiar material is appropriate to a range of electromagnetic problems, as well as for new type of miniature design of low-profile antennas.

A high-impedance surface consists of an arrangement of metal, protrusions on a smooth metal area they are arranged in a 2-D lattice, and are generally shaped as metal plates, associated to the uninterrupted lower conductors by erect ports. They can by visualized as mushrooms or thumbtacks or other shapes protruding from the surface.

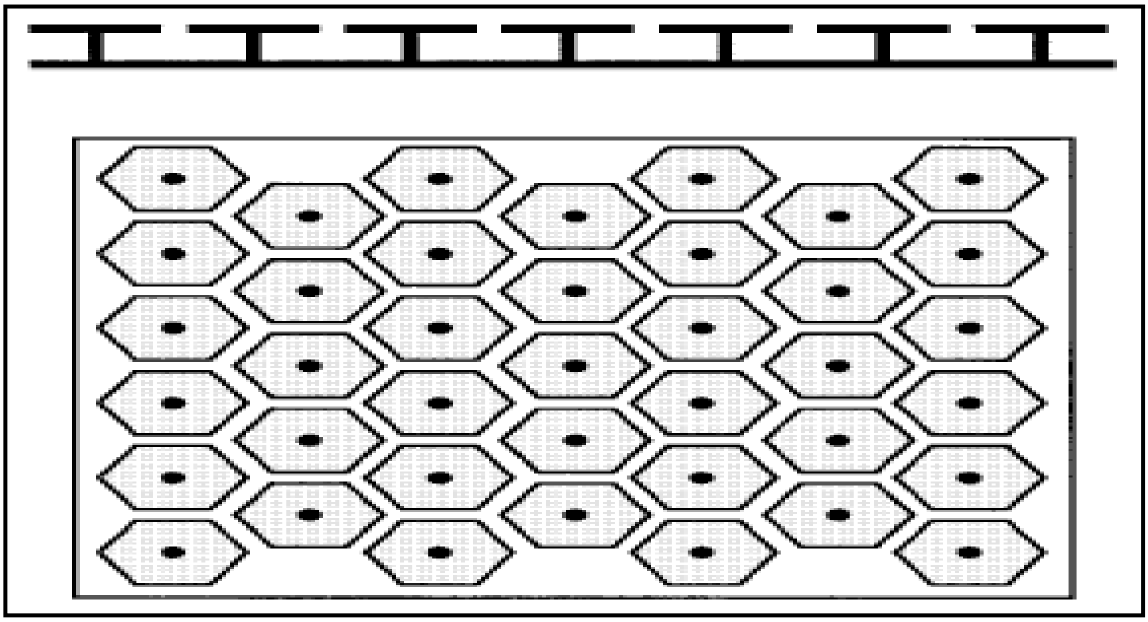


Figure3.7 Periodic metal connected to ground via holes to yield high impedance surface [21]

3.4.5 Uniplanar-Compact EBG Structures

Planar EBGs are of special attention at microwave frequencies range, due to simplicity of fabrication. These EBGs are regularly only periodic in a 2-D plane and do not show signs of a bandgap for every angles of incidence of an E.M wave, but just for all angles in that one plane. In the collection of planar EBGs, the uniplanar compact EBG [20] and the mushroom kind EBG [21] are of meticulous value. The Uniplanar-Compact EBG structures consist of a 2-D square prototype each part consists of a metal pad and four linking narrow branches to form a distributed LC network. The Uniplanar Compact EBG designs can be built by implementing standard planar fabrication techniques without any alterations.

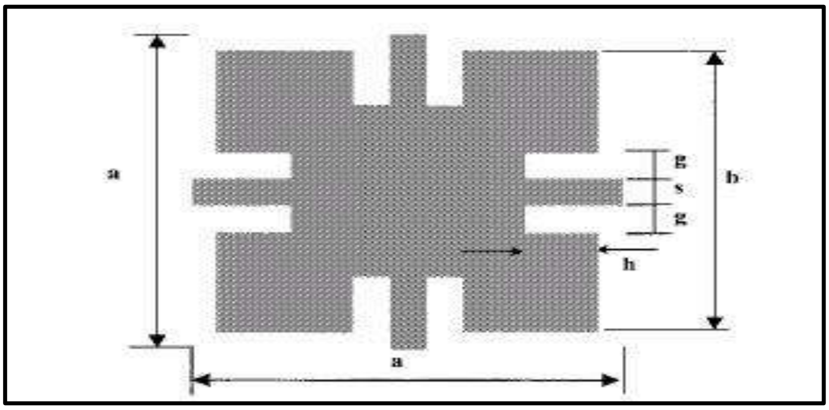
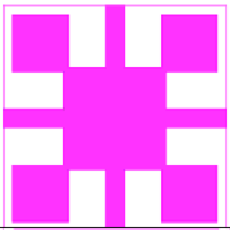
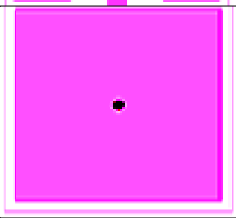
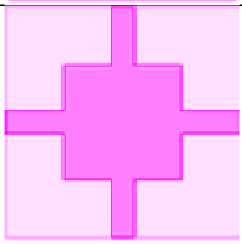
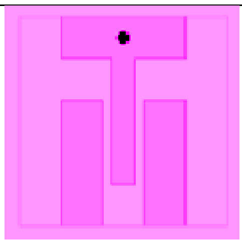
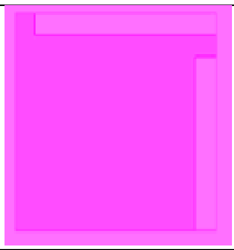
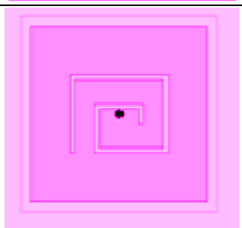
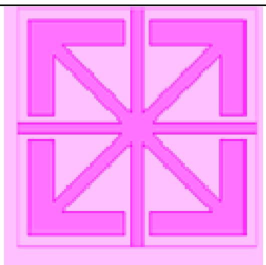
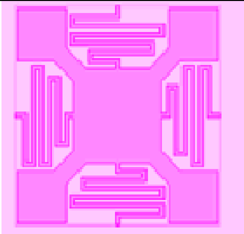


Figure3.8 Uniplanar-EBG structure [22]

The subsequent Table 3.1 lists different design geometries of EBG structures, the year of publication, the publication reference, the compactness as well as the bandgap. In the "structure" column, the plan view of only one cell of an EBG array is shown. Black circles indicate vias.

Table 3.1 Planar EBGs Structures [12]

Structure (one unit cell)	Year	Reference	Bandgap (GHz)	Remarks
	1999	[22]	10.9-13-5	Uniplanar, Compact EBG. This configuration serves as starting point
	1999	[21]	10-14	Mushroom EBG
	2001	[23]	-	-
	2004	[24]	4.61-5.22	-
	2004	[25]	1.8-5.3	-
	2005	[26]	2.07-2.34	-

	2006	[27]	4.1-5.0	-
	2008	[28]	2.26-4.53	Structure from this work, based on UC-EBG

3.5 APPLICATIONS OF ELECTROMAGNETIC BANDGAP STRUCTURES

- EBGs structures could be used to enhance the efficiency of antennas [29], due to their feature i.e. suppression of surface and substrate waves, which are the chief loss mechanisms.
- The EBGs can solve a purpose to act as an artificial magnetic conductor (AMC) at a certain Electro Magnetic Wavelength [30].
- With EBGs high level of integration would be possible on a single chip of microstrip antenna.
- By using an EBG, the antenna could be shielded from the substrate, enabling it to be integrated with additional components on the similar substrate to lessen crosstalk among neighboring components on a chip [31].
- The radiation pattern of antennas can be improved with EBG structures [32]
- Another important point about EBGs is the idea of introducing defects into the structure in order to tweak its properties, similar to doping of semiconductors [33].
- EBG structures could be used to enhance other radio frequency (RF) applications like attenuators, cavity resonators, filters, etc.

In this chapter a complete description and classification of EBG structure has been discussed along with their advantages and applications in communication engineering. Therefore the following chapter describes the more practical analysis for the design methodologies of EBG structures to work efficiently as microwave filters.

CHAPTER 4

MICROWAVE FILTERS AND ANALYTICAL MODELLING OF EBG STRUCTURE

4.1 FILTERS

Filters are essentially frequency discriminating elements. It is a network that is intended to attenuate definite frequencies but pass others devoid of any loss. According to Webster's definition "A filter is a device that passes electric currents at certain frequencies or frequency ranges while preventing the passage of others." Based on the frequencies that can be passed, the filters are classified as Low-Pass Filter (LPF), High-Pass Filter (HPF), Band-Pass Filter (BPF), Band-Reject Filter (BRF).

4.2 FILTER CHARACTERISTICS

There are four different filter characteristics regarding the signal attenuation in relation to frequency:

- Low-pass filters attenuate signals at frequencies above their cutoff frequency as shown in Figure 4.1.

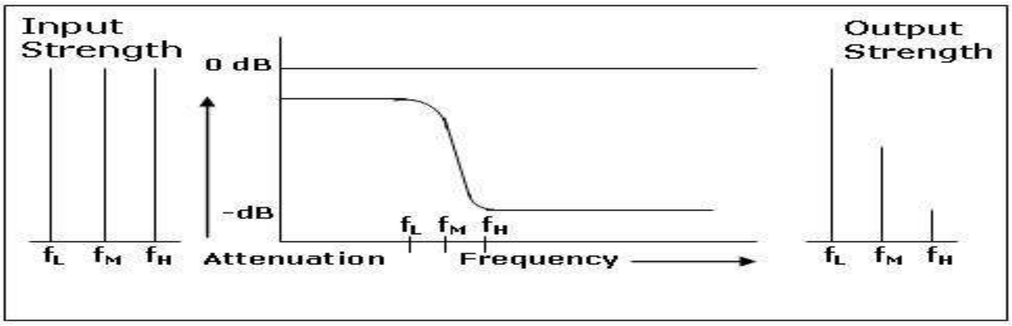


Figure 4.1 Characteristics of Lowpass filter [42]

- High-pass filters attenuate signals at frequencies below their cutoff frequency as shown in Figure 4.2

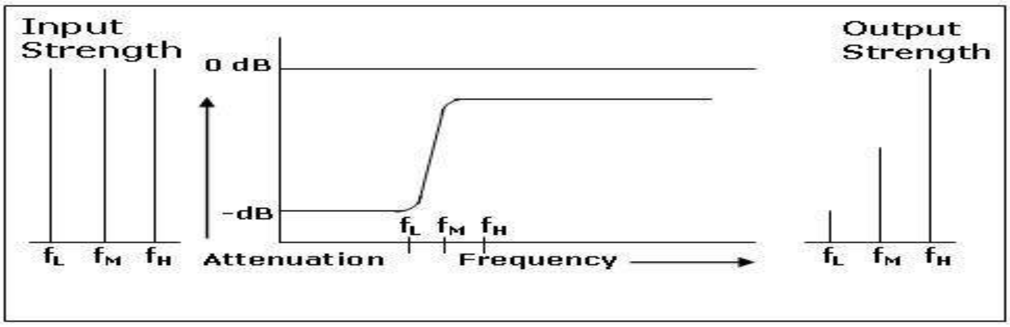


Figure 4.2 Characteristics of Highpass Filter [42]

- Band-pass filters attenuate signals at frequencies below their first cutoff frequency and above their second cutoff frequency as shown in Figure 4.3.

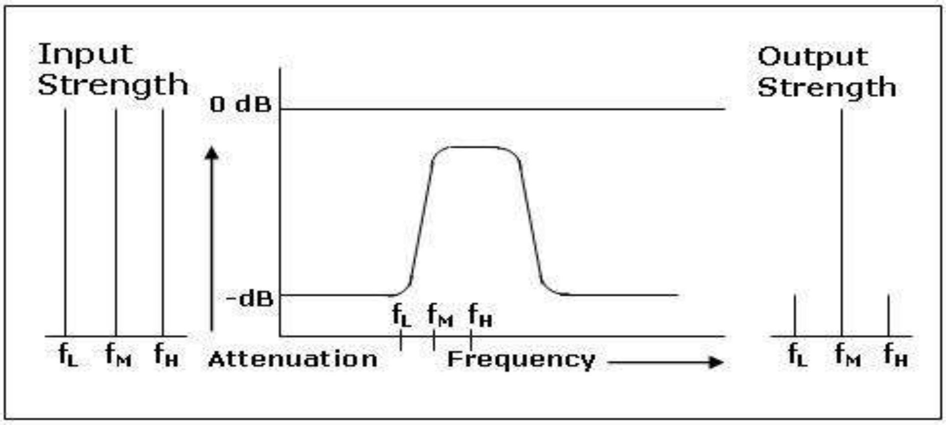


Figure4.3 Characteristics of Bandpass filter [42]

- Band-stop filters attenuate signals at frequencies above their first cutoff frequency and below their second cutoff frequency as shown in Figure 4.4.

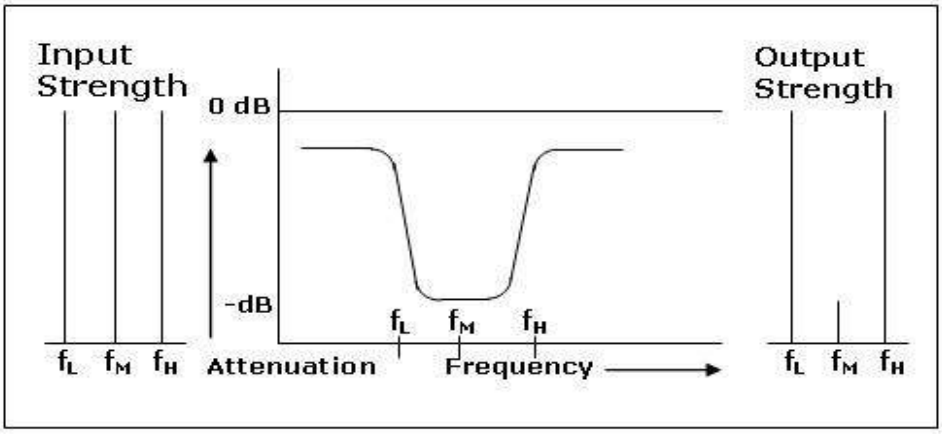


Figure4.4 Characteristics of Band-reject filter [42]

4.3 FILTER TYPES

An ideal filter would have a rectangular frequency shape, switching from high attenuation outside of its passband to zero attenuation inside its passband region. However, ideal analogue filters do not exist. Filter implementations come in different types, depending on which property is being optimized. The two most famous filter types are:

- Butterworth filters, which are also called "maximally flat filters". Butterworth filters do not have ripples.
- Chebyshev filters have a faster cutoff than Butterworth filters, but contain ripples in either the passband or the stopband, depending on the implementation.

4.4 FILTER PARAMETERS

Beside the filter characteristic and the type, different other filter parameters exist. These parameters further describe the behaviour of the filter:

- The centre frequency
- Order (roll off), the order is determined by the number of resonant pairs and in turn influences the roll off. Per order, the filter has a roll off of 20 dB / decade (or around 6 dB per octave).
- Pass band/ stop band Ripples
- 3dB pass/ stop bandwidth
- Cutoff frequency
- Insertion Loss

Figure 4.5 shows the different parameters of a lossless 3rd order Butterworth Bandpass Filter with a centre frequency of 3.5 GHz and a 3dB bandwidth of 2.2 GHz.

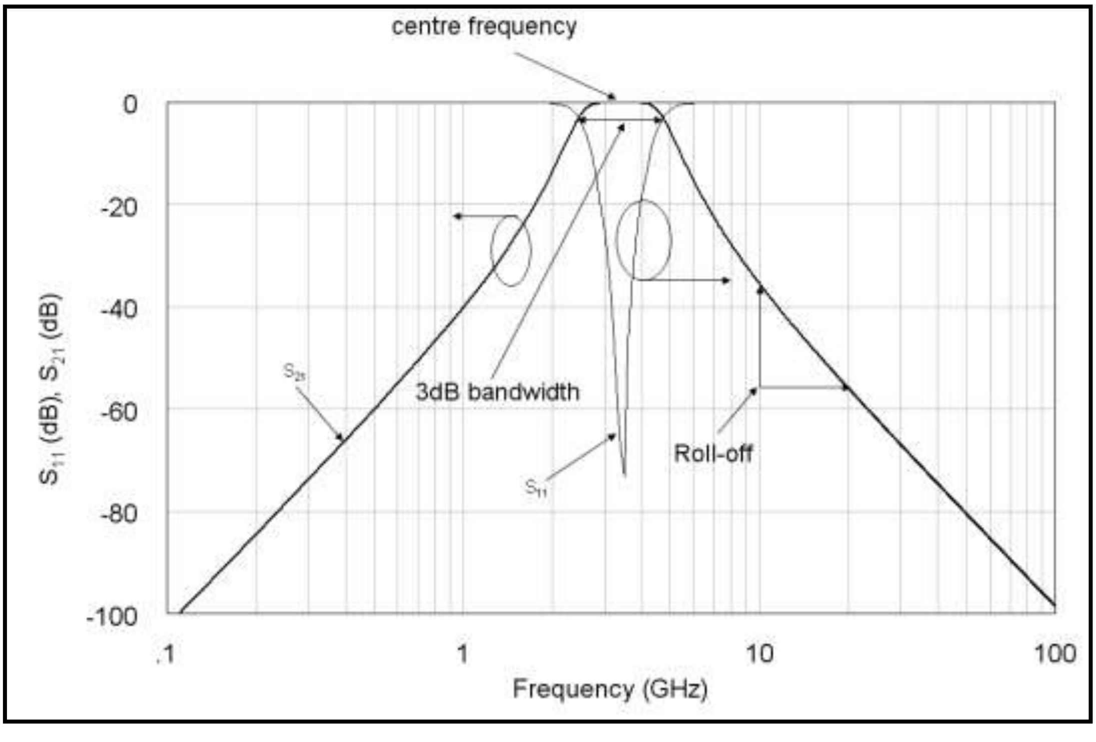


Figure 4.5 Filter Parameters [12]

At 10 GHz, the filter in Figure 4.5 has an insertion loss of -35.5 dB. At 20 GHz, it is at -56 dB. The roll off in that octave is around 20 dB, which is in line with the 6 dB per octave per filter order.

4.5 APPLICATIONS OF FILTERS

Filters are one of the most extensively used components for radio frequency as well as for microwave frequencies, whereas at microwave frequency generally transmission line section and waveguide fundamentals are used. Microwave filters design techniques when used in their most broad way are elemental to the well-organized design of a wide range of microwave components

Applications of filters can be found in almost any type of microwave communication, radar and measurement system. The most obvious application of filter structures is for the elimination of redundant signal frequencies while permitting circulation of wanted frequencies.

In general, these techniques are fundamental to accuracy design when rejecting, channelling selecting of power of different frequencies is significant; when achieving a controlled time delay with low reflection over a wide band or when achieving energy transmission. The most widespread filters of this kind are modelled for lowpass, highpass, bandpass or bandstop attenuation features. Filters are also frequently used for separating frequencies in diplexers and multiplexers.

4.6 ANALYTICAL MODELLING OF EBG AS MICROWAVE FILTER

The main functions of the filters are:

- To combine or separate signals as per their frequency.
- To discard unwanted signals outside the filter pass band.
- Minimizing the losses in the pass band of a filter.
- For impedance matching
- Reduces the total losses as well as improves the noise figure when employed to work with receiver.
- Used after and before a mixer in order to reduce false signals due to image frequencies.

The EBG structure is a periodic structure that can avoid electromagnetic wave to transmit in a certain frequency band. It is primarily adopted to develop the design techniques for antennas, for example, to lessen the interference among antennas, improvement in matching of impedances of the miniature size antenna and to increase the gain of the antenna. The Electromagnetic Bandgap Structure conceals consideration owning to its skill of jamming transmission in electromagnetic mode and in microwave and millimetre waves' radiation. Subsequently, the EBG structure is drawn on electromagnetic compatibility (EMC) area. It is designed in order to improve the Electromagnetic Interference and Power consistency. It gives a noteworthy outcome of reducing the Simultaneous Switch Noise (SSN) and Ground Bounce Noise (GBN)

4.6.1 The Mushroom Type EBG Structure

Mushroom structure is a classic Electromagnetic Bandgap structure which can be seen in Figure 4.6. The elemental cell is positioned periodically on the ground plane its unit cell is made up of a patch and a vias that connects to the ground plane. The surface impedance will turn out to be very high while applying the mushroom structure to the metal surface.Therefore mushroom structure is also referred as High Impedance Surface (HIS) structure.

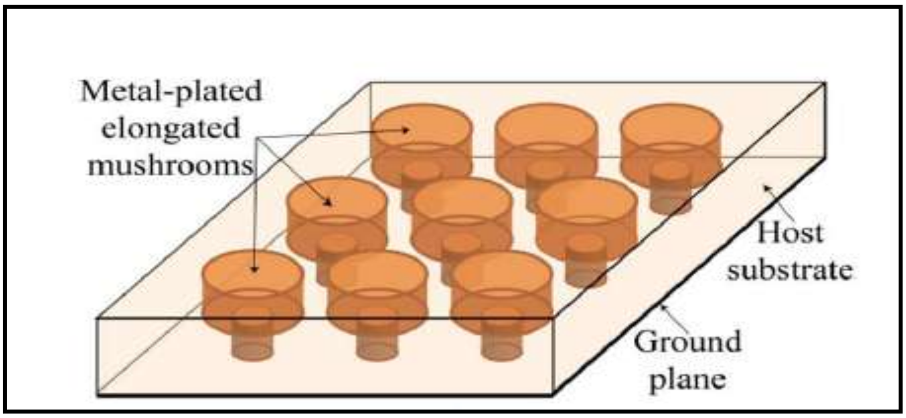


Figure 4.6 The mushroom type of the EBG structure [43]

Resonance of the Electromagnetic Bandgap structure causes the high impedance. As can be seen in Figure 4.7, across the parallel patch the voltage is capacitive which can be modelled by a capacitor.

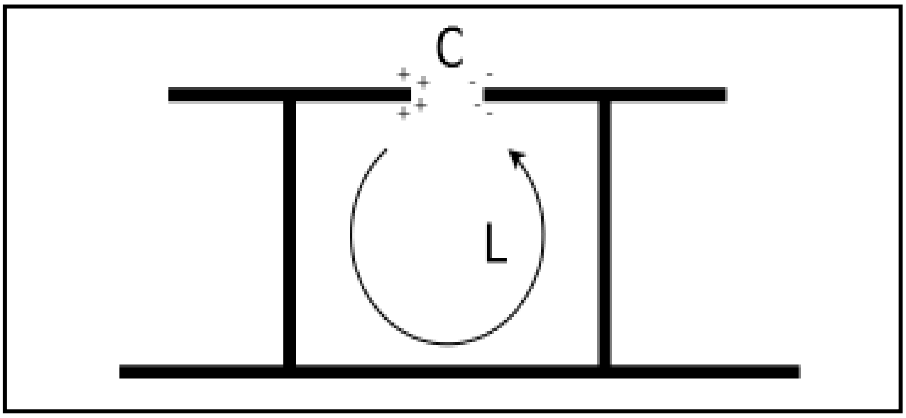


Figure 4.7 The demonstration of the capacitance and inductance of the HIS structure [43]

Also, the inductor can be modelled by a current in between the ground plane and vias. Therefore ,this high impedance surface acts as resonator more precisely it acts as an LC resonator for the particular frequency range for this particular frequency range the impedance of the surface comes out to be very high which leads to the prohibition of EM waves .

4.6.1.1The Equivalent Model of the Mushroom Type EBG Structure

The lumped circuit model of High Impedance Surface-EBG in power plane can be seen in Figure 4.8 .This model is extensively adopted in power distribution network applications for the suppression of noise.

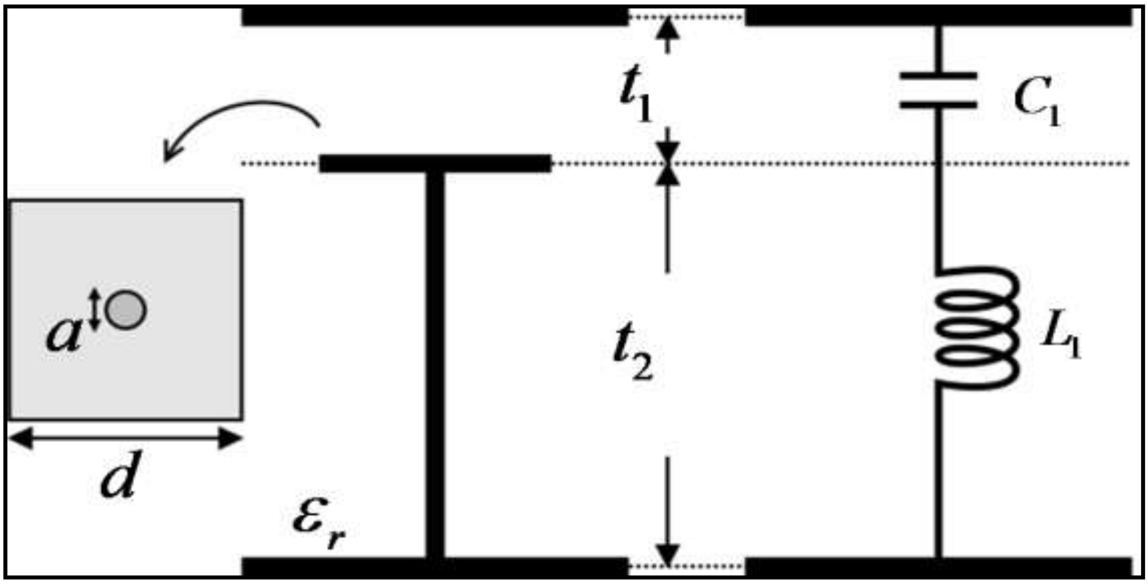


Figure 4.8 The lumped circuit model for the HIS-EBG embedded in the power plane [43]

Due to the difference in the voltage in between power plane and the mushroom's patch the height (t_1) can be modelled by a is acting as capacitive (C_1) circuit which is approximately

$$C_1 = \frac{\varepsilon_r \varepsilon_0 d^2}{t_1}, \tag{4.1}$$

where,

ε_r: effective dielectric constant in t_1 and t_2

d: width of the patch

t_1: distance between the patch and the power plane

Modelling of flow of current can be done by inductor $L_{1,}$ which is approximately

$$L_1 = \mu_0 \frac{t_2}{4\pi}\left[\ln\left(\frac{1}{\alpha}\right) + \alpha - 1\right] , \tag{4.2}$$

where, t_2: the distance between the patch and the ground plane

The ratio of the cross section of via to the one of unit cell is α:

$$\alpha = \pi \frac{a^2}{d^2}, \tag{4.3}$$

The lower cut-off frequency can be written as

$$f_{lower} = \frac{1}{2\pi\sqrt{C_1\left[L_1 + \frac{\mu_{0h}}{4}\right]}}, \tag{4.4}$$

where, $h = t_1 + h_2$

The geometry of the unit-cell structure is related to capacitance and inductance value by which determination of the value of stopband frequency of HIS-EBG structure can be accomplished.

In this chapter, we have studied about the various filters such as lowpass, highpass, bandpass and bandstop and their parameters like attenuation, bandwidth etc. Also a brief introduction about an LC modeling of mushroom type EBG structure is described.

In the next chapter, we will design non uniform Dual Window Tapered Annular-Ring EBG Structure in order to have better stopband and passband performances on the basis of mainly their aspect ratio control factor.

CHAPTER 5

DESIGNING AND CHARACTERISATION OF EBG BASED MICROSTRIP FILTER STRUCTURE

In this chapter, the procedure for designing microstrip dual-plane filter structures is explained. The designs are simulated using Computer Simulation Technology (CST) Microwave Studio. Finally the results obtained from the simulation are demonstrated and studied.

5.1 ANALYSIS OF EBG STRUCTURE

Figure.5.1 shows the Dual-Plane Electromagnetic Bandgap Microstripline Bandstop Filter structure, in this structure there are two planes out of which one plane is a modulated microstrip line, while the other is a ground plane with etched circles, there is a dielectric material between these two planes with a relative permittivity of $\in_r$ and a thickness of h.

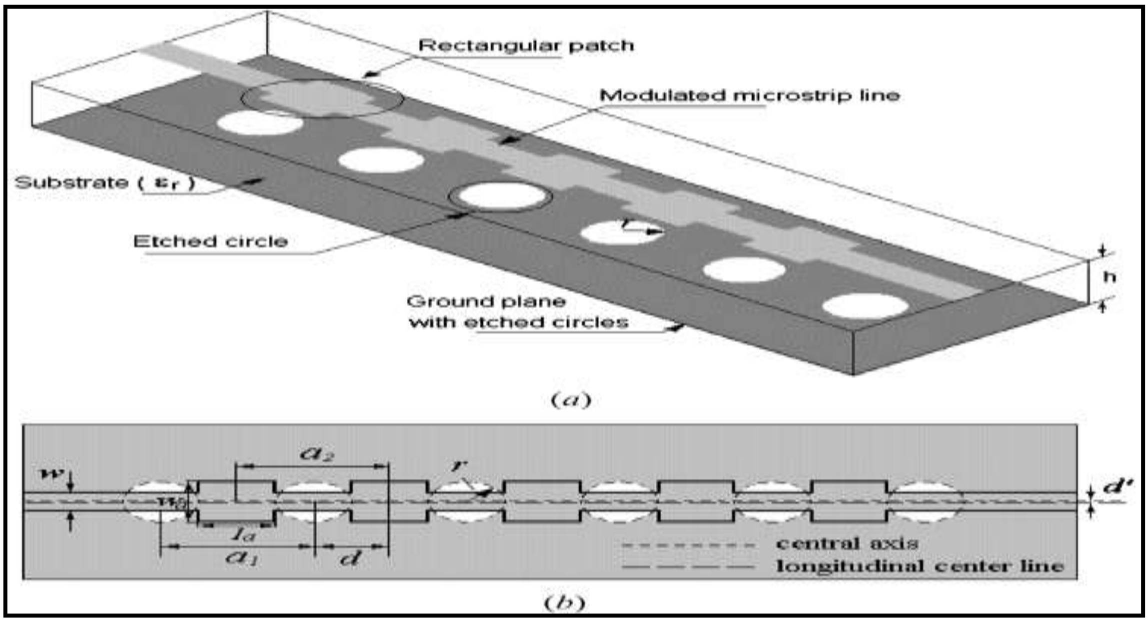


Figure.5.1. Dual-Plane Electromagnetic Bandgap Microstripline Bandstop Filter Structure **[7]**

5.1.1 Type-1 Single-Plane EBG Microstrip Structures

The Type-1 single-plane Electromagnetic Bandgap (EBG) Microstripline bandstop filter structure can be designed by etching circles in the ground plane with uniform radius dimensioned as per equation 5.1 and above the ground structure there is a simple straight microstrip shown in Figure 5.2.

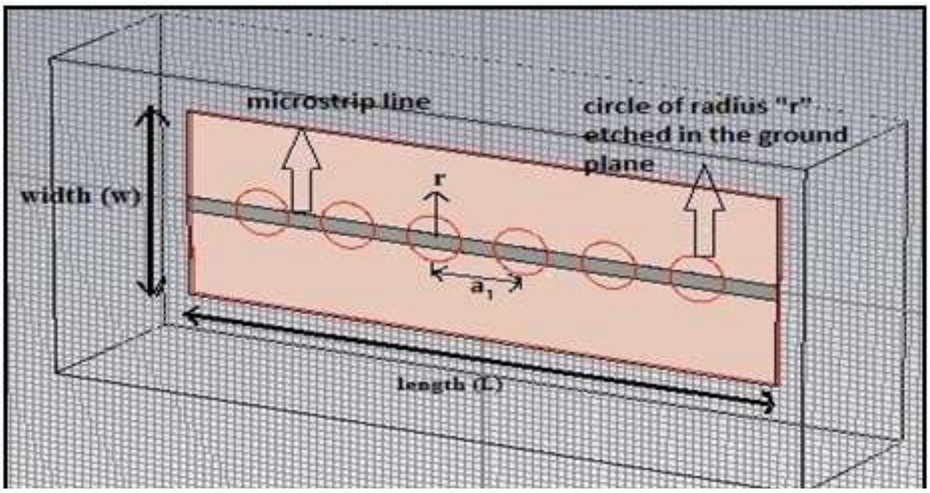


Figure 5.2 Type-1 Single-Plane EBG Microstrip Structures

The dimensions of the etched circle in the ground plane can be calculated by equation as follows:

$$r = a_1 . AR \,, \tag{5.1}$$

where ‘a_1’ is the period of etched circle in the ground and ‘AR’ is the aspect ratio.

In this structure the ground plane is etched with circles which lead to reduction in coupling in between ground plane and the transmission line. The reason of reduction in coupling is due to the occurrence of an additional inductance introduced by etched circles in the ground plane. This structure shows a stopband when the equation no 5.2 which is a necessary condition for the bandstop filter is satisfied. This condition is known as Bragg reflection condition .Period ‘a_1’ of the structure which is a distance between the centres of two adjacent circles can also be find out by Bragg reflection condition as follows,

$$\beta . a_1 = \Pi \,, \tag{5.2}$$

where β is the guided wave number in the substrate material and is described by the following equation:

$$\beta = \frac{2\Pi}{\lambda_g} \,, \tag{5.3}$$

From (5.2) and (5.3), the period a_1 equals half of the guided wavelength λ_g as expressed by the following equation:

$$a_1 = \frac{\lambda_g}{2} \,, \tag{5.4}$$

where λ_g is the guided wavelength and is given by:

$$\lambda_g = \frac{c}{f_o . \sqrt{\epsilon_{eff}}} \ , \quad (5.5)$$

where ϵ_{eff} can be computed by following expression:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2\sqrt{1 + \frac{12h}{w_e}}} , \quad (5.6)$$

where ϵ_{eff} is the effective permittivity of the substrate material, f_o the center frequency of the stopband is, and c is the speed of light in free space.

where 'h' is the height of the substrate and 'w_e' is the width of the EBG structure. The radius of the circle is represented by 'r'. The ratio of r and a_1 i.e. $\frac{r}{a_1}$ is called filling factor or aspect ratio .This aspect ratio factor plays an important role in determinining the size of the EBG cell to the period of the structure. In order to have no overlap between the two nearby etched circles the value of aspect ratio factor should be in the range of 0 to 0.5 .Parameters of the uniform 2-D EBG structure has been tabulated below in Table 5.1.

Table 5.1 Parameters of Proposed Uniform Filter Structure

Aspect Ratio (AR)	Radius (r) of etched circle in the ground plane
0.10	0.824
0.25	2.06
0.375	3.09

5.1.2 Type-2 Single-Plane EBG Microstrip Structures

The Type-2 single-plane EBG structure there is a single plane which consists of only uniform or modulated microstrip line. In this structure the ground plane is not etched with circles as shown in Figure 5.3.1 and in Figure. 5.3.2. A microstrip line which is modulated consists of square and rectangular patches periodically inserted in it and a uniform microstrip line is the one with simple straight line structure with no patches. In Figure 5.1, the width of the microstrip line is 'w' and the length and width of the patch is represented by l_a and w_a, respectively.

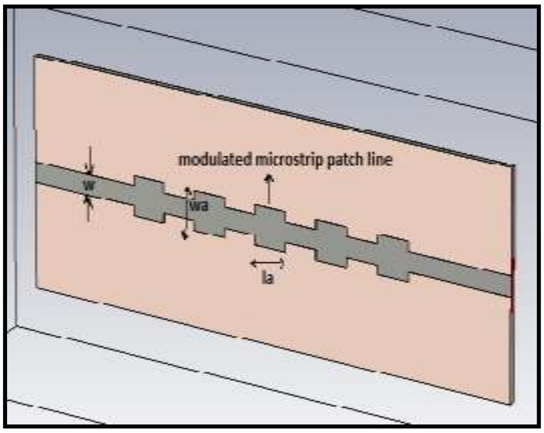


Figure 5.3.1 Type-2 Single-Plane Modulated EBG Microstrip Structures

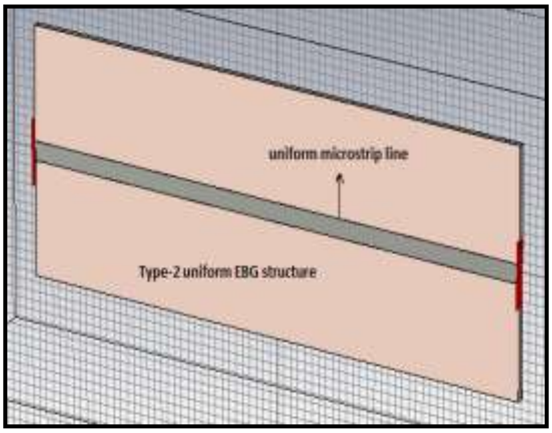


Figure 5.3.2 Type-2 Single-Plane Uniform EBG Microstrip Structures

5.1.3 Dual-Plane Compact-EBG Microstrip Structure Design

By superimposing the two discussed structure no 5.1.1 and structure no 5.1.2 we can design this dual plane compact EBG Microstrip Structure. As can be seen in Fig.5.4, This dual-plane compact EBG microstrip structure design introduces additional inductance and capacitance by etched circles and modulated microstrip line respectively which leads to enhancement in the stop bandwidth. In this Compact-EBG structure, the aspect ratio is a key element in deciding the relative location between the two single-plane EBG structures and hence deciding the passband and stopband parameters.

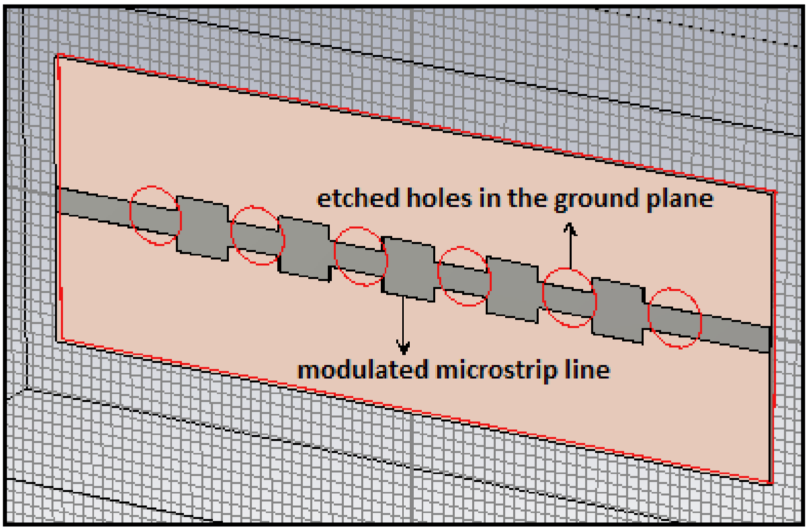


Figure 5.4 Dual-Plane Compact-EBG Microstrip Structure Design

5.2 TAPERING TECHNIQUES

Tapering Technique is an efficient way to improve the performance of an EBG structure. Window tapering techniques are adopted in order to tailor the effect to level of ripples within the passband. Hence Windowing techniques are efficient means for lessening the level of ripples in the passband. The approaches to taper EBG structures are based on Kaiser Coefficients, Binomial array, Dolph–Tschebyscheff array and Taylor array. For a 2-D planar EBG microstrip structure, the distribution of the dimension of the circle follows the following expression:

$$r_{i=}a_1.\mathrm{AR}.\mathrm{T}(x_i) \tag{5.7}$$

where $T(x_i)$ is the Kaiser –Chebyshev Tapering Coefficient given as per Table 5.2 [7] and AR is the aspect ratio or filling factor.

Table 5.2: Values of Various Tapering Functions and Normalized Coefficients

Type of Tapering Function	Tapering Coefficient		
	$T(x_1)$	$T(x_2)$	$T(x_3)$
Kaiser	0.94	0.58	0.16
Chebyshev	1	0.73	0.39
Binomial	1	0.50	0.10
Gaussian	0.98	0.86	0.66

5.3 ANALYSIS OF EBG UNITS AS BANDSTOP FILTER STRUCTURE

EBG structure can be modelled to work as different microstrip filter structure like low pass filter ,highpass filter ,bandpass filter ,bandstop filter this section describes the modelling of EBG units as bandstop filter structure with improved passband and stopband performances along with wide stop bandwidth and tailored passband ripples

5.3.1 Implementation of Non Uniform Dual Window Tapered Annular Ring EBG Based Bandstop Filter Structure

To get rid of the passband ripples due to the periodicity in the–EBG structure proposed in Figure. 5.1, the dual window Kaiser-Chebyshev tapering technique is applied in order to dimension the EBG units as shown in Figure.5.5.The dual window tapered annular ring EBG structure in which the ground plane is dimensioned as per window distributions gives less passband ripples with wide stop bandwidth and improved stopband and passband performances. The ground plane of the Figure 5.5 consists of two circular patterns as shown in Figure 5.6

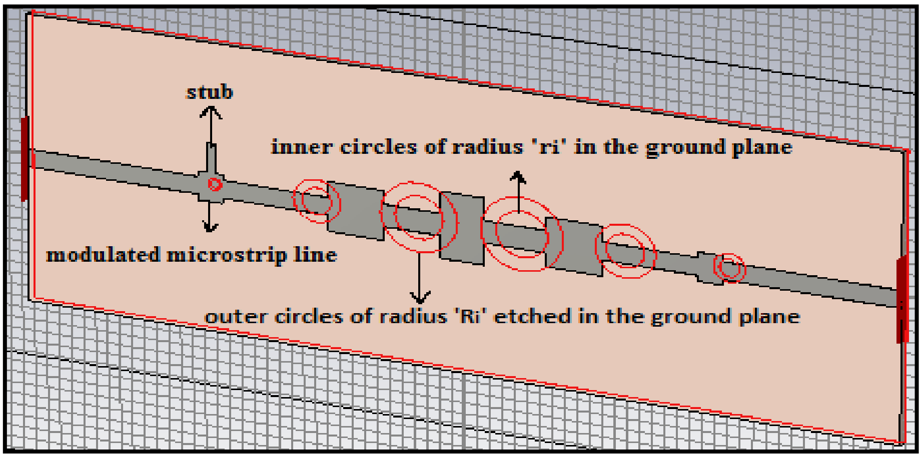


Figure 5.5 Dual Window Tapered Annular –Ring EBG Microstrip Structure Design

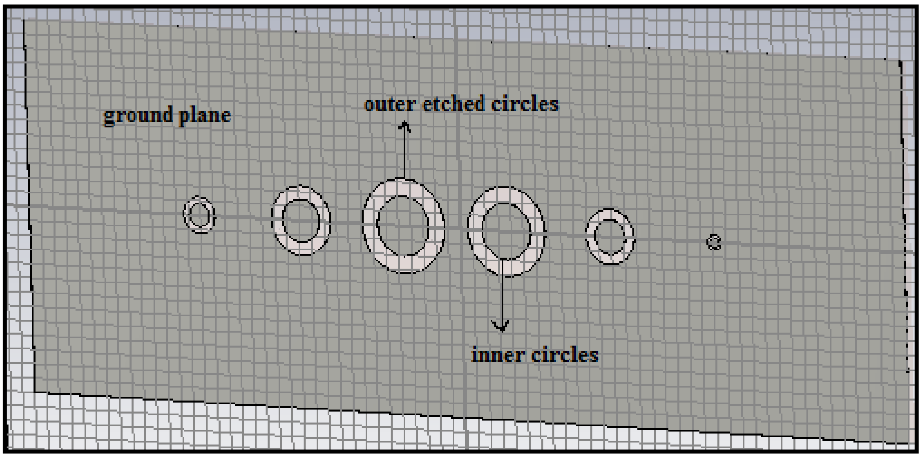


Figure 5.6 Ground -Plane of Dual Window Tapered Annular –Ring EBG Microstrip Structure Design

The radiuses of the outer etched circles and inner circles are tabulated in Table 5.3 and Table 5.4 respectively.

Table 5.3: Varying Radius of Outer Etched Circles in the Ground Plane

ASPECT RATIO (AR) 0.4			
Kaiser Tapered		**Chebyshev Tapered**	
Left three circles		**Right three circles**	
R_1	0.527	R_4	3.300
R_2	1.910	R_5	2.400
R_3	3.100	R_6	1.280

Table 5.4: Varying Radius of Inner Circles in the Ground Plane

ASPECT RATIO (AR) 0.25			
Kaiser Tapered		**Chebyshev Tapered**	
Left three circles		**Right three circles**	
r_1	0.329	r_4	2.060
r_2	1.190	r_5	1.500
r_3	1.930	r_6	0.803

5.4 SPECIFICATIONS OF EBG BASED BANDSTOP FILTER STRUCTURE

The parameters of the proposed EBG filter structure are as tabulated in Table 5.5

Table 5.5: Specifications of the Proposed EBG Based Bandstop Filter Structure

Parameters	Specifications
Substrate Used	Rogers R04350
Dielectric constant (ϵ_r)	3.48
Height of substrate (h)	0.762mm
Center Frequency	10GHz
Frequency range	4-16 GHz
Length of proposed structure	70 mm
Width of proposed structure	26mm
Period of EBG structure	8.24mm

5.5 SIMULATED RESULTS ANALYSIS OF EBG UNITS AS BANDSTOP FILTER STRUCTURE

To validate the above analysis and design, a prototype is implemented on CST Microwave Studio Software, following figures shows the simulated insertion loss and return loss curves for various types of EBG filter structure

5.5.1 Simulated Result of Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

Figure 5.7 and Figure 5.8 show simulated insertion and return loss curves analysis of Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

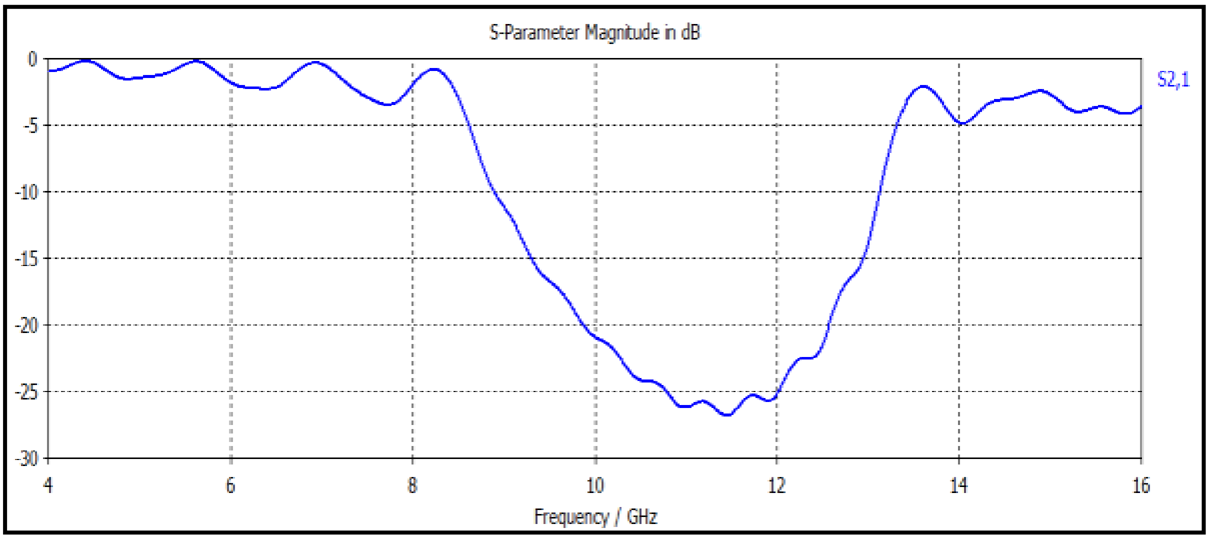


Figure 5.7 Insertion loss (S21) curve for Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

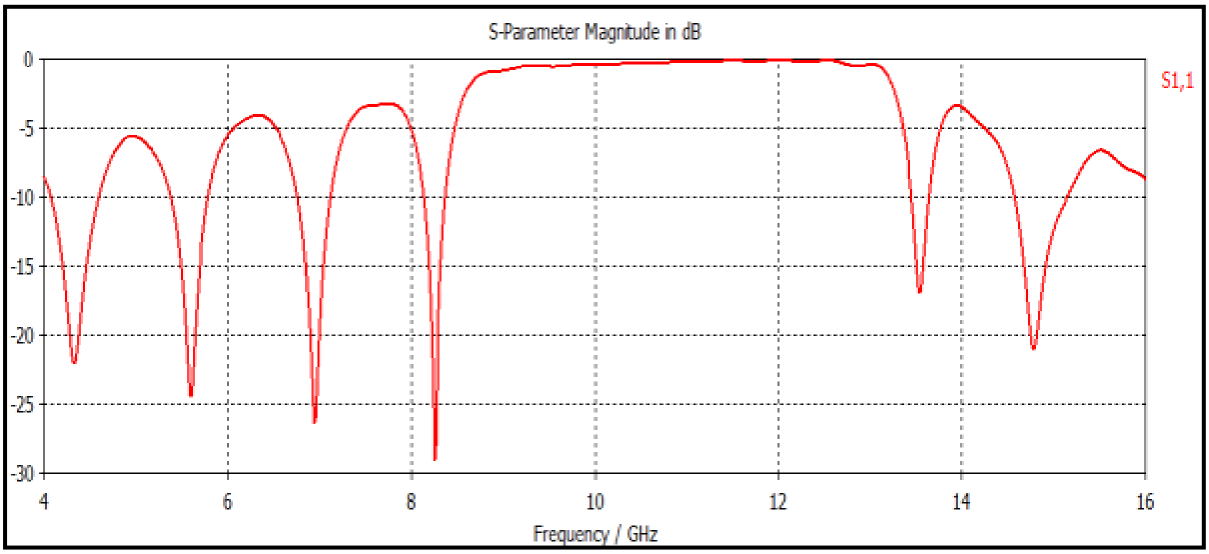


Figure 5.8 Return loss (S11) curve for Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

5.5.2 Simulated Result of Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

Figure 5.9 and Figure 5.10 shows simulated insertion and return loss curves analysis of Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

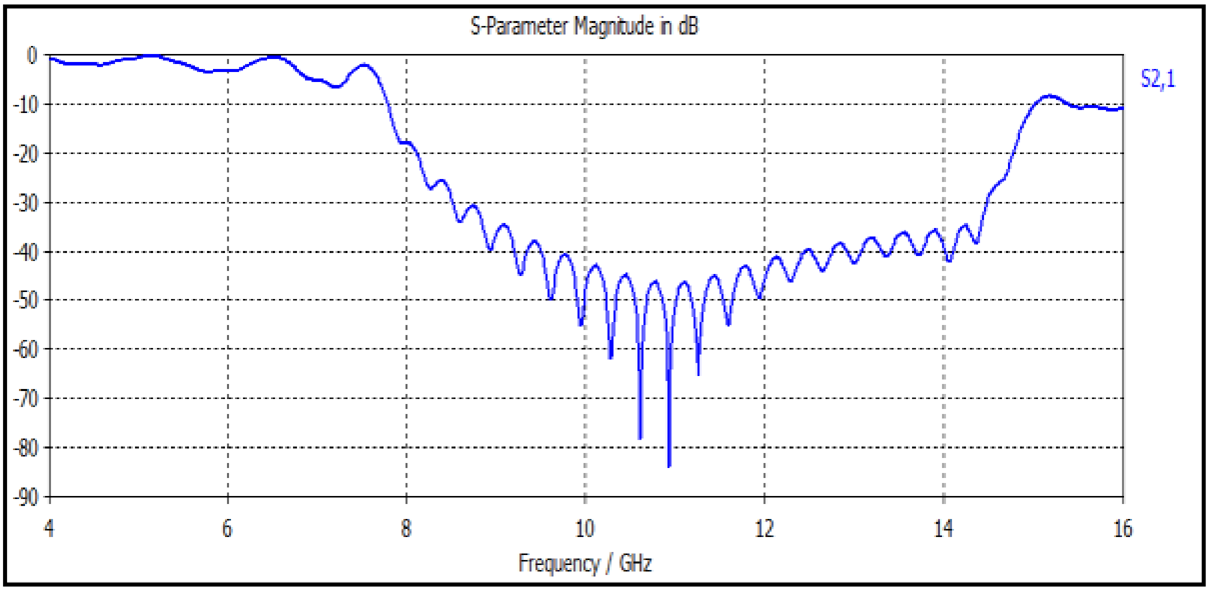


Figure 5.9 Insertion loss (S21) curve for Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

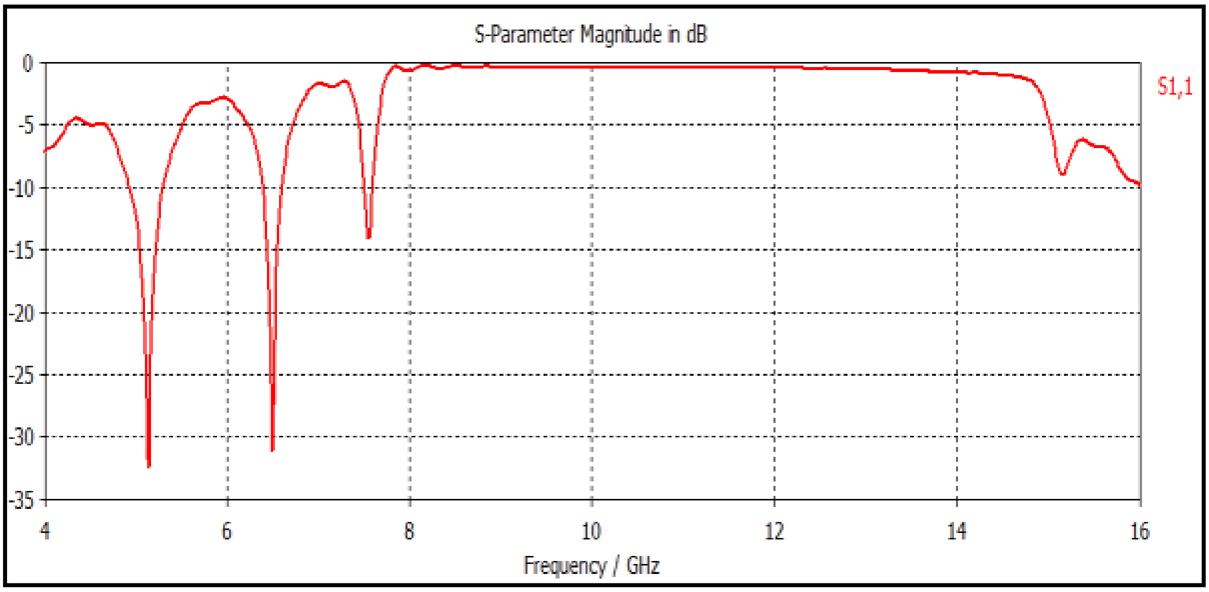


Figure 5.10 Return loss (S11) curve for Type-1 Single-Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

5.5.3 Simulated Result of Type-2 Single-Plane Uniform EBG Microstrip Structures

Figure 5.11 and Figure 5.12 shows simulated insertion and return loss curves analysis of Type-2 Single-Plane Uniform EBG Microstrip Structures

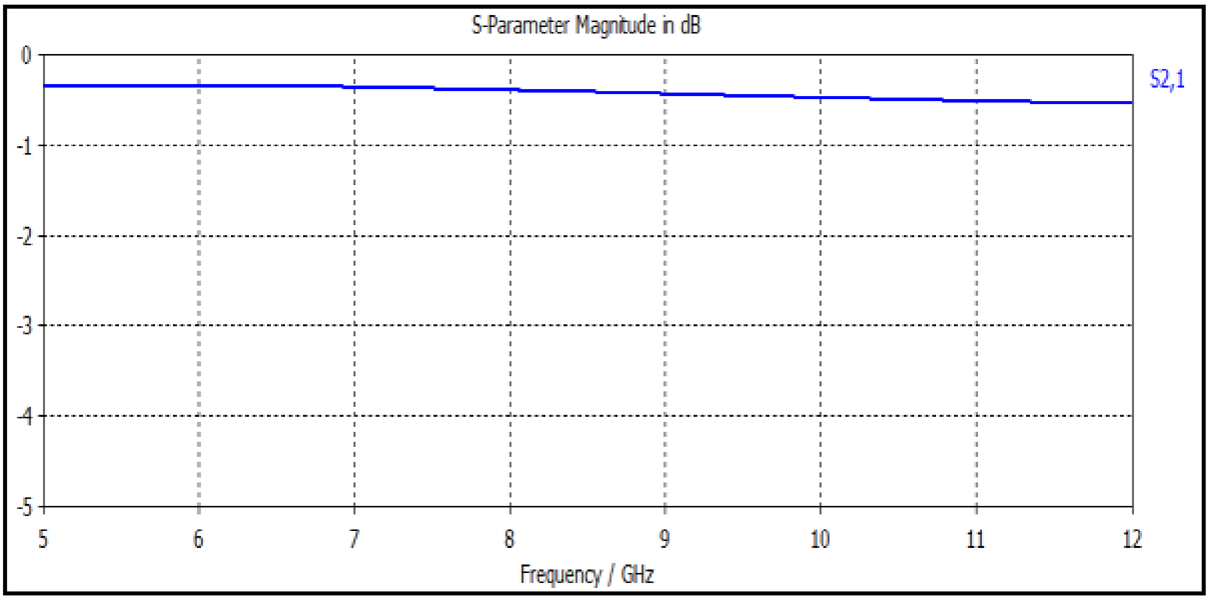


Figure 5.11 Insertion loss (S21) curve for Type-2 Single-Plane Uniform EBG Microstrip Structures

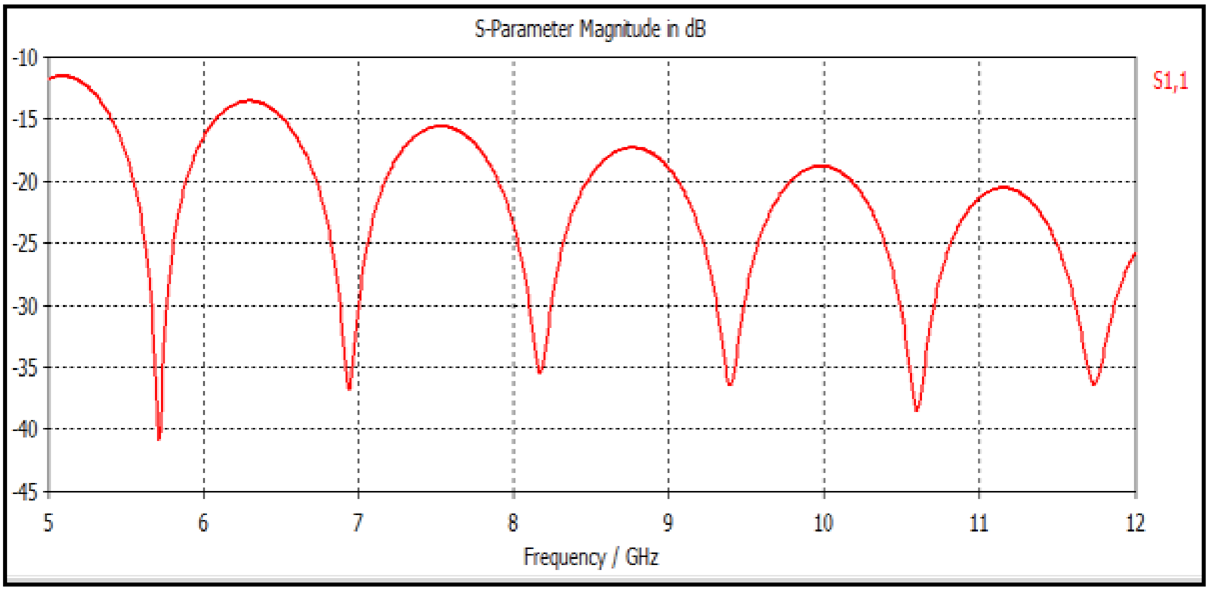


Figure 5.12 Return loss (S11) curve for Type-2 Single-Plane Uniform EBG Microstrip Structures

5.5.4 Simulated Result of Type-2 Single-Plane Modulated EBG Microstrip Structures

Figure 5.13 and Figure 5.14 show simulated insertion and return loss curves analysis of Type-2 Single-Plane Modulated EBG Microstrip Structures

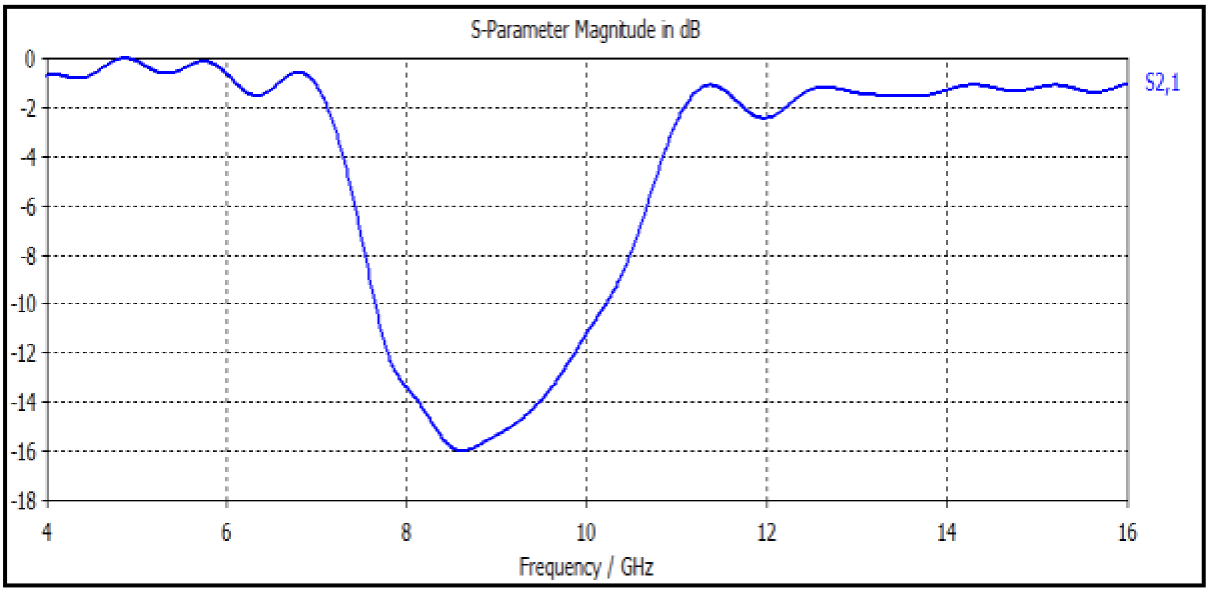


Figure 5.13 Insertion loss (S21) curve for Type-2 Single-Plane Modulated EBG Microstrip Structures

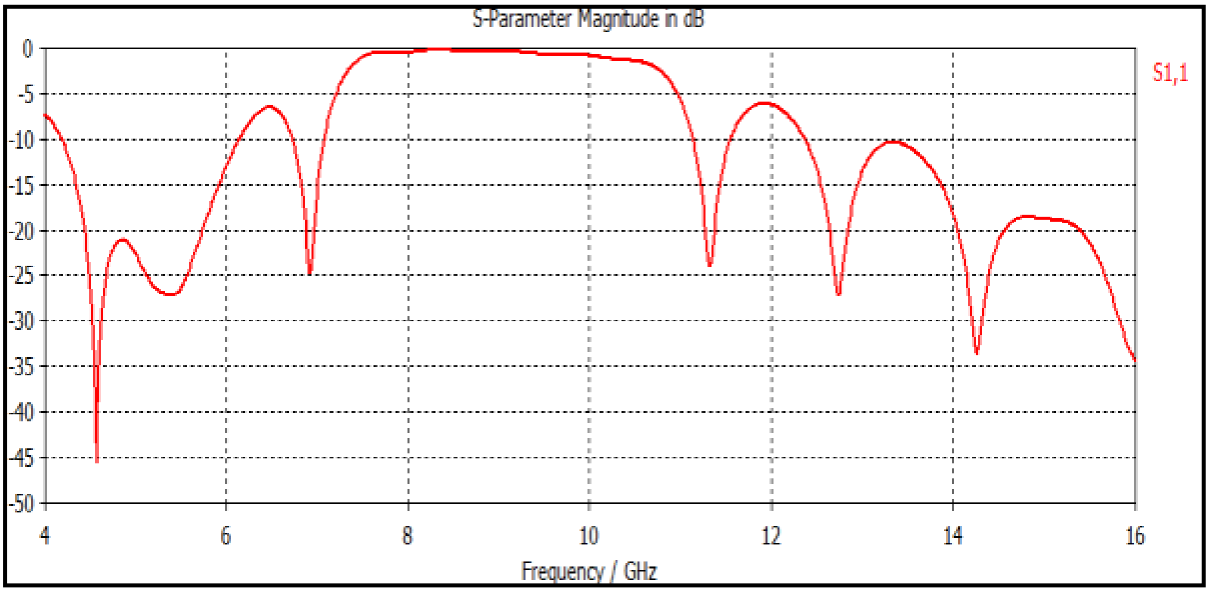


Figure 5.14 Return loss (S11) curve for Type-2 Single-Plane Modulated EBG Microstrip Structures

5.5.5 Simulated Result of Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.10

Figure 5.15 and Figure 5.16 shows simulated insertion and return loss curves analysis of Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.10

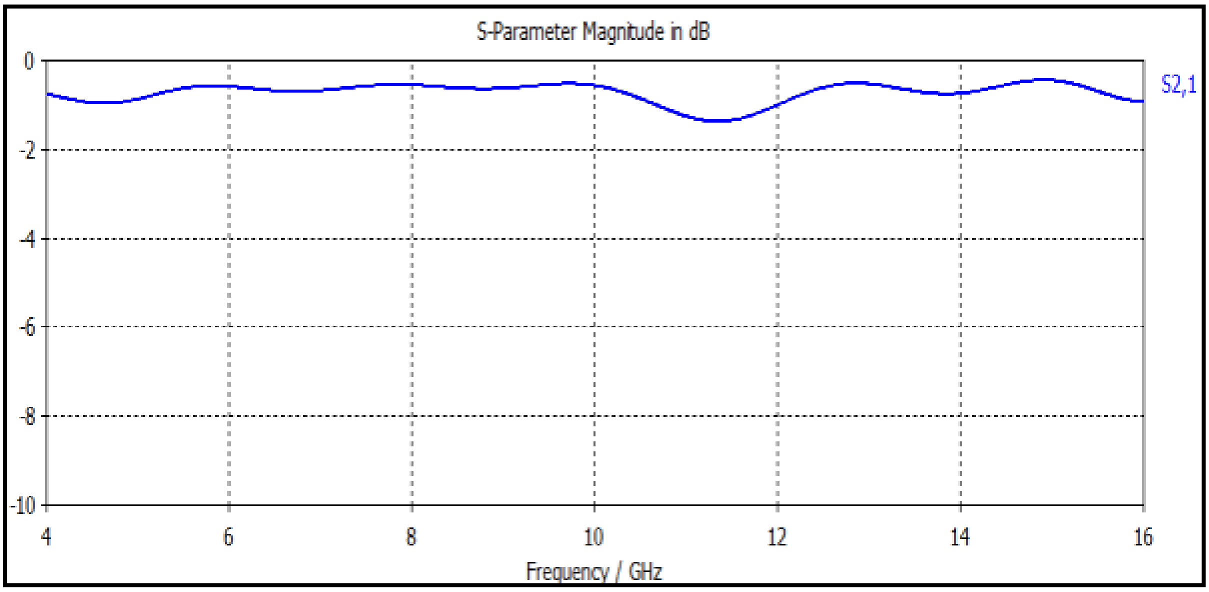


Figure 5.15 Insertion loss (S21) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.10

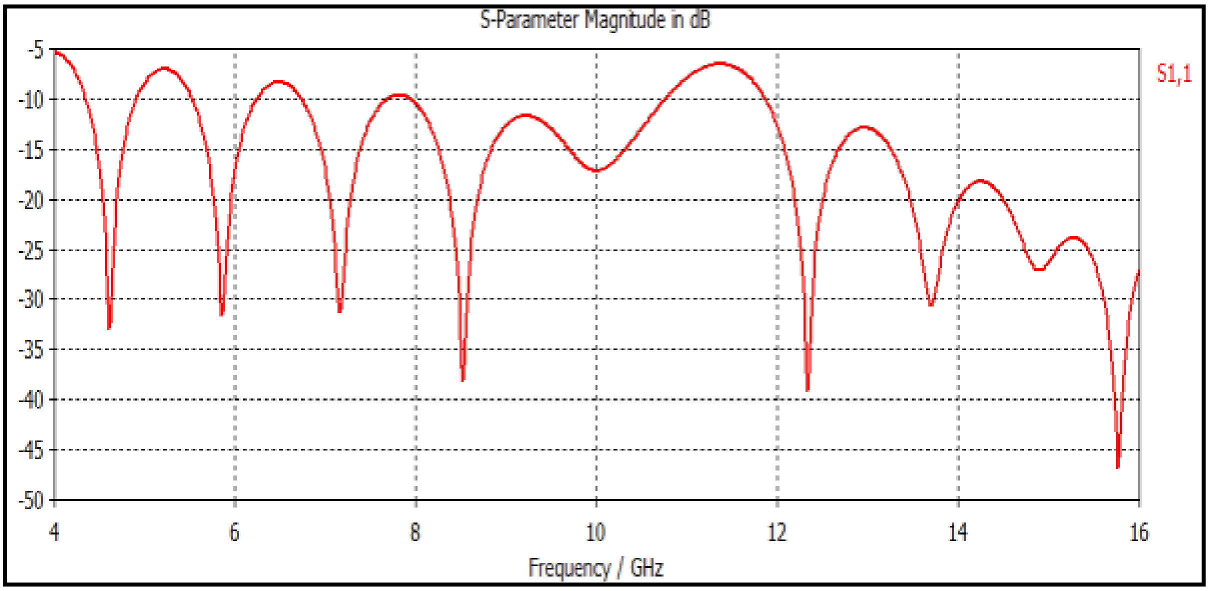


Figure 5.16 Return loss (S11) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.10

5.5.6 Simulated Result of Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

Figure 5.17 and Figure 5.18 shows simulated insertion and return loss curves analysis of Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

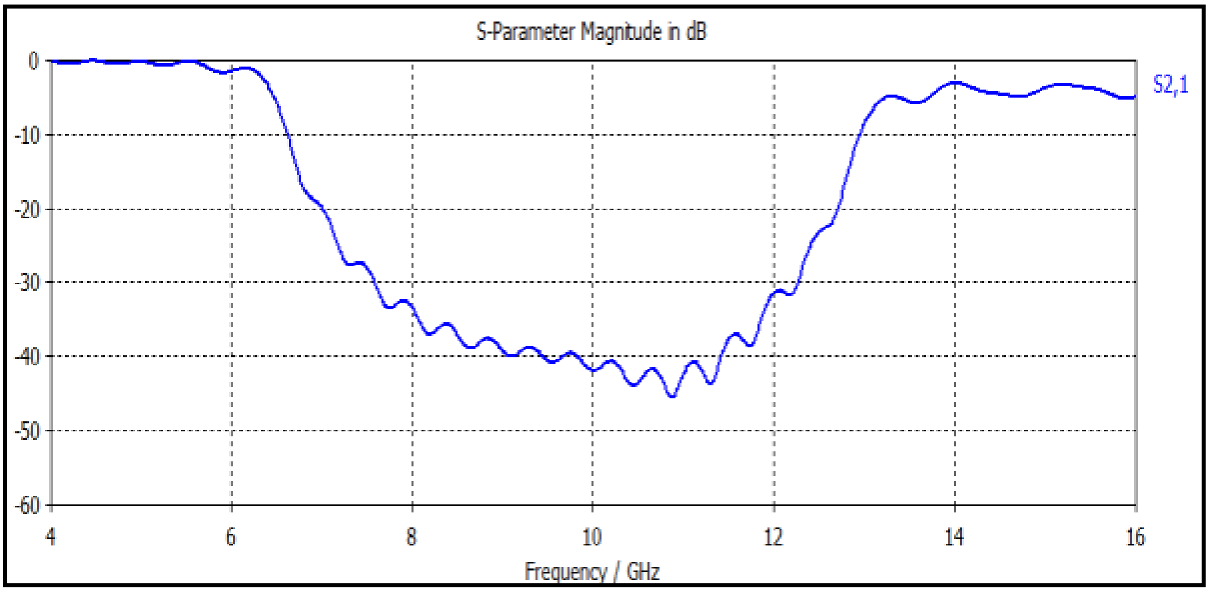


Figure 5.17 Insertion loss (S21) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

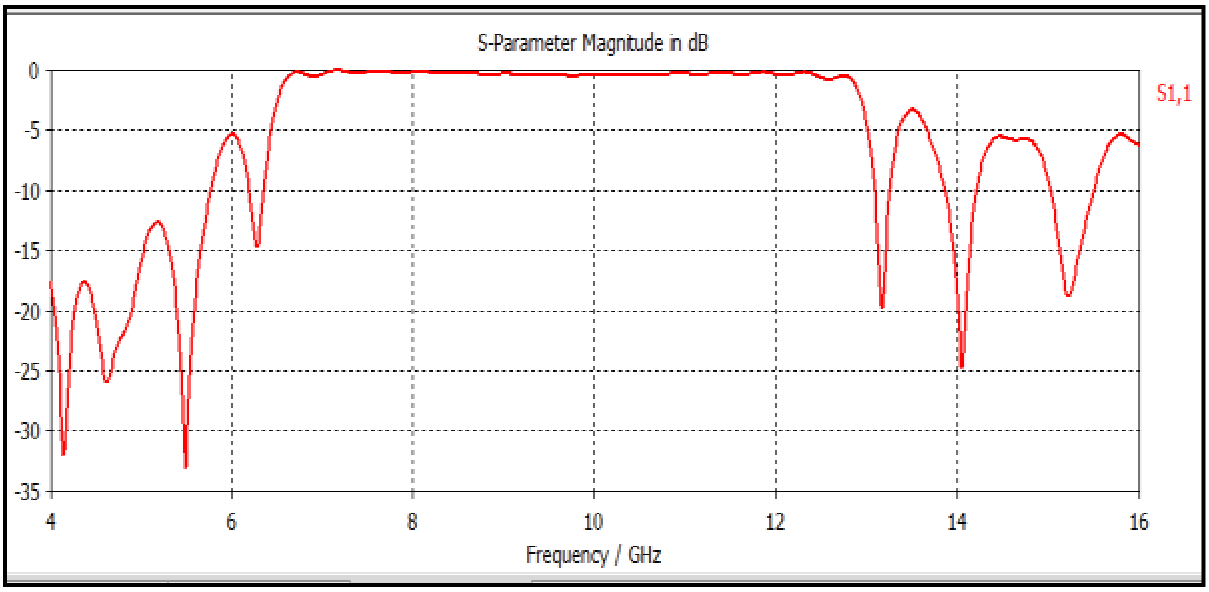


Figure 5.18 Return loss (S11) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.25

5.5.7 Simulated Result of Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

Figure 5.19 and Figure 5.20 shows simulated insertion and return loss curves analysis of Dual Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

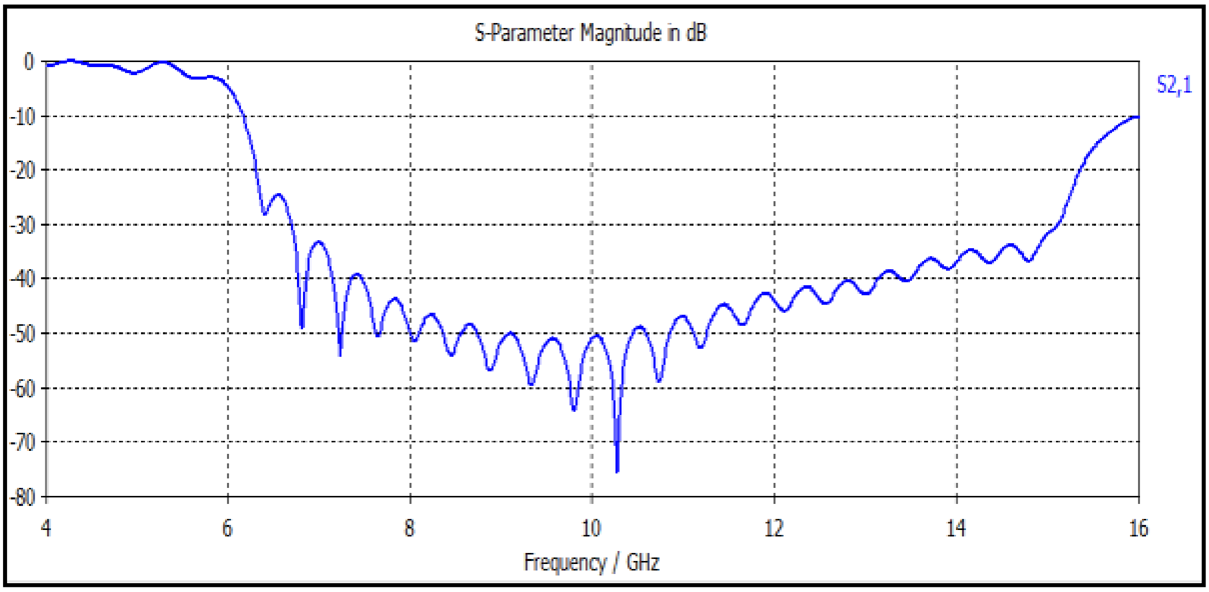


Figure 5.19 Insertion loss (S21) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

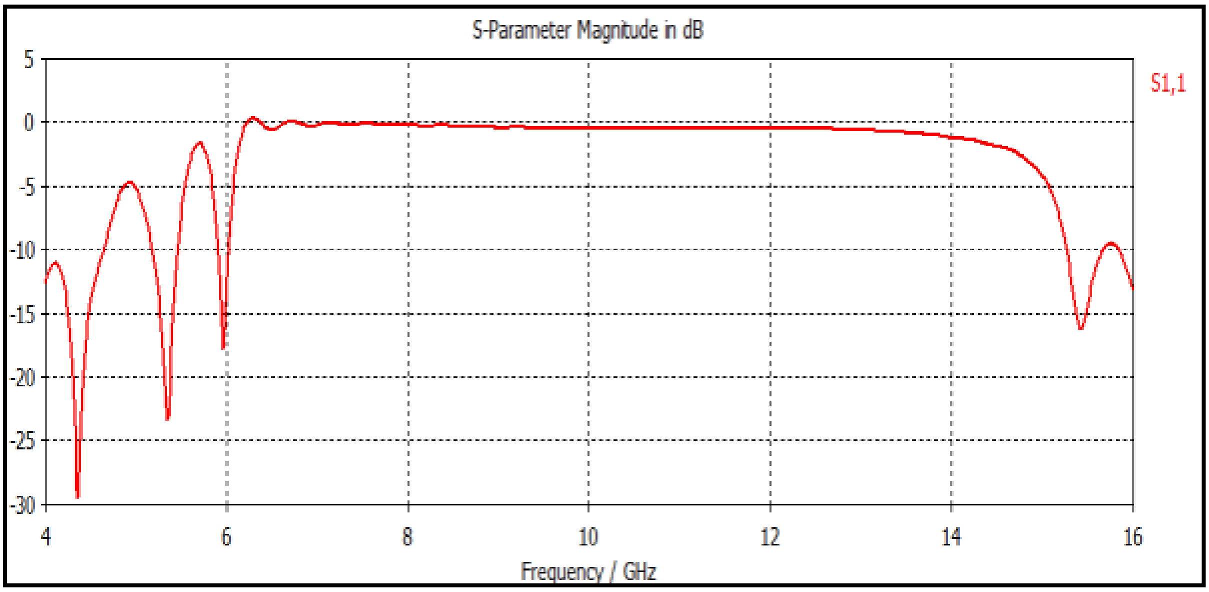


Figure 5.20 Return loss (S11) curve for Dual -Plane Uniform EBG Microstrip Structures with aspect ratio 0.4

5.5.8 Simulated Result of Dual Window Tapered Annular-Ring EBG Microstrip Filter Structure with aspect ratio 0.25 and 0.10 for outer and inner circles respectively

Figure 5.21 and Figure 5.22 shows simulated insertion and return loss curves analysis of Dual Window Tapered Annular-Ring EBG Microstrip Filter Structure with aspect ratio 0.25 and 0.10 for outer and inner circles respectively

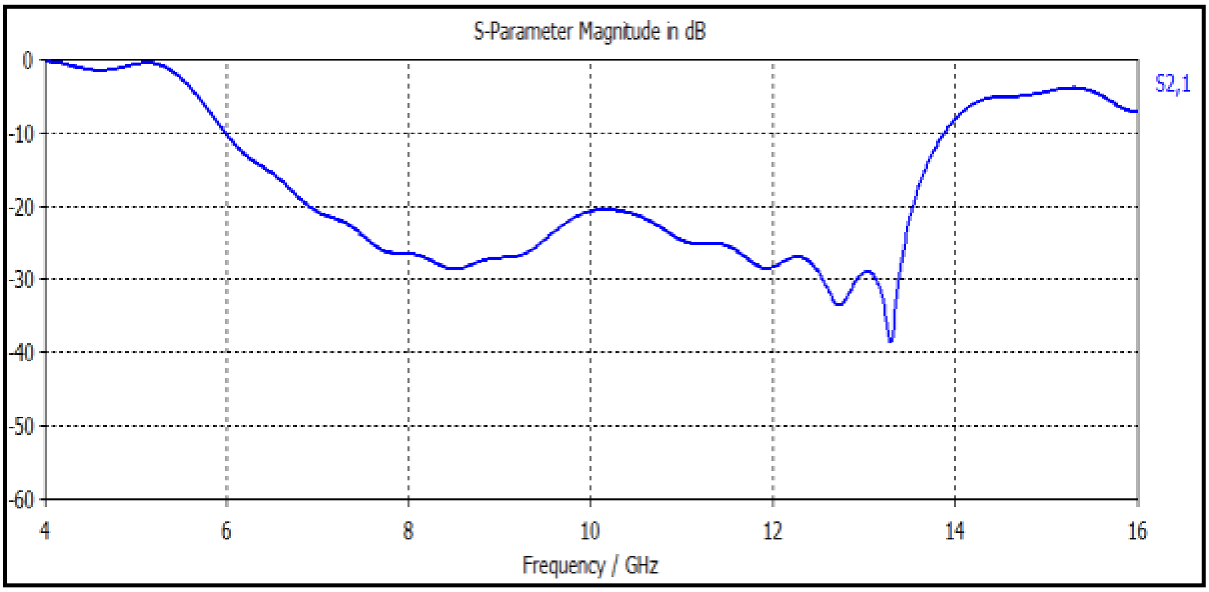


Figure 5.21 Insertion loss (S21) curve for Dual Window Tapered Annular-Ring EBG Structure with aspect ratio 0.25 and 0.10 for outer and inner circles respectively.

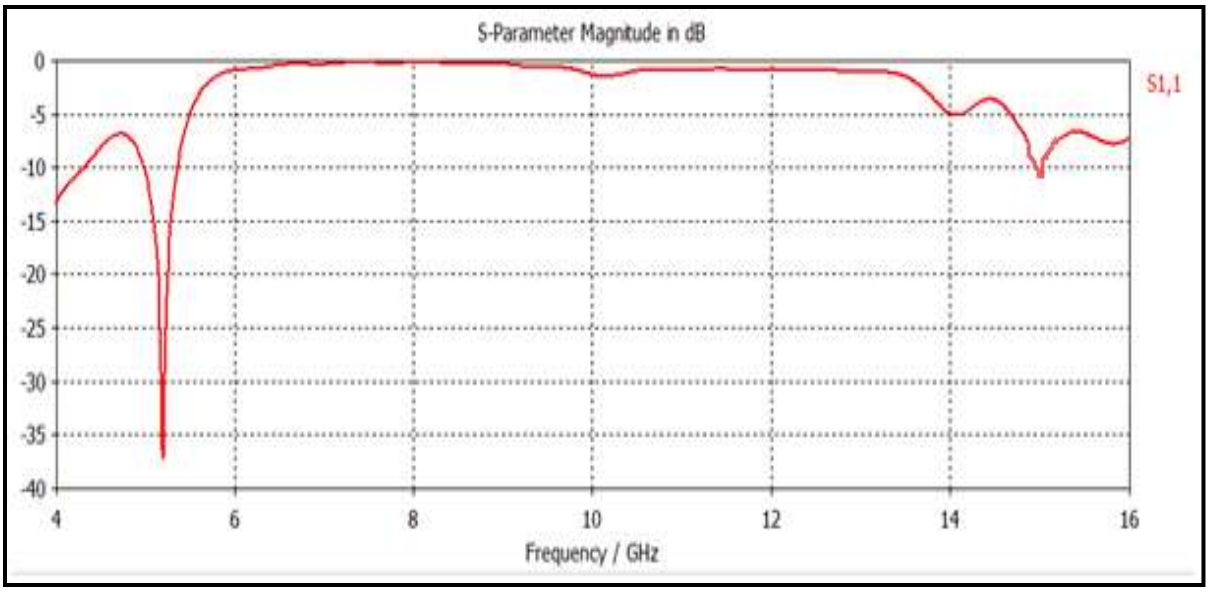


Figure 5.22 Return loss (S11) curve for Dual Window Tapered Annular-Ring EBG Structure with aspect ratio 0.25 and 0.10 for outer and inner circles respectively.

5.5.9 Simulated Result of Dual Window Tapered annular ring C-EBG Microstrip Filter Structure with aspect ratio 0.4 and 0.25 for outer and inner circles respectively

Figure 5.23 and Figure 5.24 shows simulated insertion and return loss curves analysis of Dual Window Tapered Annular-Ring EBG Microstrip Filter Structure with aspect ratio 0.4 and 0.25 for outer and inner circles respectively

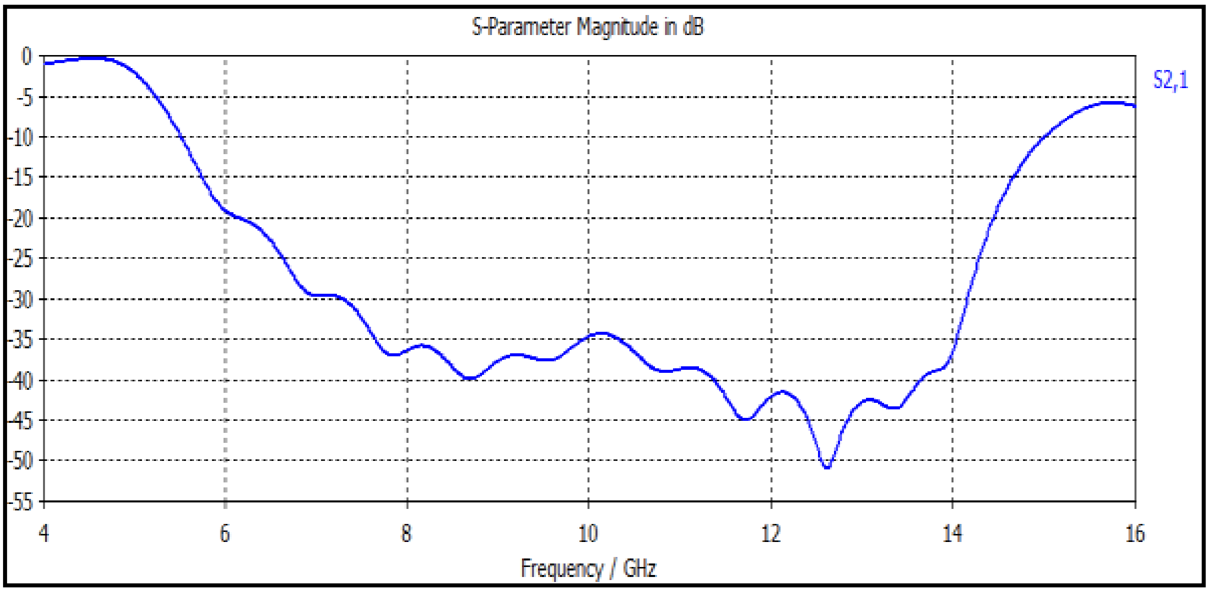


Figure 5.23 Insertion loss (S21) curve for Dual Window Tapered Annular-Ring EBG Structure with aspect ratio 0.4 and 0.25 for outer and inner circles respectively

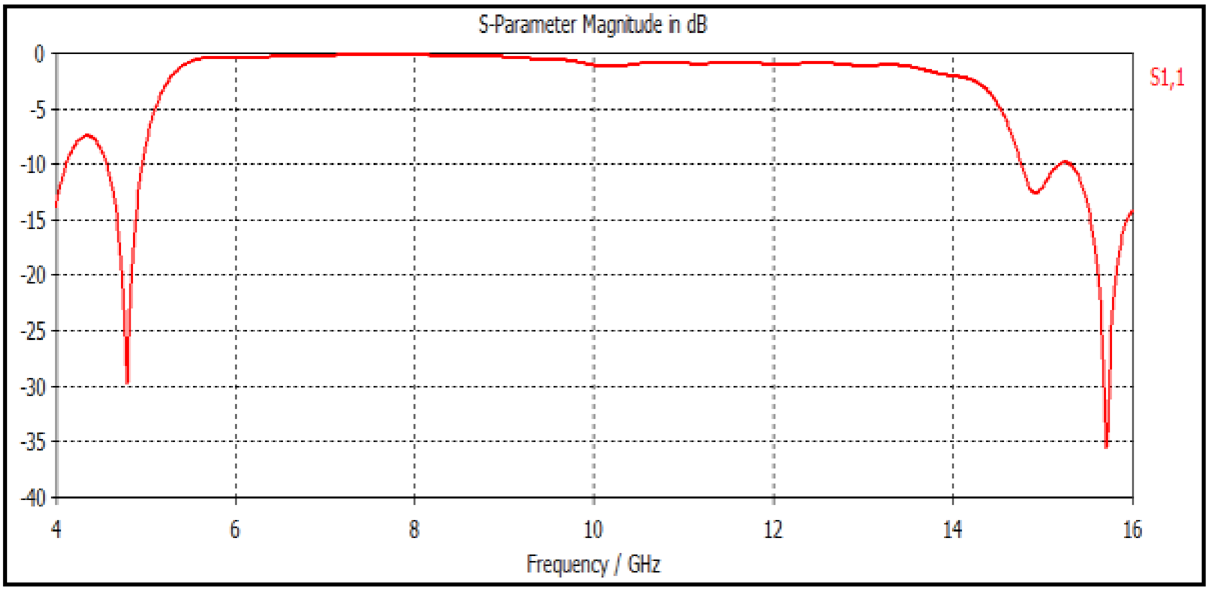


Figure 5.24 Return loss (S11) curve for Dual Window Tapered Annular-Ring EBG Structure with aspect ratio 0.4 and 0.25 for outer and inner circles respectively.

5.6 COMPARISON OF DIFFERENT KINDS OF EBG BASED BANDSTOP FILTER STRUCTURES

In this section a comparison between conventional uniform patterned EBGs structure and non uniform tapered EBGs structure has been tabulated from Table 5.6 to Table 5.8 on the basis of mainly aspect ratio control factor. After comparison it is observed that conventional uniform patterned EBGs structures increase the bandgap with more stop band attenuation at the cost of increased level of ripples in the passband. Hence in order to reduce the level of ripples in the passband, a novel annular EBG structure is designed with dual window tapering technique. In which the radius of EBG units is varied proportionally to the coefficients of Kaiser-Chebyshev polynomial in correspondence with their aspect ratio factor.

TABLE 5.6: Comparison of Type-1 and Type-2 Single-Plane EBG Based Bandstop Filter Structures

Structure Type	Aspect Ratio	Stop Bandwidth (GHz)	Stopband Attenuation (dB)	Lower Passband Ripple Level (dB)	Upper Passband Ripple Level (dB)
Type-1 Uniform	0.25	5.40	28	1.8~4.21	5.5~7.4
Type-1 Uniform	0.40	7.30	80	2.2~6.40	8.5~10.0
Type-2 Uniform	N.A.	All-Pass	0.0	0.3~0.87	0.3~0.87
Type-2 Modulated	N.A.	2.61	16	1.5~0.60	1.1~3.0

TABLE 5.7: Comparison of Dual -Plane Uniform EBG Based Bandstop Filter Structures

Aspect Ratio	Stop Bandwidth (GHz)	Stopband Attenuation (dB)	Lower Passband Ripple Level (dB)	Upper Passband Ripple Level (dB)
0.10	0 (All pass)	0.0	1.8~2	0.46~0.5
0.25	5	40~45	1.6~1	5.4~5.15
0.4	8	70~75	2.1~4	7.0~8.00

TABLE 5.8: Comparison of Dual Window Tapered Annular-Ring EBG Based Bandstop Filter Structures

Aspect Ratio		Stop Bandwidth (GHz)	Stopband Attenuation(dB)	Lower Passband Ripple Level(dB)	Upper Passband Ripple Level (dB)
outer circle	**inner circle**				
0.25	0.10	8	39	0.510~1.000	4.1~5.0
0.40	0.25	10	52~54	0.378~0.863	4.5~5.7

While simulation it has been observed that both ripple performances and bandwidth can be controlled and improved with the adequate selection of window distributions. Moreover level of ripples in the pass band is lessened by proper dimensioning of etched circles by adopting the dual window tapering techniques along with their unique feature of filling factor or aspect ratio control factor. In this chapter it is shown that rejection bandwidth and stop band attenuation increases with increase in aspect ratio along with reduction in passband ripples.

As etched holes in the ground are dimensioned as per tapering coefficients similarly the microstrip transmission line is also modulated in order to perform impedance matching so that proper coupling in between ground and transmission line at the upper portion of the substrate can be established, as it can be seen in Figure 5.5 there is a stub in the microstrip transmission line this stub has a path length equals to half wavelength so as to establish a 180 degrees phase difference between EM waves flowing in the transmission line.

As can be seen by surface current distribution Figure 5.25 that at the position of stub the current reverses its path and shows a phase difference of 180^0 and due to this phase difference the ‘Bragg Reflection’ condition is satisfied and this leads to reflection of current which results in stopband generation.

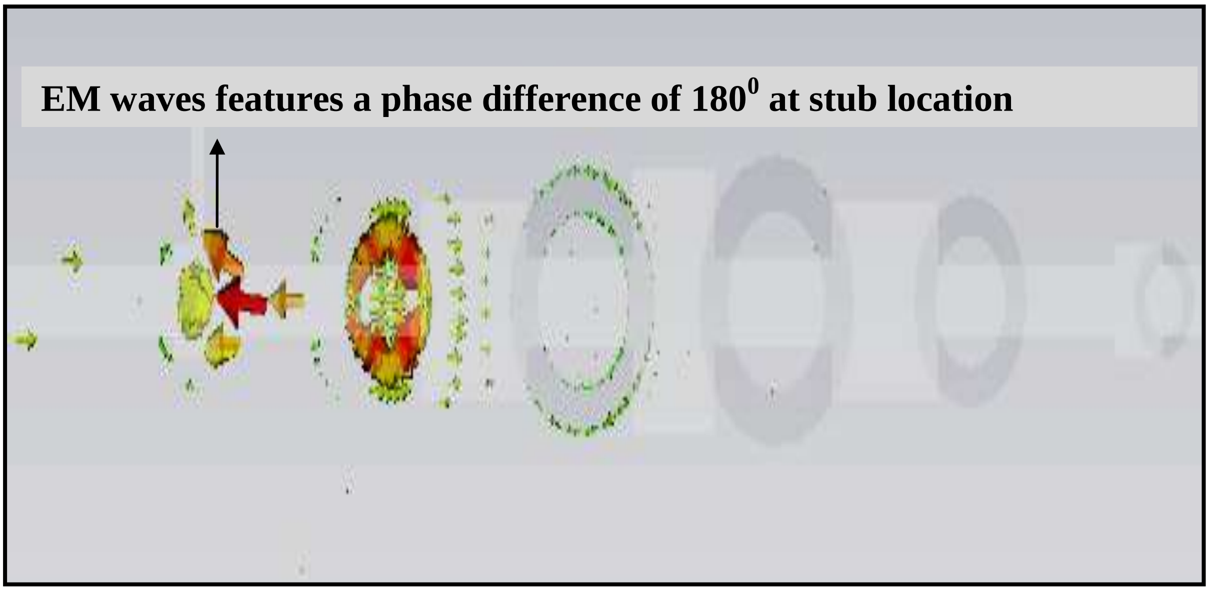


Figure 5.25 Surface Current Distribution of Dual Window Tapered Annular- Ring EBG Based Bandstop Filter Structure

Moreover nonuniform distributions of annular-ring patterned EBGs gives larger bandwidth, less ripples level in the passband along with improved passband and stopband performances than that for the conventional circular-patterned EBG structure. In the annular ring EBG structure ripple level in the pass band is well tailored by adopting the dual window distribution of Kaiser and Chebyshev coefficients along with their unique feature of aspect ratio control factor. In this chapter it is shown that rejection bandwidth and stop band attenuation increases with increase in aspect ratio along with reduction in level of passband ripples.

5.7 ANALYSIS OF EBG UNITS AS LOW-PASS FILTER STRUCTURE

EBG structure can be modelled to work as different microstrip filter structure like low pass filter ,highpass filter ,bandpass filter ,bandstop filter this section describes the modelling of EBG units as low-pass filter structure with improved passband and stopband performances along with tailored passband ripples

5.7.1 Designing of Dual Plane Uniform U-SHAPED EBG Based Low Pass Filter Structure

A uniform dual lane EBG low pass filter structure is formed by etching holes in the ground plane and the distribution of dimensions of the circle follows the equation no 5.1 along with a U-shaped microstrip line structure, this U shaped microstrip line is in an additional plane separated by a dielectric material of dielectric constant (ϵr) 3.48 and height (h) 0.762 mm as shown in Figure5.26. The ground plane is created by etching circles with radius 'R' altering correspondingly with the filling factor "R/a_1" where 'a_1' is the period of occurrence of etched circle in the ground plane. The period'a_1' of the structure is defined by the distance between the centers of two neighbouring etched circles in the ground plane

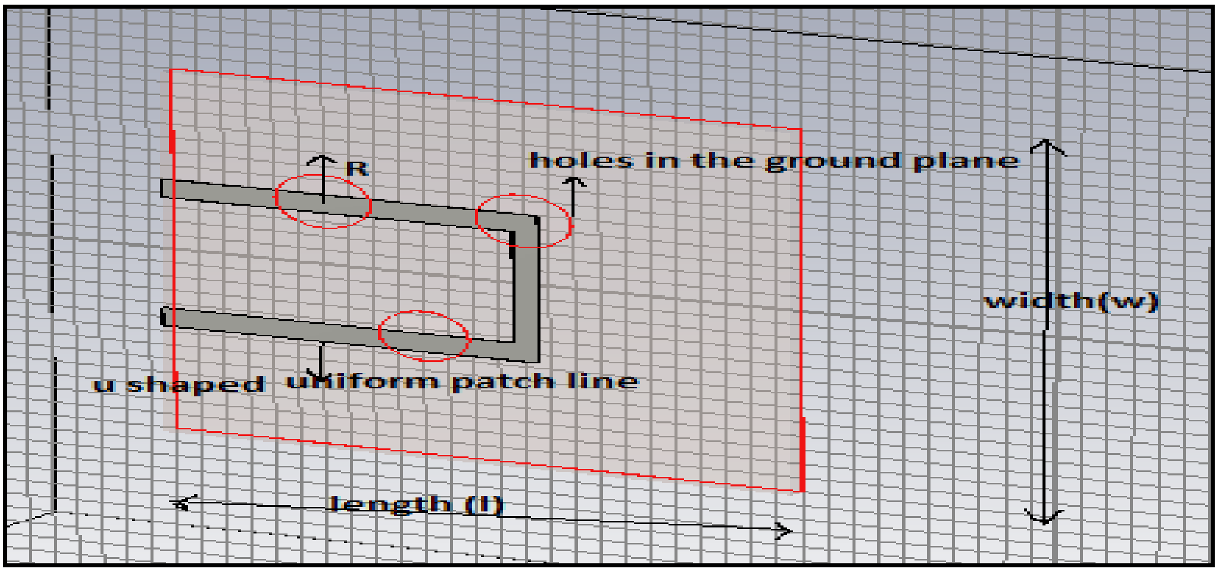


Figure 5.26 Dual Plane Uniform U-SHAPED EBG Based Low Pass Filter Structure

5.7.2 Designing of Dual Plane Non Uniform Kaiser Tapered EBG Based Low Pass Filter Structure

Uniform 2-D low pass EBG filter structure as shown in Figure 5.26 preludes a boost in the bandwidth with an elevated attenuation in the stopband at the cost of increased level of ripples within the passband as shown in Figure 5.28 therefore Kaiser window tapering approach in correspondence with their peculiar quality of filling factor control are to be applied to lessen the ripple level intensity in the passband as shown in Figure 5.30. In dual plane non uniform Kaiser tapered low pass structure as shown in Figure 5.27 the ground plane is created by etching holes with radius altering and the distribution of dimensions of the circle follows the equation no 5.7 and the modulated U shaped microstrip patch line is created by inserting square and rectangular patches of changing length and width.

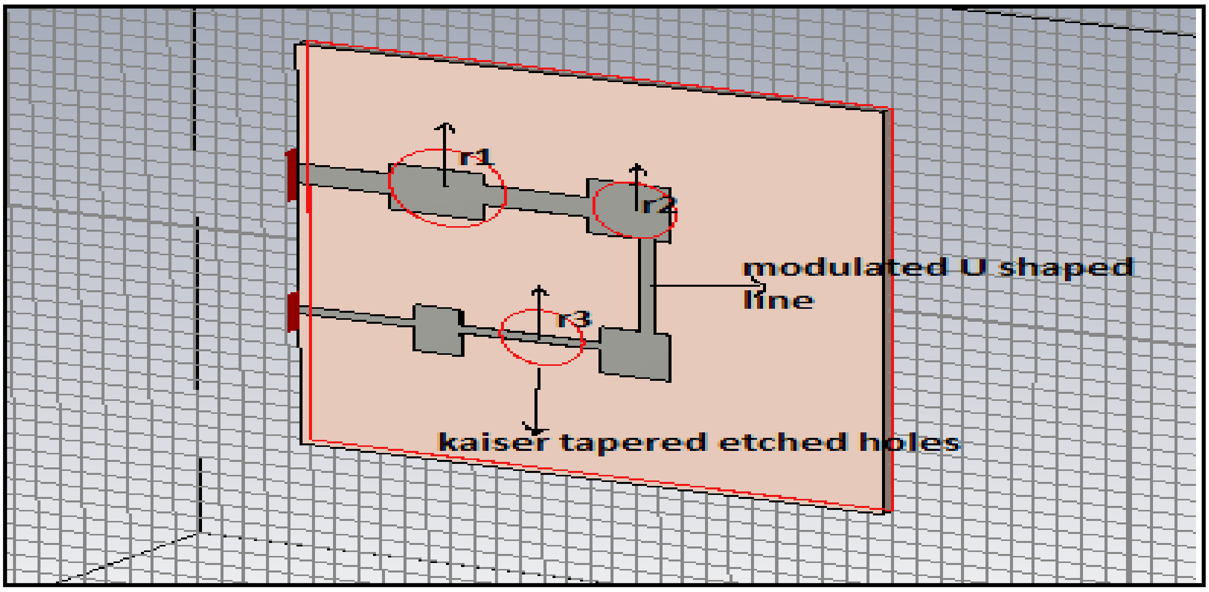


Figure 5.27 Dual Plane Non Uniform Kaiser Tapered EBG Based Low Pass Filter Structure

5.8 SPECIFICATIONS OF EBG BASED LOW PASS FILTER STRUCTURE

The parameters of the proposed EBG low pass filter structure are as tabulated in Table 5.9

Table 5.9: Specifications of the Proposed EBG Based Low Pass Filter Structure

Parameters	Specifications
Substrate Used	Rogers R04350
Dielectric constant (ϵ_r)	3.48
Height of substrate (h)	0.762mm
Frequency range	4-16 GHz
Length of proposed structure	70 mm
Width of proposed structure	26mm

5.9 SIMULATED RESULTS ANALYSIS OF EBG BASED LOW PASS FILTER STRUCTURE

5.9.1 Simulated Result of Dual Plane Uniform U-SHAPED EBG Based Low Pass Filter Structure

Figure 5.28 and Figure 5.29 show simulated insertion and return loss curves analysis of Uniform EBG design techniques to work as low pass filter.

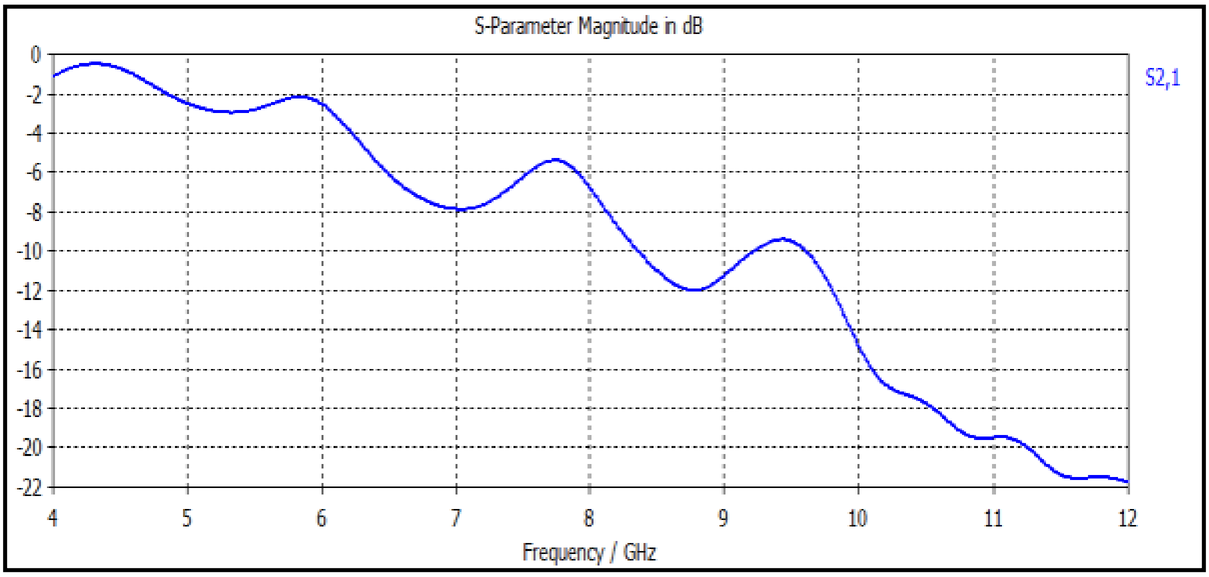


Figure 5.28 Simulated (S_{21}) Parameter of Dual Plane Uniform U-Shaped EBG Based Low Pass Filter Structure

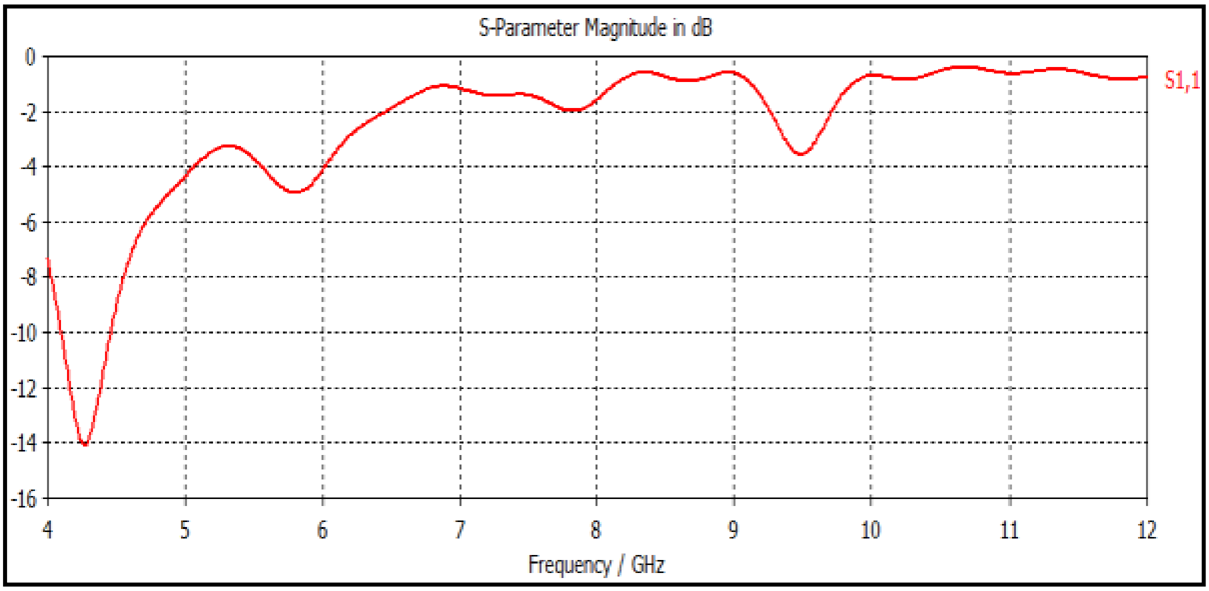


Figure 5.29 Simulated (S_{11}) Parameter of Dual Plane Uniform U-Shaped EBG Based Low Pass Filter Structure

5.9.2 Simulated Result of Dual Plane Non Uniform Kaiser Tapered EBG Based Low Pass Filter Structure

Figure 5.30 and Figure 5.31 shows simulated insertion and return loss curves analysis of non uniform Kaiser tapered dual plane EBG design techniques to work efficiently as low pass filter

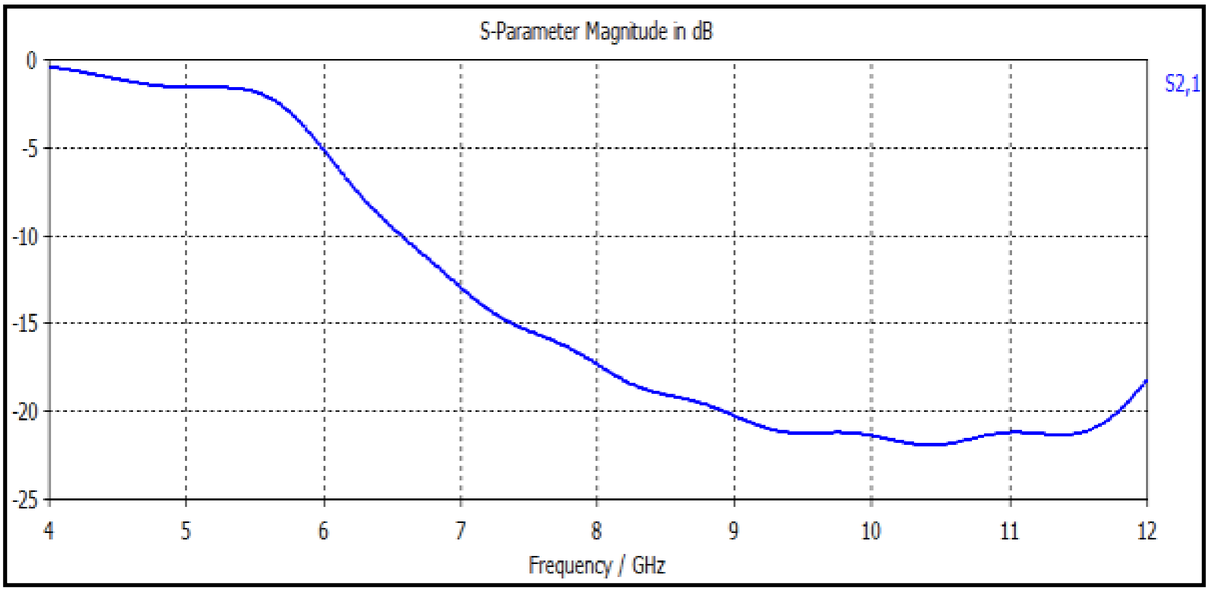


Figure 5.30 Simulated (S_{21}) parameter of Dual Plane Non Uniform Kaiser Tapered EBG Based Low Pass Filter Structure

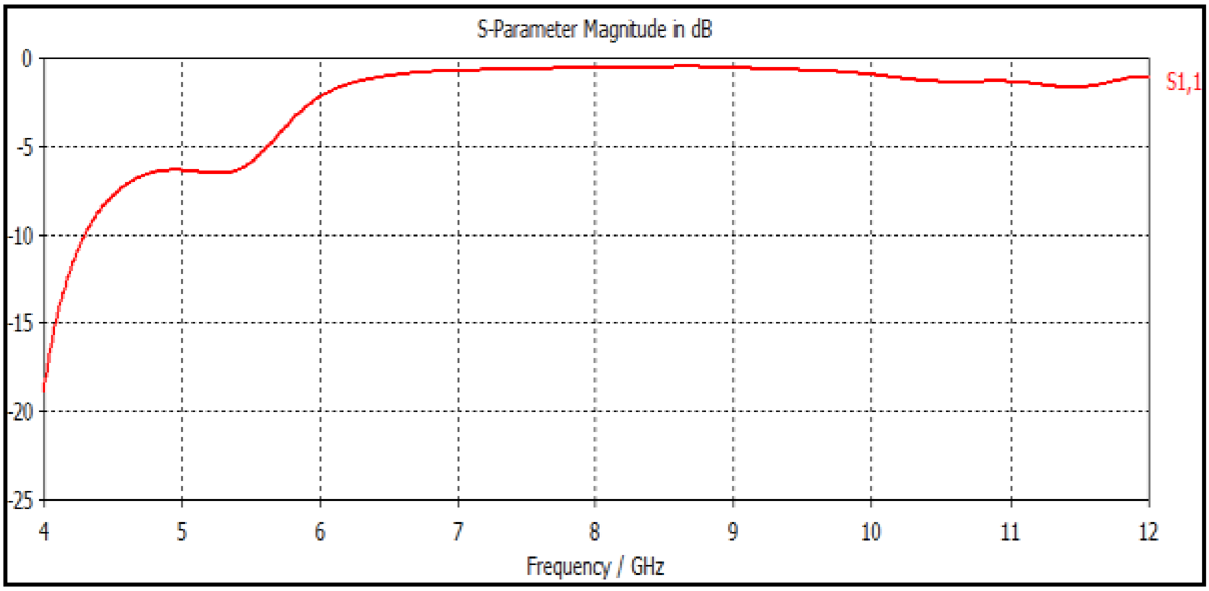


Figure 5.31 Simulated (S_{11}) parameter of Dual Plane Non Uniform Kaiser Tapered EBG Based Low Pass Filter Structure

5.10 COMPARISON OF UNIFORM AND KAISER TAPERED EBG BASED LOW PASS FILTER STRUCTURES

TABLE 5.10: Comparison of Uniform and Kaiser Tapered EBG Based Low Pass Filter Structure

Filter type	Aspect Ratio	Passband Ripple Level (dB)	Stopband Attenuation (dB)	Bandwidth (GHz)
Uniform Lowpass Filter	0.25	7.80~9.80	18	6~8
Kaiser Tapered Lowpass Filter	0.25	0.65~1.17	22	6~7

5.11 MATHEMATICAL VIEWPOINT OF EBG BASED MICROSTRIP FILTER STRUCTURE DESIGNS

5.11.1 Coupling vs. Width of Patch

As can be seen in Figure 5.1 the width and length of the patch can be denoted by ‘w_a’ and ‘la’ respectively whereas microstrip line has a width equals to w. In this dual plane EBG structure, the variation range of the width of patch ‘w_a’ is expressed as:

$$w_a > w, \quad (5.8)$$

the above stated condition is also known as coupling condition because when the width of a patch is more than the width of the microstrip line then the coupling between the ground plane and the microstrip line increases

5.11.2 Longitudinal offset (d) vs. EBG Based Bandstop Filter Performances

As it can be seen in Figure 5.1 there is a longitudinal offset d, and transversal alignment offset d’, these two offsets plays an important role in order to define the stopband performances. Hence relative location between the two single-plane EBG Structures is an essential key element for the location of the stopband width within the specified frequency range of filter. Longitudinal offset and Transversal alignment offset can be defined as follows:

Longitudinal offset (d): can be defined as the longitudinal distance between the centers of adjacent patch and circle.

Transversal Alignment Offset (d'): transversal distance between the longitudinal center line of the microstrip line and central axis of the circles. While simulations following cases are observed:

Case 1: Longitudinal Offset (d) =0

This a condition of complete overlap i.e. etched circles and inserted patches completely overlaps each other when d is 0 then no stopband is observed because due to the overlap of patches and etched circles the capacitive effect and inductive effect gets cancelled.

Case 2: Longitudinal offset (d) > 0

In this case the capacitive and inductive effects do not get cancelled completely hence optimum value of inductor (L) and capacitor (C) is observed in operation and as it is known that each patch has its own resonance frequency. Hence by the equation no 4.1 and by equation no 4.2 we can set the values of inductance (L) and capacitance (C) to fit in equation no 5.9 in order to find out resonance frequency as per the requirement of filter at which impedance is to be matched or mismatched so that minimum or maximum losses are observed respectively.

$$f_r = \frac{1}{2\pi\sqrt{LC}}, \tag{5.9}$$

where f_r is the resonance frequency , L and C are inductance and capacitance values respectively

but we are designing a bandstop filter in which we need to follow the Bragg reflection condition hence in our design the relative location of patches and etched circles plays an important role in order to decide the location of stopband location, stop bandwidth, stopband attenuation and passband ripples. In the Case 1 the impedance matching occurs and hence the resonance occurs at each patch which leads to a design of 'All Pass Filter' but when longitudinal offset is greater than '0' than desired value of capacitance and inductance can be set as per aspect ratio factor .Therefore if we observe from the simulation results that the parameters like: location of the stopband, bandwidth of the stopband, attenuation within the stopband etc are not constant, then for this there is no other reason but the relative location of patches and circles which leads to impedance matching or impedance mismatching as per the requirement of EBG filter structure.

5.11.3 Length of patch (la) vs. Dimension of EBG units

The proper determination of length of patch and radius of EBG units is very essential in order to decide the overlap. The radius of EBG units are calculated as per filling factor (r/a_1) , and to prevent any overlap the length of inserted patch should follow following expression:

$$l_a \leq a_1 - 2r \, , \tag{5.10}$$

Condition for optimum filter performance is:

$$l_a = a_1 - 2r \, , \tag{5.11}$$

The length of the patch must follow equation no 5.11 for the optimum performances in terms of stop bandwidth, stopband attenuation and passband ripples.

5.12 FABRICATION AND TESTING OF EBG FILTER ON VECTOR NETWORK ANALYZER

This section describes the fabrication and testing of **"Dual Window Tapered Annular-Ring Electromagnetic Bandgap Filter Structures."** The fabricated dual window tapered annular-ring EBG design in which the dimension of the etched circles in the ground plane were determined using the dual window distribution are shown in following figures. Figure 5.32 and Figure 5.33 show the top view and bottom view of the fabricated dual window tapered annular ring EBG based bandstop filter structure respectively. The material used for fabrication is PEC (Copper) of height 0.02mm with Rogers R04350 substrate of dielectric constant 3.48 and height 0.762mm.

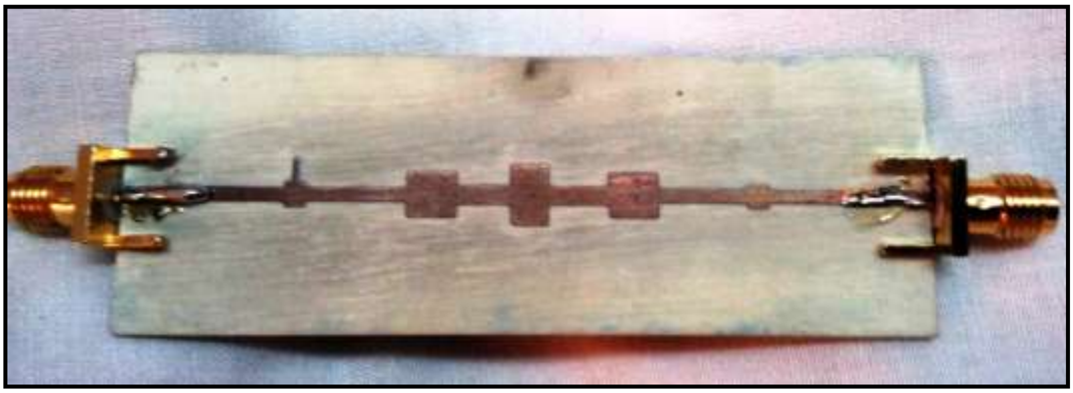


Figure 5.32 Top View of Fabricated Dual Window Tapered Annular Ring EBG Based Bandstop Filter Structure

Figure5.33 Bottom View of Fabricated Dual Window Tapered Annular Ring EBG Based Bandstop Filter Structure

5.12.1 TESTING OF FABRICATED STRUCTURE ON VECTOR NETWORK ANALYZER

TheDual Window Tapered C-EBG Microstrip Filter Structure with aspect ratio 0.4 and 0.25 for outer and inner circles respectively was designed using the Computer Simulation Technology (CST)-2010 studio suite software and This simulated Dual Window Tapered C-EBG Microstrip Filter Structure has been fabricated using Printed Circuit Board (PCB) technology and in order to have more precise practical results this fabricated design is tested on Agilent Vector Network Analyzer (VNA) of model no : N9917A, with frequency range 4GHz-16GHz. The simulated and measured results are shown below in Figure 5.34 and in Figure 5.35 respectively.

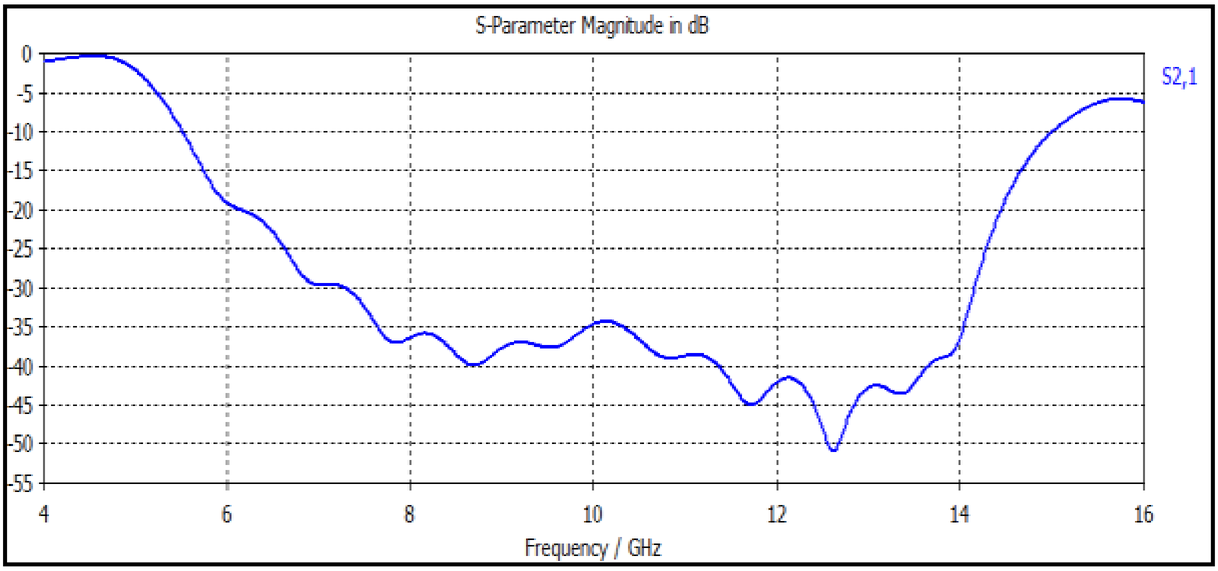


Figure 5.34 Simulated Insertion Loss (S21) Curve for Dual Window Tapered Annular-Ring EBG Based Bandstop Filter Structure

Figure 5.35 Measured Insertion Loss (S21) Curve for Dual Window Tapered Annular-Ring EBG Based Bandstop Filter Structure

The measured insertion loss S_{21} parameter of '**Dual Window Tapered Annular- Ring EBG Based Bandstop Filter Structure'** is shown in Figure 5.35. A comparative study between Simulated and Measured parameters of fabricated results are tabulated in Table 5.11

Table 5.11: Comparison between Simulated and Measured Results

Reference Design	Aspect Ratio		Stop Bandwidth (GHz)	Stopband Attenuation (dB)	Lower Passband Ripple Level (dB)	Upper Passband Ripple Level (dB)
	outer circle	inner circle				
Simulated	0.4	0.25	10.0	52~54	0.378~0.863	4.5~5.7
Fabricated	0.4	0.25	9.80	50~51	0.500~0.800	5.0~5.8

Hence from the above Table 5.11 we observe that the measured results are in good agreement with the simulation results. The novel design of this structure is able to achieve high performance as a bandstop filter with superior passband and stopband characteristics.

Chapter6

CONCLUSION AND FUTUTRE WORK

6.1 CONCLUSION

The motivation of this thesis is to implement EBG based microstrip filter structure that has improved stopband and passband performances. Initially designs in this thesis work are formed by using single plane EBG structures.This single plane filter design shows deteoriated output performances in terms of high ripple level in the passband and stop bandwidth.

Therefore dual EBG based microstrip structure is formed by etching circles in the ground plane and using a microstrip line in other plane. The etched circles in the ground plane are dimensioned as per aspect ratio control factor. This Dual plane structure shows a large stop bandwidth large ripple level. So, a Dual Window Tapered EBG based microstrip filter structure is proposed to improve both the passband and stopband performance of the filter structure. This structure shows ultra-wide bandwidth and stopband attenuation. Hence, in order to improve the performance and to reduce the ripple different Kaiser and Chebyshev Window Functions are used to taper the radius of etched circles in the ground plane. With the help of these Window Functions the ripple level is reduced to a very small value.

An EBG microstrip structure with dimension of etched circles determined by the Kaiser-Chebyshev window distributions in association with aspect ratio control factor was fabricated and tested on the Agilent Vector Network Analyzer. The measured results are in very good agreement with the simulated results. Moreover novelty in this design is the application of Dual Window Tapering functions along with Varying Aspect ratio. Hence this proposed design leads to:

- Large bandwidth of 9.8~10 GHz
- High attenuation of about 50~52 dBs within the stopband
- Better passband and stopband characteristics than uniform EBG structure

6.2 FUTURE WORK

Annular ring dual window tapered EBG-based filter structures are proven to exhibit broad applications to satisfy the needs of designing various microstrip circuits.The proposed 1-D EBG configuration will be further employed in other applications for compact microwave circuits. It will be used as the reflectors in the design of resonators or for the coupling elimination of two close microstrip lines.

- This novel structure technique has its application in wide-band planar antenna, band stop filter, amplifiers, reflectors, resonators and in many more GHz frequency circuits' applications.
- EBG structures can also be designed to work as bandpass and high pass filters.
- EBG Structures can be used to provide Transmit–Receive Isolation in radar applications as shown in Figure 6.1 and in Figure6.2.An efficient isolation structure combining two EBG walls, is presented to improve the Transmit Receive isolation. By applying such isolation, Surface wave suppression effect of the EBG structure is observed which leads to minimization of interference in proximity of two closely placed antennas.

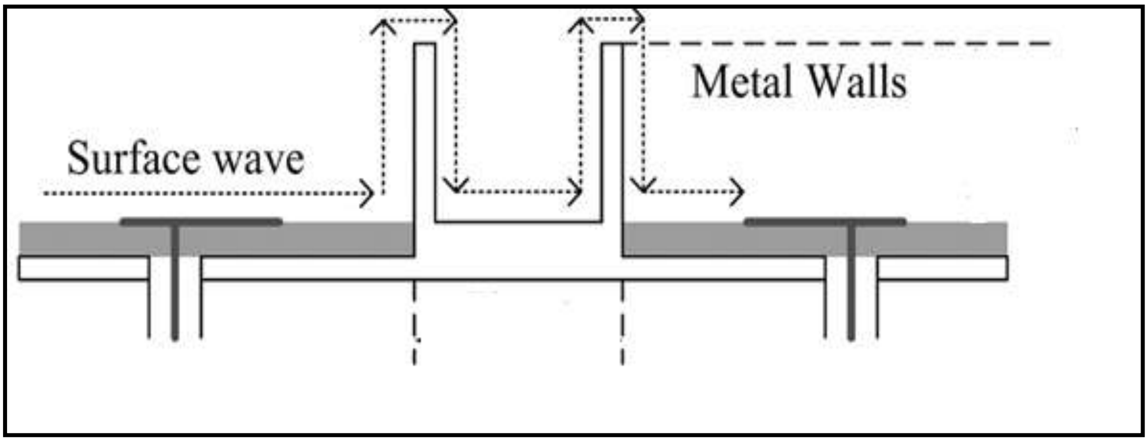


Figure 6.1 Transmit–Receive Isolation in radar with metal walls [44]

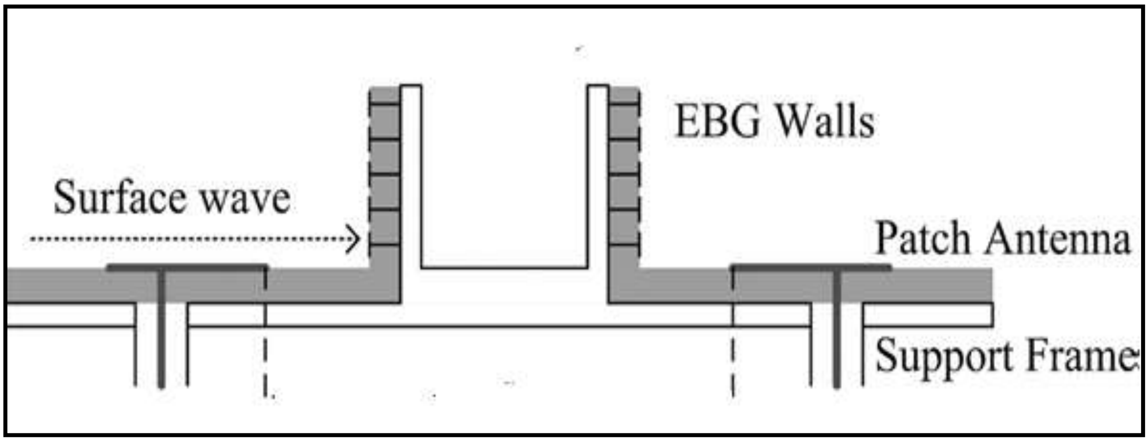


Figure 6.2 Transmit–Receive Isolation in radar with EBG walls [44]

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