Annular Squared Tapered EBG Microstrip Bandstop Filter with Improved Performance

Dissertation submitted in partial fulfillment of the requirements for the award of the degree of

Master of Engineering

in

Electronics and Communication Engineering

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(Established under the section 3 of UGC Act, 1956)

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July 2015

CERTIFICATE AND DECLARATION

I, Isha Gupta hereby declare that the work which is being presented in the dissertation entitled **"Annular Squared Tapered EBG Microstrip Bandstop filter with improved performance"**, by me in partial fulfillment of the requirement for the award of degree of Master of Engineering in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Dr. Rajesh Khanna (Professor)**, Electronics and Communication Engineering Department. The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

Date: 10/7/15

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

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ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to **Dr. Rajesh Khanna**, Professor, Electronics & Communication Engineering Department, Thapar University Patiala for his patient guidance and support throughout this work. I am truly very fortunate to have the opportunity to work with him. I found his guidance to be extremely valuable.

I am also thankful to **Dr. Sanjay Sharma**, Head, Department of Electronics and Communication, Thapar University, Patiala, for providing the opportunity to carry out the present work.

I also want to express my gratitude to **Dr. Amit Kumar Kohli**, P.G. Coordinator, Electronics and Communication Engineering Department, the entire faculty and staff of Electronics and Communication Engineering Department for their help in all possible ways for successful completion of this work. I thank all those who have contributed directly or indirectly in this work. Lastly, I would like to thank my parents and friends for their constant support and encouragement throughout making of this report .They have always wanted the best for me and I admire their love and sacrifice.

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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 the 2-D EBG structures is due to the presence of the stopband where electromagnetic waves are prohibited to propagate.

In this thesis a Low Pass Filter is designed with squared EBG etched in the ground plane. It is concluded that by employing the squared uniform EBG instead of circular EBG in the ground plane the bandwidth is improved. By employing other tapering technique on the square EBG other filter characteristics such ripple level in the passband and attenuation of the stopband are also improved.

Secondly this thesis presents squared Chebyshev (SC-EBG) tapered and squared annular Chebyshev and Kaiser (SACK-EBG) tapered compact electromagnetic bandgap microstrip bandstop filter. The compact EBG provides a good transmission and rejection characteristics in the passband and stopband, respectively. The SC-EBG band stop filter gives a 10-dB bandwidth of 3.57 GHz and ripple content of 1.85 dB in lower passband and 2.12 dB in upper passband. The SACK-EBG bandstop filter gives an improved 10-dB bandwidth of 5.25 Ghz with ripple content of 0.74 dB in lower passband and 4.8 dB in the upper pass band. The proposed SA-EBG and SACK-EBG filters give ultrawide stopband and lower ripple content in lower pass band with small circuit area. The measured and simulated results are found to be in good agreement.

The Computer Simulation Technology (CST)-2010 studio suite software is used to design the filter structure and the simulated 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) with frequency range 0 -11 GHz and 4 -16 GHz.

TABLE OF CONTENTS

CONTENTS **PAGE NO.**

CHAPTER 1: INTRODUCTION

CHAPTER 2: LITERATURE SURVEY

CHAPTER 3: TYPES OF FILTER USED IN MICROWAVE CIRCUITS

CHAPTER 4: EBG BASED LPF AND ALL PASS FILTER

CHAPTER 5: EBG BASED BAND STOP FILTER

CHAPTER 6: CONCLUSION AND FUTURE SCOPE

LIST OF ABBREVIATIONS

MPA	Microstrip Patch Antenna
CST	Computer Simulation Technology
EBG	Electromagnetic Bandgap Structure
DGS	Defected Ground Structure
RF	Radio Frequency
MMIC	Monolithic Microwave Integrated Circuits
VNA	Vector Network Analyzer
PCB	Printed Circuit Board
PBG	Photonic Bandgap Structures
HIES	High Impedance Electromagnetic Structures
LSAMC	Large Spiral Artificial Magnetic Conductor
SSAMC	Small Spiral Artificial Magnetic Conductor
CPW	Coplanar Waveguide
WLAN	Wireless Local Area Network
GSM	Global Services for Mobile
FSS	Frequency Selective Surface
MIMO	Multiple Input Multiple Output
SC-EBG	Squared Chebyshev Electromagnetic Bandgap Structure
SACK-EBG	Squared Annular Chebyshev and Kaiser Electromagnetic Bandgap Structure

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

1.1 MOTIVATION

Electromagnetic bandgap structures are a specific class of photonic semiconductors used to construct filters like low pass, high pass, bandpass, bandstop filter used in communication. Filters are used to satisfy the band rejection and band selection properties in a specific frequency region. EBG is nowadays extensively used in filter designing with a better performance in the passband and stopband characteristics. EBG which is a class of metamaterial is a topic for immense field of interest for various research scholars throughout the world. EBG has an ability to change the surface properties of substance by increasing its surface impedance. This high surface impedance property of EBG has made it widely used in various antenna applications such as filtering, amplifying, resonators, reflectors and many more. There is an increasing demand for larger bandwidth nowadays, low ripples in the passband for radio frequency (RF) devices, new designs are used and are implemented throughout the world.

EBG are extensively used because of its use in small circuit area with less difficulty in fabrication and integration with MMICs (monolithic microwave integrated circuits). EBG has an advantage that it exhibits a bandgap where no EM (electromagnetic) waves are allowed to propagate and are generally used with the microwave circuits like patch antenna in order to suppress the surface waves. In this entire thesis designs of various EBGs are studied and new designs are proposed in order to improvise various bandgap characteristics for a filter. All the designs are simulated on CST microwave studio 2010 and some of the designs are fabricated with PCB (printed circuit board) technology and the fabricated results are tested on VNA (vector network analyser) model no N9917A.

1.2 OVERVIEW

Any filter has a unique feature to allow a certain frequency to pass and rejecting some of them. Microstrip patch antennas are very popular in the study of antennas due to their wide range of applications and flexibility with the substrate. Patch antennas has a wide range of merits and demerits as well. Some of their merits are its economic costs, low weight, operations in a high range of frequency. Some of their demerits are their narrow bandwidth operation, very poor efficiency and a large physical size. The main challenge for all the researchers working in the field of patch antennas is to operate the antenna in wide bandwidth range by minimizing the physical size of the antenna, hence reducing the size of the patch. In order to overcome the demerits of the patch antennas they are studied over different substrate material and the best out of them is obtained for the antenna fabrication with patch. Amongst all of them metamaterials are considered to be most suitable amongst all the materials [1]. Figure 1.1 (a) shows the patch antenna and Figure 1.1 (b) shows the surface waves on the ground plane.

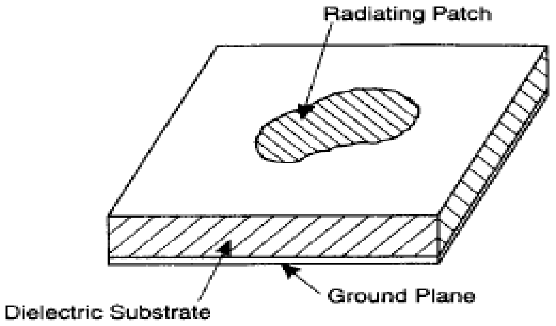


FIGURE 1.1 (a) Microstrip patch antenna [6]

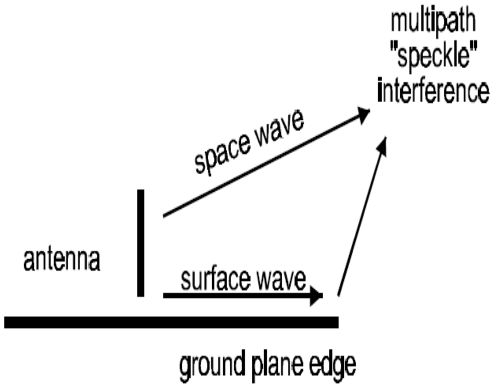


FIGURE 1.1 (b) Surface wave produced on the ground plane [21]

1.3 INTRODUCTION TO EBG STRIUCTURE

EBG structures are well characterized as a type of metamaterial with their advantage of suppressing the surface waves and providing a unique bandgap advantage. EBG generally used with patch antennas improve the bandwidth and directivity by suppressing their surface waves. EBG also results in a reduced physical size and increasing the efficiency, gain of the antenna. EBG is the main field of interest for various researchers for past 20 years and is still popular amongst them. Various improvements in the designs are done with better performance and results and many new designs are implemented by using different types of EBGs in order to reduce return loss and improve bandwidth in every antenna design.

EBG has many applications in the study of antenna engineering. The revolutionary change which EBG bought in antenna is its ability to suppress surface wave thus resulting in high antenna gain performance like increased directivity, bandwidth, reduce the physical size of antenna by reducing the return loss and many more. The simplest design of EBG is shown in figure 1.2 where the vias leads to the inductance L and the gap between the two patches comprises of the capacitance C thus forming a complete LC circuit and is used as a filter. As it is a filter so definitely it will have a resonant frequency which is calculated by the equations given below.

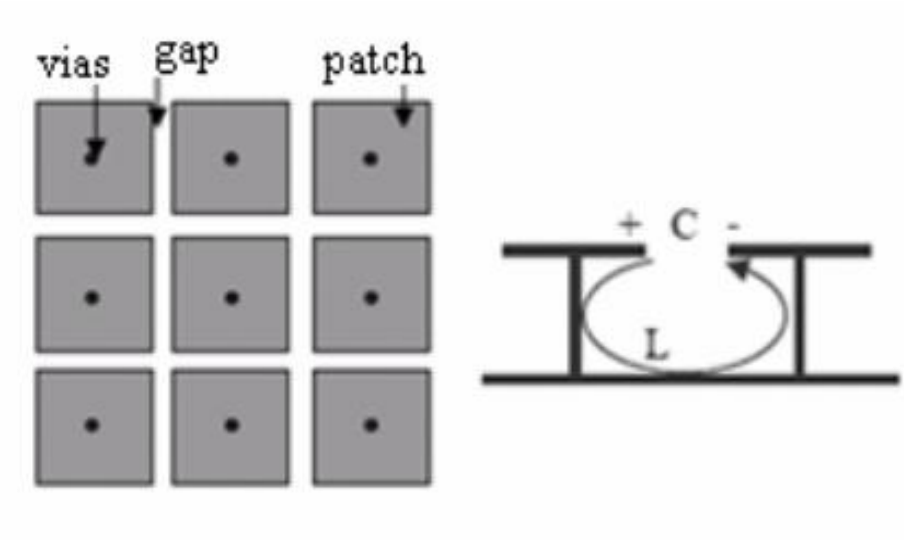


Figure 1.2 EBG structure basic design [5]

Resonant frequency of EBG structure is given as

$$f_r = {}^{1}/_{2\pi\sqrt{LC}}\,, \qquad (1.1)$$

where,

Inductance (L) = μo h

$$C = \text{Capacitance} = W\varepsilon_o \frac{(\varepsilon_r+1)}{\pi} cosh^{-1}\left(\frac{2W+g}{g}\right) \tag{1.2}$$

Thus bandwidth of EBG is given by

$$\text{BW}=\frac{1}{\eta}\sqrt{\frac{L}{C}} \tag{1.3}$$

Figure 1.3 shows a comparison of patch antenna with and without EBG. The figure completely shows when patch antennas is utilized alone, the surface waves gets propagated through the antenna form the ground plane and radiation waves are dissipated at the edge of the antenna whereas when the EBG is used, the vias and the patches together work as an LC filter in the design resulting in suppression of radiation completely in a band gap region and stopping of propagation of surface wave at the edges.

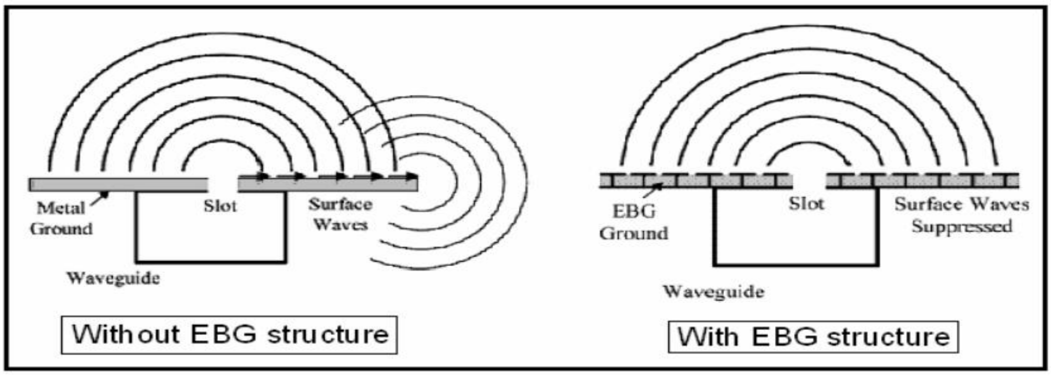


Figure 1.3 Comparison of patch antenna with EBG and without EBG [22]

1.4 CLASSIFICATION OF EBG STRUCTURES

EBG structures are classified as shown in figure 1.4. They are classified on the basis of their arrangements in the ground plane and their property of minimizing surface waves in order to improve the surface impedance of the substrate.

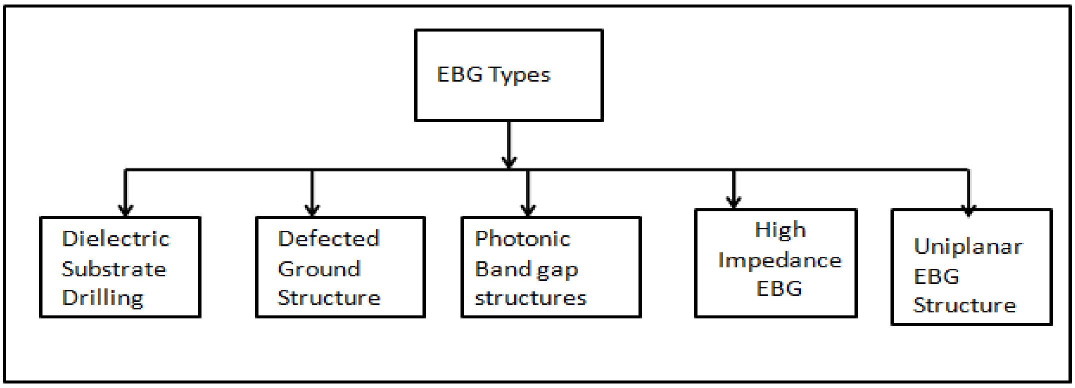


Figure 1.4 Classification of EBG structure

1.4.1 Dielectric Substrate Drilling Periodic Structures

In this type of EBG structure a defined arrangement of holes are etched in the substrate. The arrangement is shown in figure 1.5 which describes the dielectric inclusion with a substrate changed from that to the host dielectric substrate. This design of EBG is very complicated drilling through the substrate.

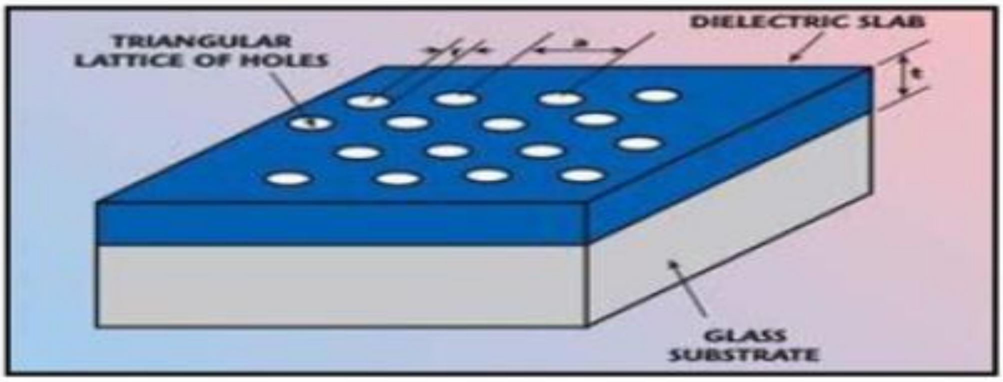


Figure 1.5 Dielectric substrate drilling periodic structures [4]

1.4.2 Defected Ground Structure

As the name defines in this type of EBG the ground plane is made etched or defected in order to minimize the surface waves present near the edge of the substrate material. This is one of the easiest EBG to design and has a wide application in filter designing. DGS can acquire any shape as shown in figure 1.6 where squares are etched in the ground plane. As compared to photonic bandgap structures, the bandgap and slow wave characteristics of DGS structure is better than the customary ground plane. DGS structure is used for filter designing as shown in [13] where the circles are etched in the ground plane acting as DGS and later a chebyshev tapering technique (discussed in this thesis in the later section) is applied on the DGS where the results are further improvised. In the entire thesis work the DGS design is used in order to design our improvised filter in terms of bandwidth.

DGS structure has a wide area of application and its features are discussed below:

- DGS increases the value of inductance and capacitance of transmission line
- DGS increases the value of effective permittivity
- DGS generally disturb the protecting field on the ground plane
- DGS reduces the size of the module

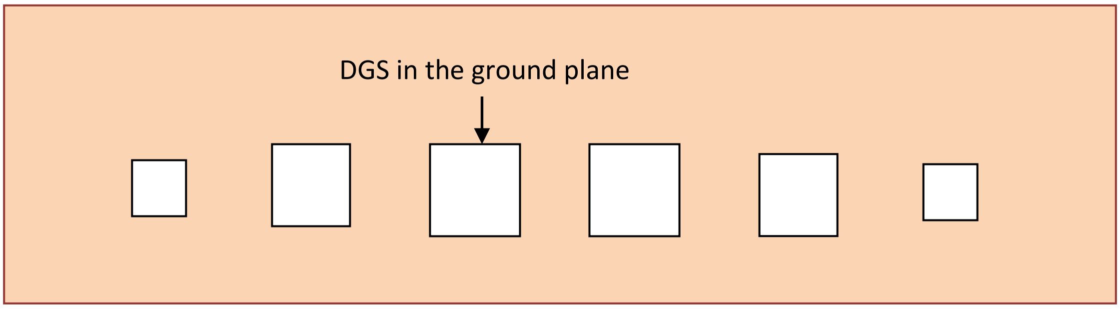


Figure 1.6 Defected ground structure

1.4.3 Photonic Bandgap Structures

A photonic crystal acts as a band elimination filter that suppresses the spread of power over a group of predetermined frequencies. Semiconductor consists of a

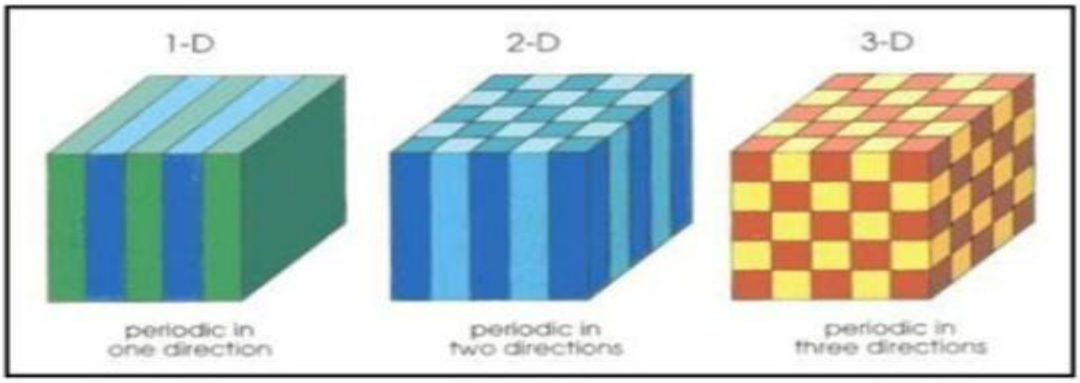


Figure 1.7 Photonic band gap structure periodic in different directions [4]

bandgap region where no electron exists. PBG structures are defined as periodic structure that influence electromagnetic radiation in a way like semiconductor influences electrons. Figure 1.7 gives the design of PBG structure.

As an EBG, photonic structure contains a similar bandgap at optical frequency range where it obstructs the propagation of electromagnetic radiation in the bandgap region.

1.4.4 High Impedance Electromagnetic Structures (HIES)

A novel kind of metallic electromagnetic arrangement has been developed. It is categorised 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 surface waves and reflects EM waves with zero phase reversal.

The figure of HIES is shown in figure 1.8 which acts as a lumped circuit that describes the EM characteristics related to the surface. HIES is generally a kind of metal protusions on its flat surface arranged in 2-D space.They are generally seen as mushrooms or other shapes protruded on the surface.

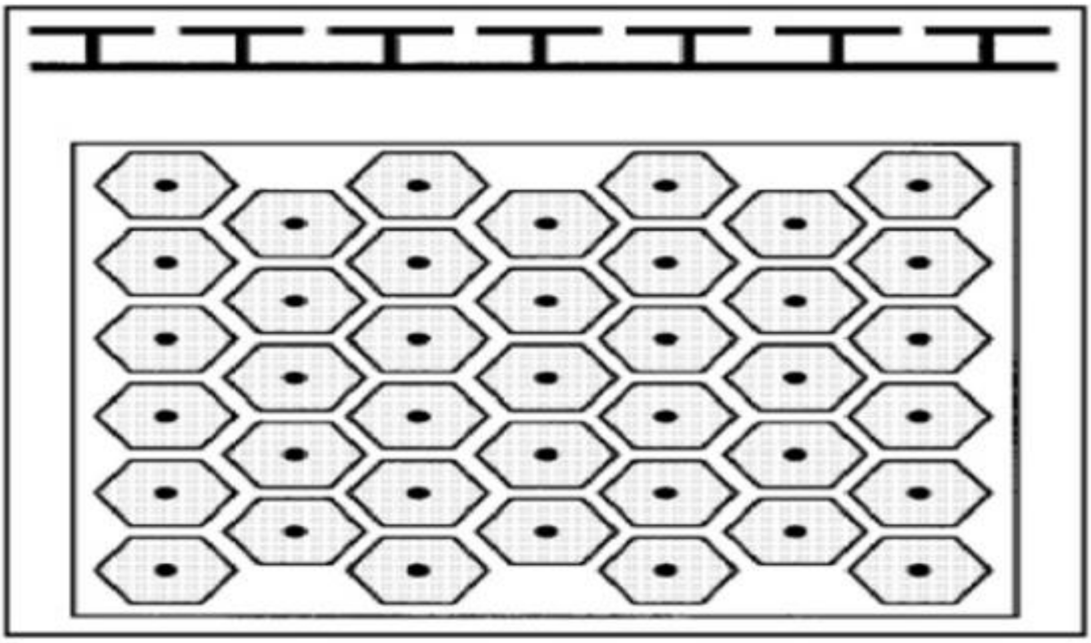


Figure 1.8 High impedance electromagnetic impedance (HIES) periodic structure [5]

1.4.5 Uniplanar Compact EBG Structure

EBG structures which are planar and compact is of vast attention for various researchers working in the microwave engineering field because of its easy fabrication. In this type of EBG structure the bandgap region exists for only one plane in which the angle on incidence of EM wave falls. There are many planar structures available in microwave engineering but popularly used planar structure is uniplanar and mushroom type. Figure 1.9 gives a uniplanar structure in which there are various squares, each one consisting of a metal pad with four branches linking each other in order to form a LC resonate structure. This EBG is very simple and easy to design and fabricate without any alterations.

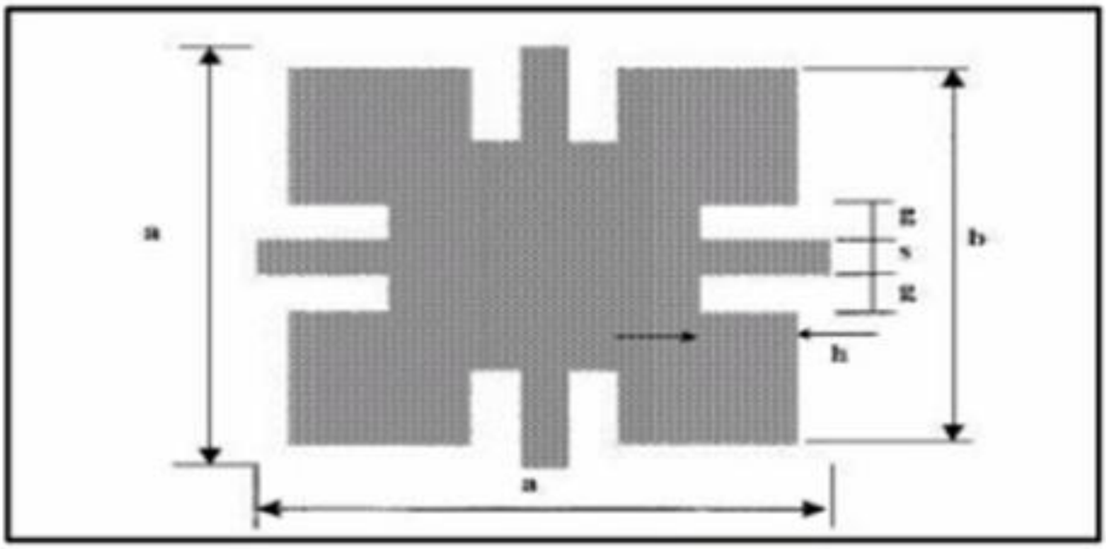


Figure 1.9 Uniplanar compact EBG structure [7]

1.5 OBJECTIVE OF THESIS

1. Design of squares EBG low-pass filter with improved performance in the stop band
2. Design of band-stop filter by using squared EBG Chebyshev Tapered structure in the ground plane
3. Design of band stop filter using annular squared tapered EBG structure by employing a combination of Chebyshev-Kaiser taper for improved performance in the passband

4. Fabrication and testing of band stop filter mentioned in objectives 2 and 3.
5. Comparison of simulated and measured results.

The complete process adopted in order to accomplish the thesis in proper and efficient manner is shown by a flow chart given in figure 1.10. In the first step the research of various researchers is studied and analyzed then their results are improved by modifying their designs.

1.6 THESIS ORGANISATION

Before starting the thesis the **chapter 2** is discussed in which the literature survey by various research scholars is studied in order to proceed with the further enhancement of their work.

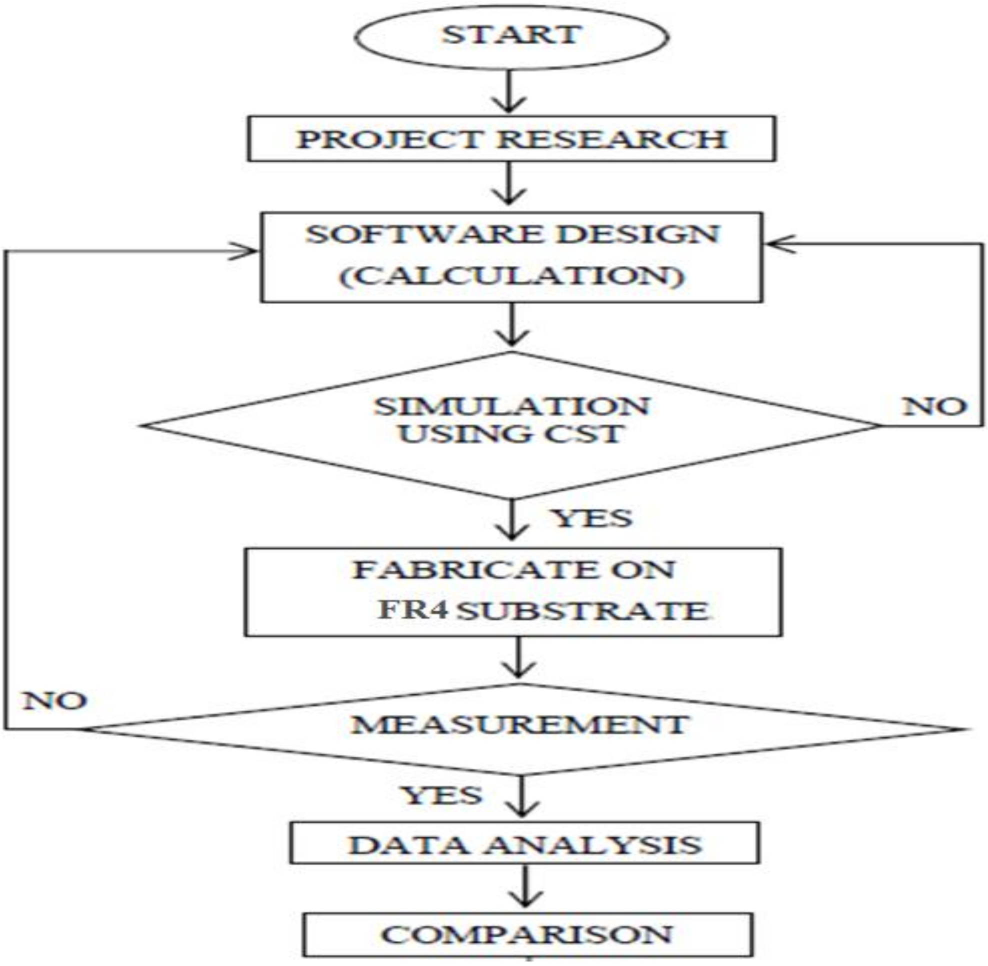


Figure 1.10 Flow chart depicting the entire thesis work [2]

Many publications were read to understand the concept of electromagnetic band gap structure thoroughly so that they may be implemented in the entire thesis work in a most efficient manner

In **Chapter 3** gives a brief introduction of filters. It describes the characteristics, properties applications of various types of filters used in communication engineering. It also gives a brief introduction to EBG structures used to design a filter in communication engineering. Moreover in this chapter it is shown that an EBG design exhibits better compatibility with microstrip elements which allow it to be used with LPF designed in next chapter.

In **Chapter 4** low pass filter and all pass filter are designed with squared EBG etches in the ground plane. A low pass filter is designed by using a U-shaped microstrip line on the top of the substrate and S-EBG in the ground plane. Further in the chapter the modulated microstrip line is used instead of simple U-shaped line with an improved frequency response. In the last section of this chapter an all pass filter is designed with S-EBG in its ground plane.

In **Chapter 5** a band stop filter is designed with S-EBG taper in the ground plane. This chapter is divided into two sections. In section 1 bandstop filter with chebyshev S-EBG is designed with a bandwidth of 3.57 Ghz with a lower ripple level of 1.85-dB and higher ripple level of 2.12-dB. In section 2 a new bandstop filter is designed with an annular tapered ground plane. This filter gives an improved bandwidth of 5.25 Ghz with a lower ripple level of 0.74-dB and a higher ripple level of 4.88-dB.

In **Chapter 6** the conclusion of the entire thesis work is discussed in the detailed form and in the future scope further enhancement related to the thesis are presented.

Chapter 2

LITERATURE SURVEY

2.1 INTRODUCTION

Before starting the thesis we will go throw some of the reference papers which have been published by various research scholars throughout the world. Only with the help of these papers it was able to do the thesis very efficiently. In the following papers various tapering techniques were studied and are utilized in order to implement the filter with an efficient passband and stopband characteristics. The tapering techniques used are Chebyshev, Kaiser, Binomial, Hanning, Hamming, Taylor.

2.2 LITERATURE SURVEY

Nemai Chandra karmarkar, Mohammad Nurunnabi Mullah **[8]** proposed an improved performance of the bandgap by implementing circular PBGs (photonic bandgap structures) and introducing non-uniform dimensions of the proposed filter design. In this paper they implemented the chebyshev tapering technique by determining their coefficients, accordingly calculating the dimensions of the etched EBGs (electromagnetic bandgap structure) in the ground plane. The chebyshev tapering function gave a good suppression of ripples in the passband. The design is further extended by using the annular ring PBG cells with a fixed aspect ratio.

Fan Yang, Yahya Rahmat-Samii **[9]** utilized the mushroom-like EBG structure and the suppression of the surface wave is studied by using near-field distributions of the EM waves. The mutual coupling between the antennas is studied by taking all the coupling directions into consideration. They observed that an array of antenna on the thick substrate results a high mutual coupling due to prominent surface waves. They proposed an EBG between the two antennas in order to suppress the surface waves, reducing the mutual coupling. It results in 8-dB reduction in the mutual coupling between two antennas in an antenna array.

Shao Ying Huang, Yee Hui Lee **[10]** proposed a small size low pass filter design with U-shaped microstrip line geometry. The proposed structure results a flat stoband with a 10 Ghz center frequency resulting in a high selectivity. They utilized the Chebyshev distribution function as a tapering function to taper the EBG cells in the ground plane. The paper results good filtering properties for a low pass filter design. U-shaped design is very easy to fabricate and gave a flexible layout design.

Dalia Nashaat, Hala A. Elsadek, Esmat A. Abdallah, Magdy F. Iskander, Hadia M. El Hennawy **[11]** proposed different types of EBG structures and design a patch array antenna in order to increase the bandwidth by reducing the physical size of antenna array. The different EBGs designs are spiral artificial magnetic conductor (SAMC), large spiral artificial magnetic conductor (LSAMC), small spiral artificial magnetic conductor (SSAMC). LSAMC, SSAMC both are embedded with SMAC and gave different advantages. LSAMC gives the best response in the physical size reduction and in result improving the bandwidth of the antenna array. SSAMC gives the best response in the reflection phase and thus improving the gain of the antenna array. All the radiation patterns are well improvised by using the different EBG structures and hence increase the array gain to a large extent with a size reduction upto 85%.

Rens Baggen, Marta Matinez- Vazquez, Jens Leiss **[12]** designed an antenna with low profile for geodesic application. They use the property of alleviation of multipath signal for its high precision. In this paper choke rings are used in order to reduce the multipath interference. The antenna is low temperature patch antenna in conjunction with an EBG substrate. The EBG suppress the surface waves to a large extent resulting in multipath rejection with a constant phase angle. The design is made at low price, small size with a low profile.

Shao Ying Huang, Yee Hui Lee **[13]** designed a dual plane EBG structure which gives stopband with high attenuation by using a very small circuit area. They adopted the chebyshev distribution as a tapering technique in order to taper the two sides of the substrate uniformly. The tapering technique is only implemented in order to reduce the ripples in the passband and to achieve high performance of the stopband. The ripples are only introduced due to the periodicity of the substrate so tapering technique basically changes the periodicity of the substrate. The result of this paper is reduced size of the structure by giving high performance of the filter structure. They were the first research scholars who introduced the concept EBG in order to form a band stop filter.

Hossein Sarbandi Farahani, Mehdi Veysi, Manouchehr Kamyab, Alireza Tadjalli **[14]** reduced the mutual coupling in an antenna array between the elements. They reduced the mutual coupling by using the EBG structure and results in novel design with a reduced physical size of the circuit area. They placed the EBG structure on the top layer of the substrate. They achieved both the reduction of element separation and the mutual coupling between them, hence increasing the directivity of the antenna.

Halim Bourtayeb, Tayeb A. Denidni **[15]** introduced the concept of cylindrical EBG structure. The feeding technique they used is coaxial feeding with a coaxial probe which is introduced in integration with the EBG substrate. The effect of antenna is increased array gain, directivity etc. Basically cylindrical EBG is integration of two periodic structure having different periods. Parametric analysis of EBG structures is done by them and the results are fabricated and tested. The result shows a good radiation pattern and a low return loss by good impedance matching.

Johan Joubert, J.(Yiannis) C. Vardaxoflou, Willam G. Whittow, Johaan W. Odendaal **[16]** proposed a coplanar waveguide (CPW) which is fed by a slot antenna. A slot antenna is used in integration with an EBG structure thus results in an excellent performance between the upper and lower conducting surface of the slot antenna. On the upper surface the etching of the slot is done and on the lower surface the waveguide is fed. The dimension plays a major role for minimizing the power loss of the antenna. They proposed 1.5 λ_0*1.5 λ_0 back lobe and increases the gain upto 10 dBi by lowering the polarization by 25 dB. The proposed antenna can be well utilized for the WLAN application which is 2.4 Ghz.

Marzieh Salar Rahimi, J-Rashed Mohassel, M. Edalatipour **[17]** proposed an antenna used in GSM/WLAN applicatons. He proposed a circular patch which has improved properties of radiation pattern at GSM and WLAN has a frequency range of 1.8 Ghz and 2.4 Ghz. He proposed a circular EBG structure in integration with the patch on the upper side of the substrate. The proposed structure is well simulated and tested giving an excellent performance in the radiation pattern with high directivity and reduced antenna losses. The results show an excellent improvement of the antenna to be used in GSM and WLAN applications. They demonstrate a massive reduction in the cross-polarization and antenna array loss.

Abbas Pirhadi, Hadi Bahrami, Javed Nasri **[18]** proposed a very high directive EBG structure antenna which operates in a wide frequency region for giving a reduced value of return loss. In this paper aperture antenna is used as a feeding source and FSS (Frequency Selective Surface) as a super substrate. Both are suitable to operate at a fixed resonate frequency and thus are capable to give suitable results of high directivity and low return loss. High directivity and low return loss is only achieved by FSS layer as a super substrate. The FSS layer consists of square loop patches. An aperture coupled is designed in such a way in order to operate in X-band region by utilizing an appropriate coupling aperture which has a great importance. Then afterwards the aperture coupled is used with the FSS layer to give a better bandwidth and reduced returnloss with high directivity.

Mu’ath J. Al-Hasan, Tayeb A. Denidni, Abdil Razek Sebak **[19]** proposed DRA (Defected Ground Structure) which is used in integration with an EBG structure. It describes the Mushroom-like EBG, circular EBG cell which are both fabricated and tested. The results are checked by using asymmetric concept for microstrip line. Both the DRA alone and DRA with integration with EBG is checked and analysed at a bandwidth of 60 Ghz. Both the results are compared and shows a massive improvement in the radiation pattern and antenna chararteristics when surrounded by EBG structure. gain is increased by a value of 1.5 dBi and gives a flat gain over a bandwidth of 0.7db. A huge suppression of back lobe is obtained which results in a reduced radiation at the edges.

Soham Ghosh, Thanh-Nagon Tran, Tho Le-Ngoc **[20]** proposed an EBG mushroom-like structure. They reduced the size of the antenna by 61%. The EBG reduced the size of antenna its upper layer behaves as bandstop filter which reduces the mutual coupling between the two patches. They proposed various two and four element patch antennas at WLAN frequency which is 2.4 Ghz. The spacing between the array elements is as small as 0.5λ which results in reduced mutual coupling at about -28 dB and -50 dB. The results are implemented in MIMO models using kronecker approach for channel estimation in MIMO channels. The design results in a high MIMO capacity gain even by introducing the fading effects like Rayleigh and ricean fading environments.

Dan Sievenpiper, Johan James, Zhang Losay, Liyen Robal **[21]** proposed a metallic EBG structure which has a very high surface impedance. It consists of continuous metal which conducts the direct current but obstructs the alternating current. The new surface introduce do not support the propagation of the surface waves unlike normal surface. Also the image current do not reverses the phase of the current. In this design a corrugated surface is not used thus a lumped and distributed 2-d lattice structure is utilized. The surface is described by using band theory, the periodicity has a very low value than the vacuum wavelength. Here a unique metal is used which improves various electromagnetic problems which also includes low profile antennas.

Harish Kumar, Manish Kumar, Mohit Kumar, Abhijeet Kumar, Rajeev Kant **[22]** proposed a mushroom type EBG pattern with a varying diameter of each vias in order to analyse its behavior. A simple EBG structure is proposed and analysed with an improved bandwidth of 2.5 to 3.7 Ghz which is used in Bluetooth application. This paper concludes that when the radius of each vias is increased the bandgap shifts to a high frequency range. An appropriate model for high impedance EBG structure is used for wide frequency ranges. The proposed design gives high accuracy over a wide frequency ranges. The optimization of the design specifically the EBG structure has done in order to achieve high efficiency and high performance of radiation pattern with high degree of directivity.

An-Shyi Liu, Yin-Chi Chen, Ruey-Bee Wu **[23]** proposed a very simple pattern of periodic structure that are etched in the ground-plane under the strip conductor in order to achieve good performance in the low pass and band stop filter characteristics. It achieves a superior wide stop band which results by combining two techniques. One is the tapering of the etched holes and the other is multiple period of all EBG units. The structure comprises of combination of both the above techniques and result in a new design pattern. The result of the design gives an increased radiation loss only at high frequency. At low frequency there is low radiation loss thus results in a better antenna gain and directivity.

Kai Herbertz [24] demonstrated the wide use of various EBG structure on different patch antennas. The geometries of 1-D and 2-D dielectric slab and its air pockets were studied in a detail manner in their approach. In this paper the different antennas used are patch antennas, a slot antenna and dielectric resonator. The patch antennas when used with EBG structure results in the suppression of backlobe radiation. The dielectric resonator antenna used with EBG improves the radiation pattern by suppressing the side lobe level (SLL) in the pattern. The dielectric slab when used with EBG nullifies the radiations in the non-propagating directions. All the three types of antennas are completely analysed with an objective of reducing the side lobe levels in each antenna without altering any other parameter.

F.R Yang, K. P. Ma, Y.Qian **[25]** designed a uniform compact electromagnetic bandgap structures which consists of a square patterns where each pattern has a metal pad and a distributed RC network. A new metallic arrangement which is electromagnetic in nature develops a higher value of surface impedance. The proposed due to its easy fabrication the planar EBG results in a special attraction at millimeter and micrometer frequency ranges. All such electromagnetic bandgap structures are periodic in their 2-d plane and suppress the surface wave in each bandgap for a huge range of angle of incidence of electromagnetic wave. All the collection of mushroom type, compact uniform EBG and also planar EBG results in different meticulous values. They proposed the designs which are very easy to fabricate and has economic price with a low weight.

X. Q. Chen, X W Shi, Y. C. Guo, C. M. Xiao**[26]** analysed the photonic bandgap (PBG) structure used as substrates to operate in microwave frequencies and their performance is studied. They proposed a new DGS structure that provides a good performance attribute of bandgap for specific frequency bands with one lattice structure. the results were studied by using circuit analysis of the design. The parameters which are extracted and analysed for the study of bandgap characteristics has been done and are completely described in this paper. The same results are also checked by using the three dimensional field analysis approach. The study was utilized to implement low-pass filter and bandstop filter parameters. The simulated and the measured results are in an outstanding agreement with each other.

Y. Fei-Ran, M. Kuang-Ping, T. Itoh, Q.Yongyi **[27]** gave a novel metallic arrangement which gives improved surface impedance for the substrate. This paper describes the planar EBG pattern which provides a special attention towards the millimeter range of frequencies, due to its ease of fabrication. All these EBG structures are periodic in its plane and show no signs of bandgap in a wide range of angle of incidence for an EM wave. All the EBGs are planar, compact and mushroom type EBG are of different meticulous values. The compact EBG consists of square patches with metal pad linking branches to form a LC network which is generally distributed. In this paper it is also explained that a uniform compact EBG design can also be built by use of planar technique of fabrication without alterations.

Arjun Kumar, Jagannath Malik, M V Kartikeyan **[28]** discuss the performance of various filters made by using the geometry of dumbbell-shaped DGS for its bandstop characteistics. They proposed a new type of Dumbell shaped structure with square slots in the ground plane. They have done the complete simulation of the proposed structure using HFSS software.

M Thottappan, P. K. Jain **[29]** proposed a photonic bandgap which is metallic waveguide. They have use the FDTD technique for the analyzation and have obtained the global regions of bandgap which has a 2-D array triangular geometry. They also developed a mode map for studying the characteristics related to the antenna propagation. The waveguide mode was operated in TE_{01} mode. The measured results were very similar to other modes like TE_{31} and TE_{21} mode. The transmission loss was calculated to be as minimum upto 1.01dB/cm at its operating frequency.

Mikko Komulainen, Tero Kangasvieri, Jyri Jantti, Heli Jantunen **[30]** proposed a design of compact surface mountable LTCC-BGA antenna package which is used in X-band region of wireless communication. A stacked patch microstrip antenna is embedded on top side of the LTCC package, while the electromagnetically shielded bottom side is used for RF signal routing. A broadband vertical structure is designed for a frequency range upto 15 Ghz.

2.3 CONCLUSION

From the literature survey it was concluded that many filters have been designed using EBG structures in the ground plane and has shown a wide improvement in passband and stopband characteristics in patch antenna filter structures. There are some drawbacks in the above discussed literature survey such as ripples in the passband and low bandwidth etc. In this thesis it was tried to improve certain drawbacks in the above discussed research papers. Following chapters will describe the work which has been done to fulfill the gaps and minimize the drawbacks of the above research work.

Chapter 3

TYPES OF FILTER USED IN MICROWAVE CIRCUITS

3.1 INTRODUCTION

Filters are generally frequency selective circuit elements that is they will allow only some frequencies of the entire available frequency band to pass through them and rejecting all the other frequencies. According to their behavior the filters are distinguished from each other. Generally in microwave engineering study the filters are commonly distinguished by their range of frequencies they allow to pass and classify as

1. **Low Pass Filter (LPF)** does not allow the signals whose frequency lies above the filter resonant frequency. Figure 3.1 shows the frequency response spectrum for LPF.

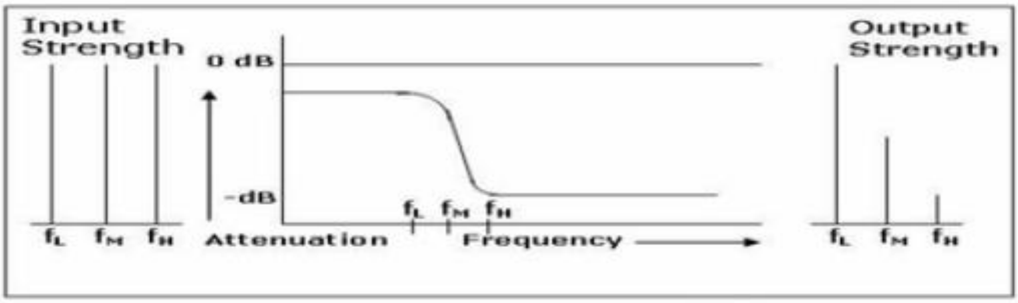


Figure 3.1 LPF frequency response [4]

2. **High Pass Filter (HPF)** does not allow the signals whose frequency lies below the filter cut off frequency. Figure 3.2 shows the frequency response spectrum for HPF.

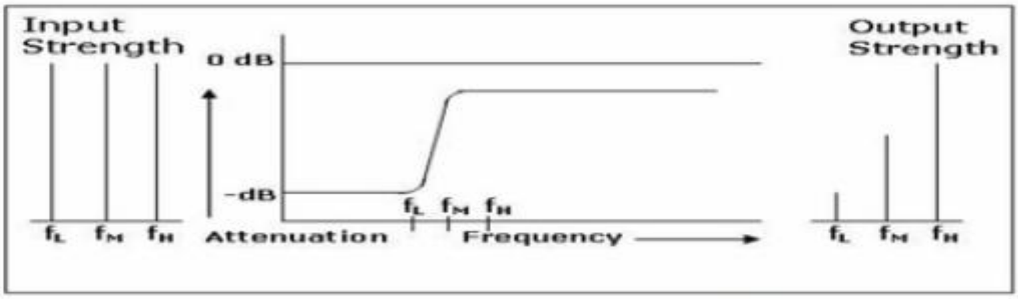


Figure 3.2 HPF frequency response [4]

3. **Band Pass Filter (BPF)** does not allow the signal whose frequency is either below the lower cutoff frequency of the filter or above the higher cut off frequency of the filter. Figure 3.3 shows frequency response spectrum for BPF.

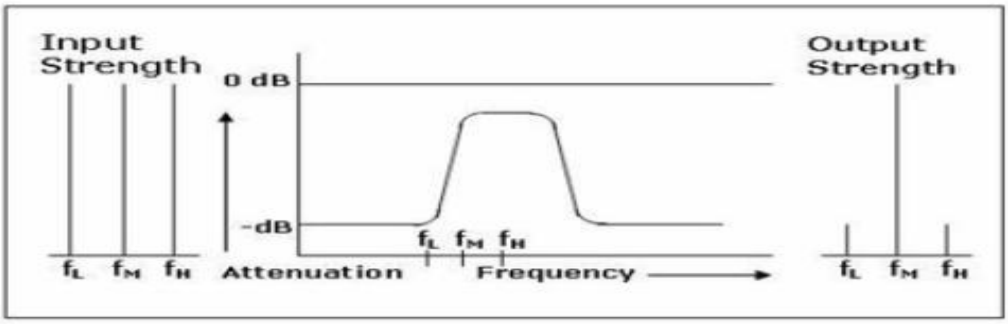


Figure 3.3 BPF frequency response [4]

4. **Band Stop Filter (BSF)** does not allow the signals to pass whose frequency lies between the filter lower cutoff frequency and higher cutoff frequency. Figure 3.4 shows the frequency response spectrum for BSF.

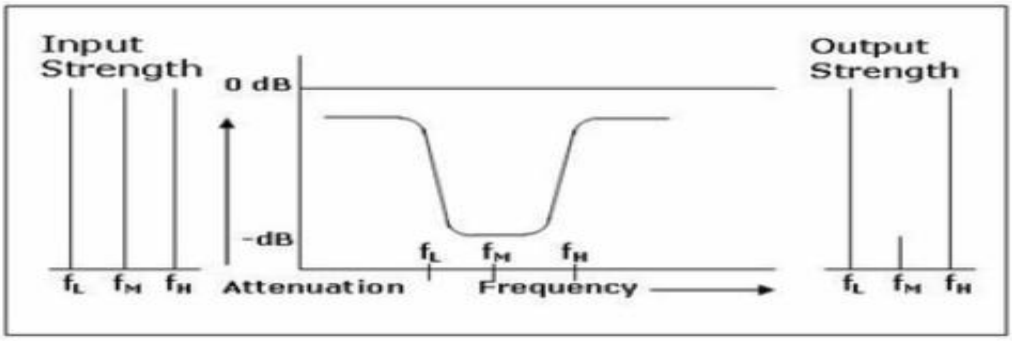


Figure 3.4 BSF frequency response [4]

3.2 BASIC TYPES OF FILTER

Generally a filter is considered to ideal when it gives a maximally flat pass band and stop band region. The attenuation should be minimum or rather zero in the passband and should be large in its stop band only then the ideal characteristics of the filter are satisfied. Filters generally are classified in many ways but the classification utilized in antenna study is generally Butterworth and Chebyshev filter distribution.

- Butterworth filters are a special type of filter which has a flat response of pass band and stop band characteristics so they are generally termed as “Maximally flat filters”
- Chebyshev filters have a pass band with all equal ripples and generally a flat stop band response in its frequency spectrum.

3.3 PARAMETERS OF FILTER

There are certain set of parameters on which any filter is characterized and are distinguished from each other in any respect. Figure 3.5 describes the frequency response of filter. The parameters certainly used in filter designing and characterizing are given below:

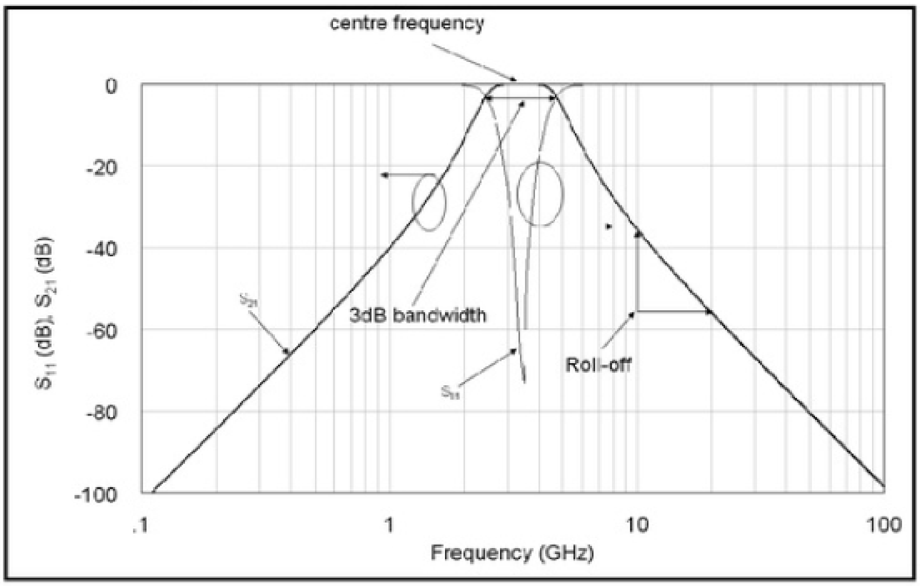


Figure 3.5 Parameters of filter in its frequency response curve [24]

- 3-dB bandwidth either for pass band or stop band
- Ripple content in the pass band or stop band
- Insertion loss of filter
- Resonant frequency
- Lower and Upper Cut off frequency
- 10-dB bandwidth of stop band
- Attenuation
- Order or roll off of the filter used i.e. whether the filter is of first, second or any higher order filter in order to use the filter in its required application. It is generally determined by either 6-dB octave or 20 dB octave

3.4 FILTER APPLICATIONS

Further in this thesis it is shown that filters play a major role in the study of antenna and microwave engineering. Filters have also shown a vast development in transmission and waveguide field of microwave physics. Microwave filters have grabbed enormous attention of various researchers in 20th century because of its high applications used in GSM, WLAN, X-band.

Although the filters have great application in communication but the most common application is its ability to allow certain frequencies to pass and rejecting all other frequencies in the huge frequency band region. This application has an advantage in many field, the most prominent is it saves power and energy.

3.5 EBG USED FOR DESIGNING MICROWAVE FILTERS

Here in this thesis we will go through the filters in which EBGs are incorporated for making their design. Before proceeding to the design of the filter we will discuss some of the basic features of any filter. The basic features of any filter are:-

- Filters usually combine two signals or separate two signals according to the frequency requirements of the circuit.
- Filters has a great advantage to eliminate any signal in of the stop band
- Filters perform the impedance matching of the circuit

- Filters main feature is to minimize all kind of losses present in the circuit thereby improving the factors like noise margin when the circuit is used with the receiver.
- One filter is used before a mixer element and one after it in order to cut down the false signals in the circuit.

As discussed above EBG is a repeated structure design which has an ability to suppress the surface waves present above the ground plane. The first job of EBG when came into being was just to suppress the surface wave in patch antenna design but later the study has extended to use the EBG in filter design in order to reduce the crosstalk and mutual coupling in the antenna array thus giving better results of gain and efficiency due to the impedance matching. Generally the EBG structure is designed in the ground plane but can also be extended on the top surface of the substrate. To start the thesis firstly a simple design of EBG is utilized to form a low pass filter and band stop filter with an improved bandwidth and a better response as compared to their reference paper. Before starting up with the thesis let us look in a short review of mushroom like EBG used in antenna designing.

3.6 INTRODUCTION OF MUSHROOM-TYPE (EBG) STRUCTURE

Mushroom like EBG is a special type of EBG structure which is a periodic pattern of patches made on the upper side of the substrate and the patches are connected with a ground plane with a vias connected with each individual patch. The vias behaves

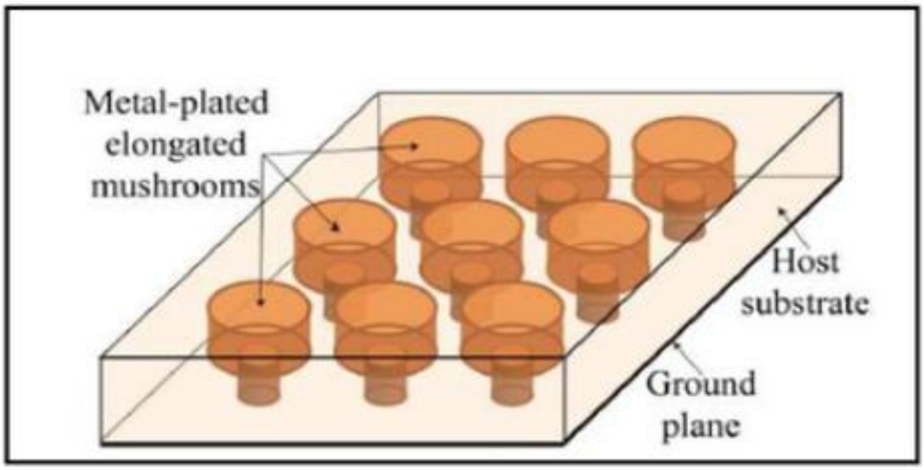


Figure 3.6 Design of mushroom-like EBG structure [5]

as an inductance L and the spacing between every two alternate patch behaves as a capacitance C thus forming a complete LC distributed network structure. This special type of EBG results in a very high impedance surface. The high impedance is maintained only due the LC distributed network which acts as a filter thus operating at a resonant frequency. Figure 3.6 gives a simple picture of a mushroom like EBG.

An equivalent model of mushroom like EBG is shown in figure 3.7. The model described below is usually used to improve the efficiency of antenna and in result improves the noise margin.

The space between patch and plane is given by t_1 which forms a capacitance C_1 as it maintains a difference in the electric energy of the two metallic conducting plates. The capacitance C_1 is given as

$$C_1=\frac{\varepsilon_0 \varepsilon_e d^2}{t_1} \tag{3.1}$$

where ε_e is effective relative dielectric permittivity, d is patch width and t_1 is space between the plane and patch.

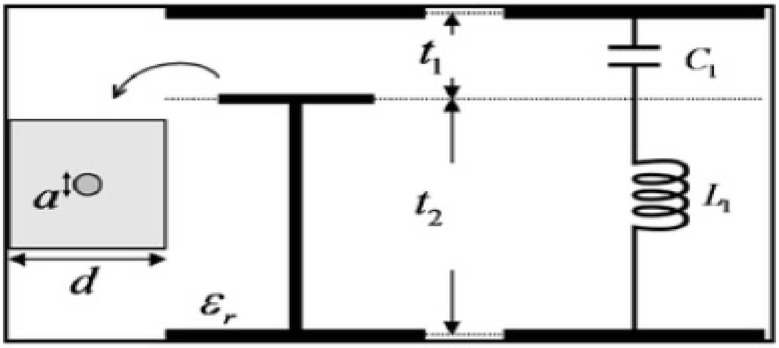


Figure 3.7 Equivalent model of mushroom type EBG [4]

Similarly, the inductance L_1 produced due to the current passing through the vias as

$$L_1=\mu_0 \frac{t_2}{4\pi} \left[\ln\left(\frac{1}{\beta}\right) + \beta-1\right] \tag{3.2}$$

t_2 is the space between the ground plane and the patch

$\beta= \pi\frac{a^2}{d^2}$ describes the ratio of diameter of a single vias to that of its unit cell

The resonate frequency is therefore given as

$$f_r = \frac{1}{2\pi C_1[L_1 + \frac{\mu_0 h}{4}]} \tag{3.3}$$

The above equation gives the resonant frequency of the filter according to which the high impedance value of the circuit is achieved.

Chapter 4

EBG BASED LOW PASS AND ALL PASS FILTER

4.1 EBG UNITS USED TO DESIGN LOW PASS FILTER STRUCTURE

4.1.1 Uniform U-Shaped LPF Designed with Squared EBG Structure

In figure 4.1 the uniform u-shaped LPF is designed by etching squares in the ground plane. In the structure below the u-shaped line acts as a microstrip feed line which are connected to ports individually.

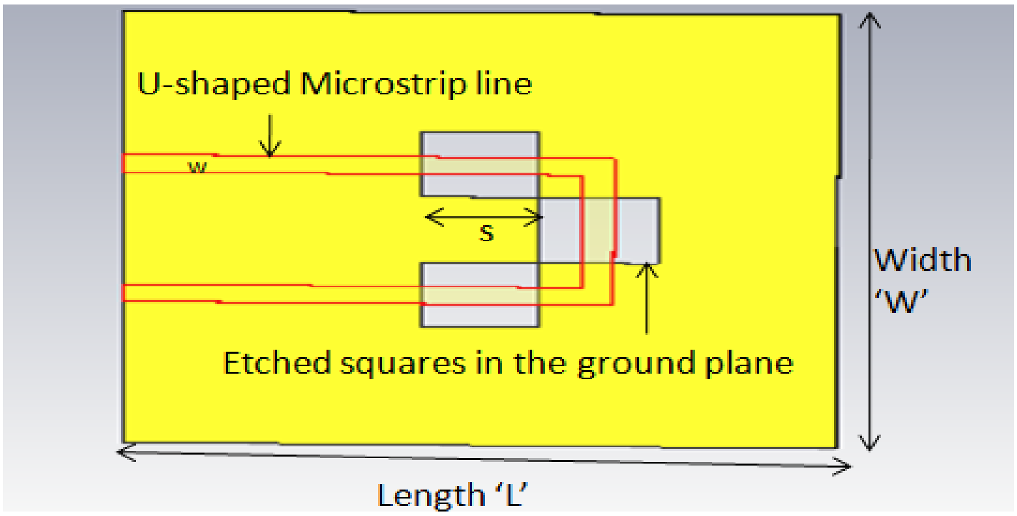


Figure 4.1 Low pass filter design with squares etched in the ground plane

The red line which acts as MLIN (microstrip feed line) is separated from the holes by a dielectric material named Taconic TLT-0 and an epsilon value (ε_r) of 2.45. W and L define the width and length of the substrate material respectively. The length L of the substrate is taken as 46 mm, width W is taken as 41mm and the thickness is taken as 0.76

mm. Table 4.1 gives the complete description of all the dimensions used to design the U-Shaped LPF filter.

Table 4.1 Dimensions of U-shaped LPF structure with squared EBG in the ground plane

Substrate Used	**Taconic TLT-0**
Dielectric constant (‘ε_r’)	2.45
Substrate height (‘h’)	0.76 mm
Length ‘L’	46 mm
Width ‘W’	41 mm
Frequency range	0-11 Ghz
Center frequency	5.5 Ghz
Side of square (‘s’)	5 mm

4.1.2 Simulated Results of U-Shaped LPF with Squared EBG Structure

The figure 4.2 shows the insertion loss (S21) result of U-shaped low pass filter structure with a frequency range of 0-11 Ghz. Similarly figure 4.3 shows its

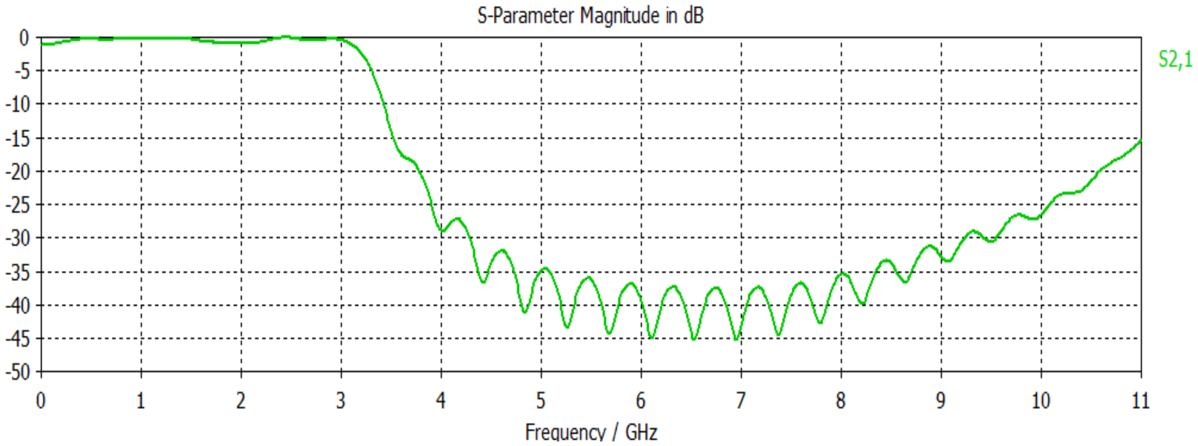


Figure 4.2 Simulated S21 result for U-shaped MLIN LPF structure

return loss (S11) result with the same frequency range. Table 4.2 gives the result parameters calculated by the curves given below.

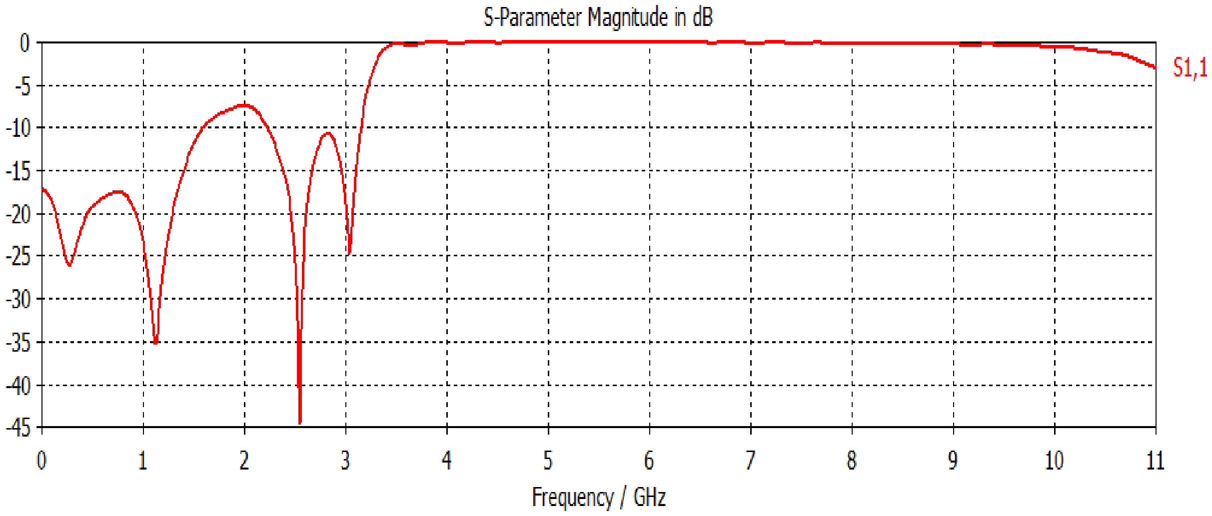


Figure 4.3 Simulated S11 result for U-shaped MLIN LPF structure

Table 4.2 Simulated result of U-shaped MLIN EBG based LPF

Parameters	**U-shaped microstrip line square EBG based LPF**
25-dB bandwidth (GHz)	3.85
Ripple level (dB)	0.75

4.1.3 U-Shaped LPF Design with Chebyshev Squared Tapered EBG Structure

The figure 4.4 given below shows the modified design of low pass filter with Chebyshev tapered squares in the ground plane. The figure describes the side of the etched square as ‘s’, the distance between the square on the front plane is given as ‘a’ and the distance between the etched square and the square present on the front plane is given as d. Table 4.3 gives the tapering coefficient of Kaiser and Chebyshev distribution function. Table 4.4 gives the complete description of dimension for the above modified low pass filter design.

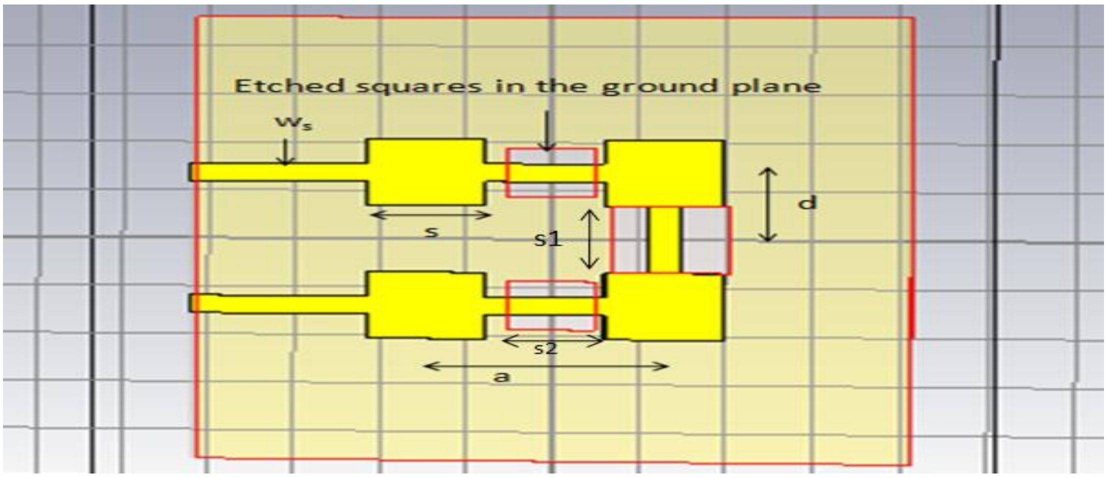


Figure 4.4 Design of U-shaped LPF structure with Chebyshev tapered squares

Table 4.3 Values of Chebyshev and Kaiser tapered coefficients

Type of tapering function	$T(y_1)$	$T(y_2)$	$T(y_3)$
Kaiser	0.94	0.58	0.16

Type of tapering function	a_1	a_2	a_3
Chebyshev	1	0.73	0.39

Table 4.4 Dimensions of LPF with Chebyshev tapered squares in the ground plane

Substrate Used	**Taconic TLT-0**
Dielectric constant (ε_r)	2.45
Substrate height (h)	0.76 mm
Length ‘L’	46 mm
Width ‘W’	41 mm
Frequency range	0-11 Ghz
Center frequency	5.5 Ghz

Side of square (s)	6.89 mm
Distance between the squares on front plane (a)	13.78 mm
Side of square on front plane	6.89 mm
Side of square etched in the ground plane (s1)	5.02 mm
Side of square etched in the ground plane (s2)	3.67 mm

4.1.4 Simulated Results of U-Shaped LPF with Chebyshev Tapered EBG Squares

The figure 4.5 shows the simulated insertion loss (S21) result of U-shaped Chebyshev tapered non uniform low pass filter structure with a frequency range of 0-11 GHz. Similarly figure 4.6 shows its return loss (S11) result with the same frequency range. Table 4.5 shows the result parameters of the above filter.

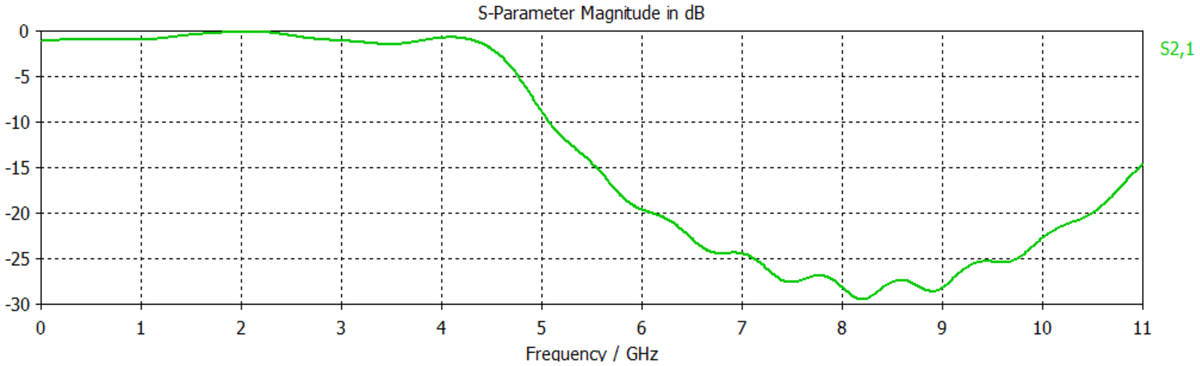


Figure 4.5 Simulated S21 result for U-shaped Chebyshev square tapered EBG LPF

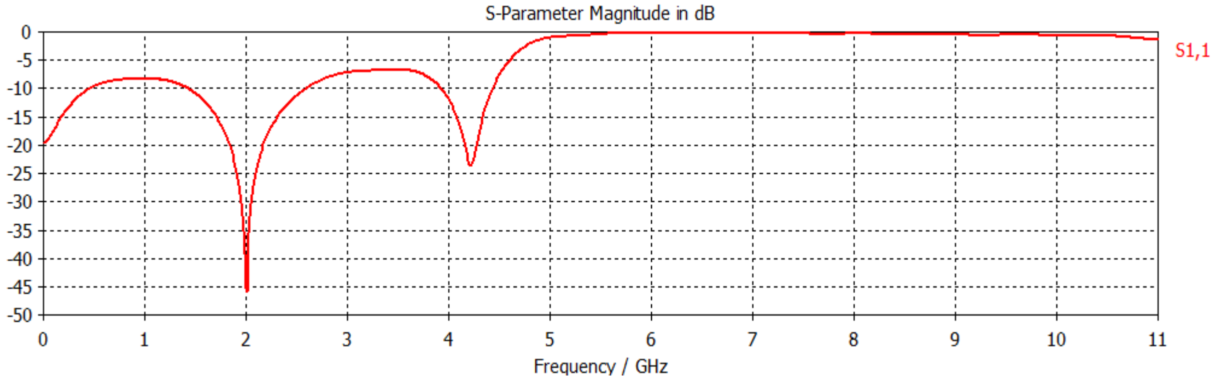


Figure 4.6 Simulated S11 result for U-shaped Chebyshev square tapered EBG LPF

Table 4.5 Simulated result of U-shaped Chebyshev square tapered EBG based LPF

Parameters	U-shaped Chebyshev square tapered EBG Low Pass Filter
25-dB bandwidth (GHz)	7.1
Ripple level (dB)	1.5

4.1.5 Comparison of U-shaped and Chebyshev Square tapered EBG Low Pass Filter

Table 4.6 gives the comparison of parameters for U-shaped LPF structure and Chebyshev Square tapered EBG Low Pass Filter.

Table 4.6 Comparison of U-shaped LPF structure and Chebyshev Square tapered EBG Low Pass Filter

Parameters	U-shaped microstrip line square EBG based LPF	U-shaped Chebyshev square tapered EBG LPF
25-dB bandwidth (GHz)	3.85	7.1
Ripple level (dB)	0.75	1.5

4.2 EBG USED TO DESIGN ALL PASS FILTER STRUCTURE

4.2.1 Design of All Pass Filter with Chebyshev Squared Tapered EBG Structure

Figure 4.7 gives the design of all pass filter structure with EBG units in its ground plane. The EBG units etched in the ground plane comprises of etched squares according to the Chebyshev tapered coefficient function. MLIN is designed on the front plane of the substrate with the ports on the two opposite sides of the microstrip line. In the figure ‘a’ gives the distance calculated between the centers of the etched squares in the ground plane, ‘s’ gives the side of the etched square situated in the center. According to the side of the center square the sides of all the other squares are calculated by using the Chebyshev coefficient tapering function. The table 4.7 gives the detailed description of the dimensions used in order tom design the all pass filter structure.

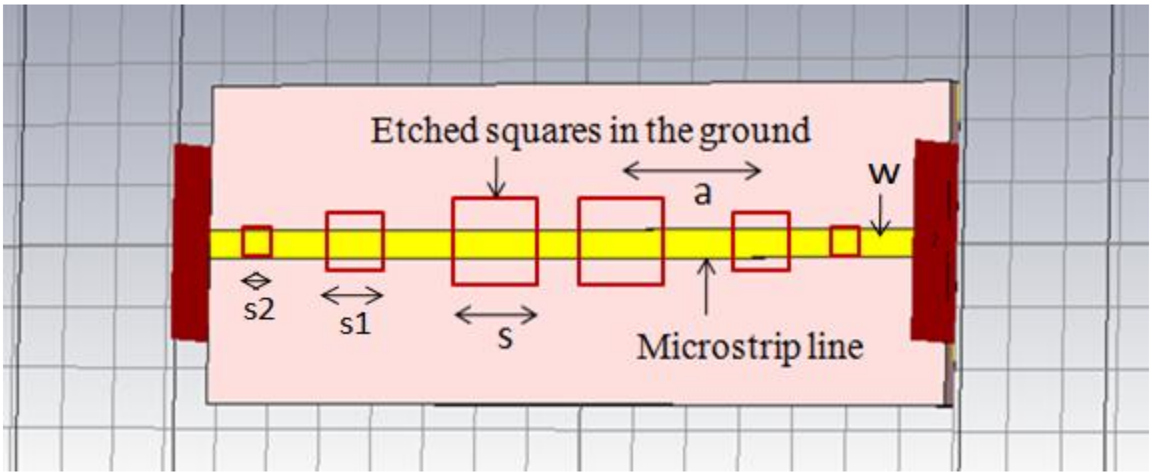


Figure 4.7 Design of all pass filter structure with EBG units in the ground plane

Table 4.7 Dimension of all pass filter structure

Substrate Used	Fr4
Dielectric constant (ε_r)	4.7
Length ‘L’	70 mm
Width ‘W’	26 mm
Frequency range	4-16 Ghz
Center frequency	10 Ghz
Side of square (s)	3.64 mm
Distance between the squares on front plane (a)	7.27 mm
Side of square etched in the ground plane (s_1)	3.64*0.73=2.6572 mm
Side of square etched in the ground plane (s_2)	3.64*0.39=1.4196 mm

4.2.2 Simulated Result of All Pass Filter

The figure 4.8 and 4.9 shows the simulated insertion loss (S12) and return loss (S11) result of all pass filter structure with a frequency range of 4-16 Ghz.

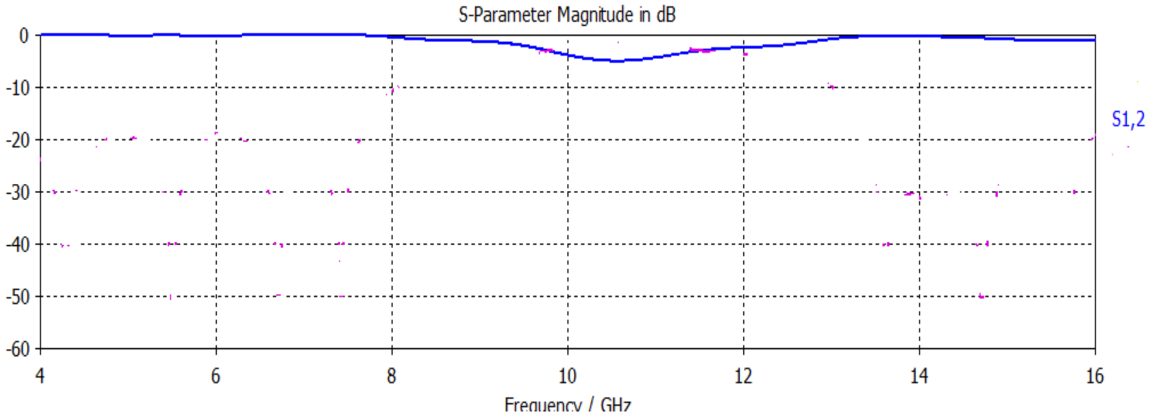


Figure 4.8 Simulated S12 result for all pass filter structure

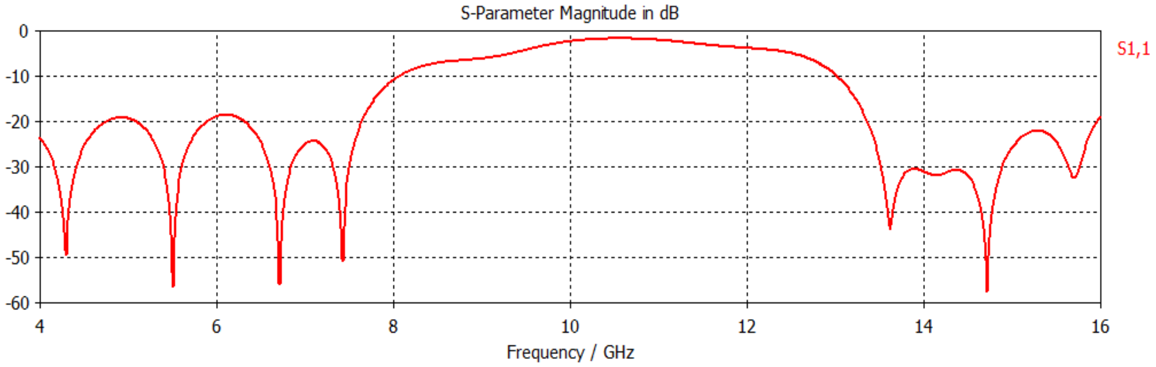


Figure 4.9 Simulated S11 result for all pass filter structure

Chapter 5

EBG BASED BAND STOP FILTER

5.1 BAND STOP FILTER WITH SQUARED EBG STRUCTURE

In this section band stop filter structure with squared EBG is designed and the simulated results of it are discussed below. It gives the complete description of all the dimensions for the design and later the result parameters.

5.1.1 Design of Band Stop Filter with Squared EBG Structure

Figure 5.1 (a) and 5.1 (b) shows the top view and bottom view of compact EBG microstrip structure respectively. They describe two single plane EBG structures:

a) Ground plane with etched squares.
b) Modulated microstrip line.

Between ground plane and microstrip line there is a substrate with 'ε_r' as its dielectric constant and thickness as 'h'. Etching squares in the ground plane results in reduced coupling between the modulated microstrip line and ground plane. Here we take distance between the squares center as the structure period and is denoted as 'd_1'. Using Bragg reflection condition, 'd_1' is represented by

$$\beta \, . \, d_1 = \pi \tag{5.1}$$

where 'β' is the guided wave number and is given as

$$\beta = \frac{2\pi}{\lambda} \tag{5.2}$$

where 'λ' is the guided wavelength given by

$$\lambda = \frac{c}{f.\sqrt{\varepsilon_{eff}}} \tag{5.3}$$

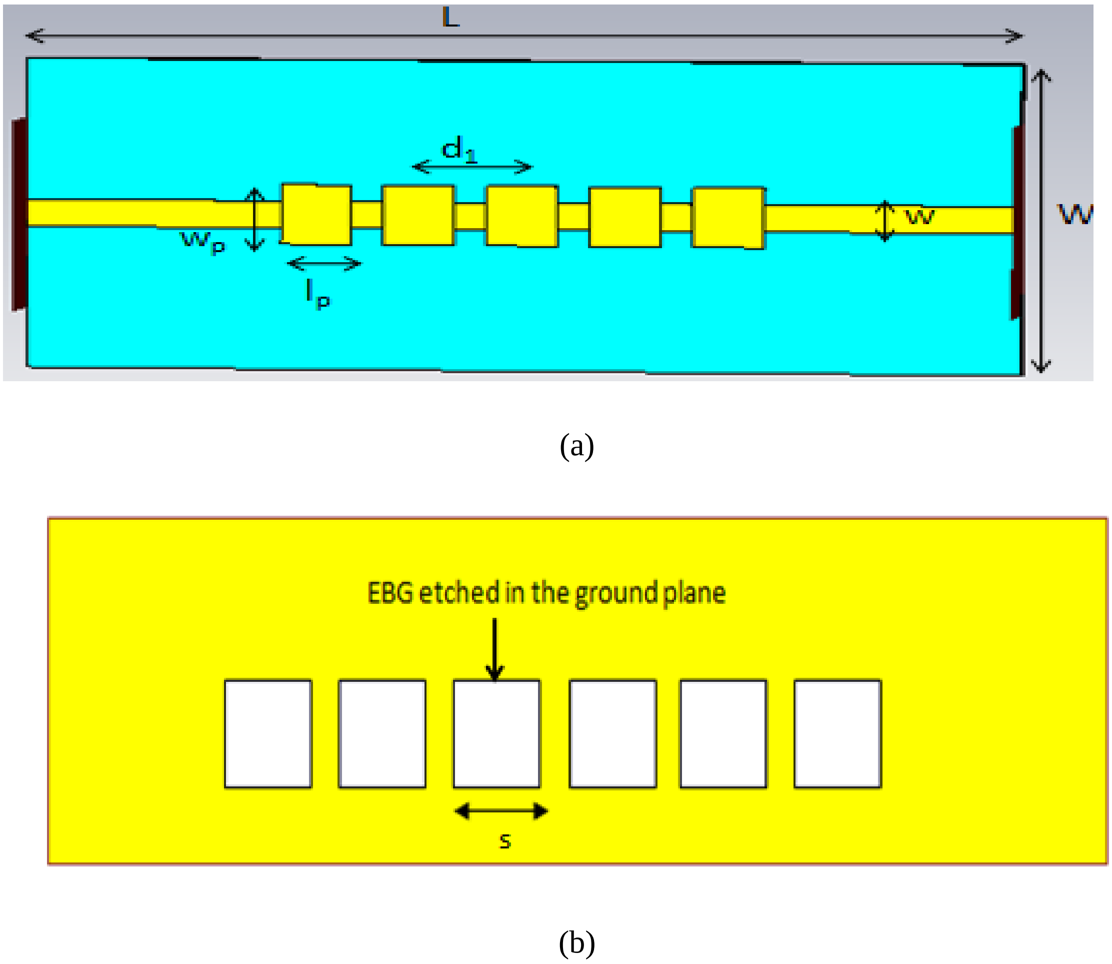
where 'f' describes the center frequency in the stop band region, 'ε_{eff}' is the effective permittivity of the substrate and 'c' is the speed of light.

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+\frac{12*h}{w}\right]^{\frac{-1}{2}} \tag{5.4}$$

Now we know 'd_1' is

$$d_1 = \frac{\lambda}{2} \tag{5.5}$$

The side of square is given by 's' and s=2*r, where 'r' is the radius of the circle which is an incircle to the square. The ratio of 'r' and 'd_1' (r/d_1) is given as Aspect ratio



(a)

(b)

Figure 5.1 Squared-EBG bandstop filter structure (a) Top view (b) Bottom view

(AR). The AR defines the EBG cell size relative to that of the substrate period. Generally the range of AR is taken from 0 to 0.5 when overlapping of adjacent squares is not considered. The large AR gives a wide stop band but in result increases ripples in the passband. So generally a compromise is made between wide stop band and less ripples.

Here we take the length and width of patch as ‘l_p’ and ‘w_p’ and width of microstrip line as ‘w’. Figure 5.1 (a), (b) gives the Top view and the bottom view of bandstop filter. The filling factor is taken as 0.25. The squares etched in the ground plane where the side of square is given as ‘s’ and calculated by s=2*r and ‘r’ is calculated by filling factor. Here we take width of the feed line w to be always greater than the width of the patch ‘w_p’. In figure 5.1(b) the squares shows the etched squares in the ground plane of the substrate. The substrate used is Fr4 with ‘ε_r’ =4.7 thickness of substrate ‘h’=1.6. The centre frequency is taken as 10 Ghz. In consideration with Bragg reflection condition the structure period is calculated as d_1=7.27 mm. The feed line width ‘w’ is taken as 2.29 mm. By taking the AR as 0.25 the resultant radius of the circle from which the side of the square is calculated is taken as 1.82 mm. ‘l_p’ and ‘w_p’ are fixed as 5 mm each. Table 5.1 gives the complete description of the required dimensions used to design the above filter.

Table 5.1 Dimension of Squared-EBG bandstop filter structure

Substrate Used	Fr4
Dielectric constant (‘ε_r’)	4.7
Substrate height (‘h’)	1.6 mm
Length ‘L’	70 mm
Width ‘W’	35 mm
Frequency range	4-16 Ghz
Center frequency	10 Ghz
Side of square (‘s’)	5 mm
Distance between the squares on front plane (‘a’)	13.78 mm
Side of square on front plane ,l_p’ and ‘w_p’	5 mm

5.1.2 Simulated Results of Band Stop Filter with Squared EBG Structure

To authenticate the above analysis the design is made on CST microwave studio software 2010. A 3-d structure is bent by using a defected ground plane structure on one plane and microstrip line on a different plane. Figure 5.2 shows the insertion loss (S21) and Figure 5.3 shows the return loss (S11) of the proposed uniform EBG band stop filter. The insertion loss (S21) gives large ripple content in its stop band region. In order to minimize the ripple content in the stop band tapering technique is employed in the subsequent sections in this thesis. Table 5.2 gives the values of parameter for EBG based BSF.

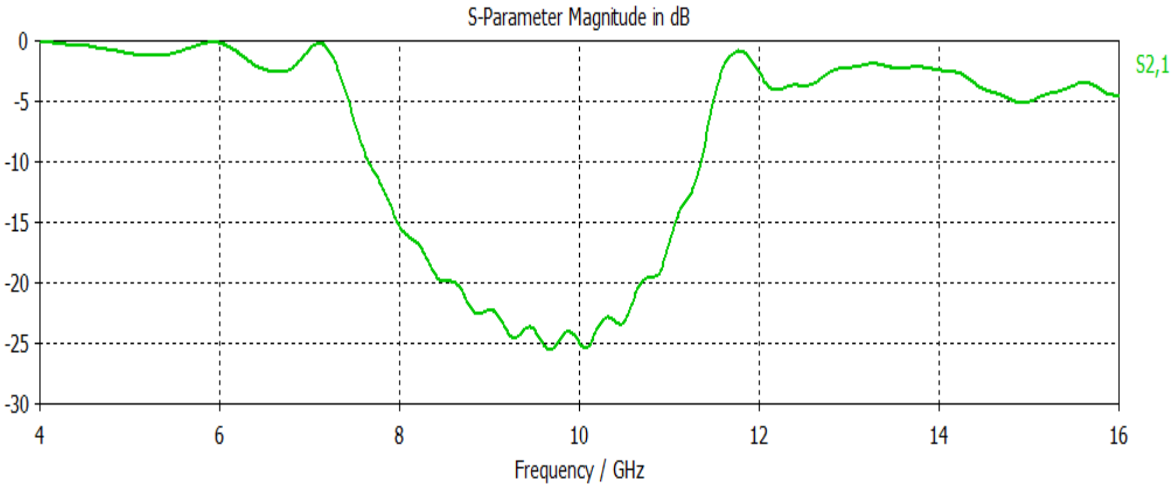


Figure 5.2 Insertion loss (S21) of uniform EBG band stop filter structure

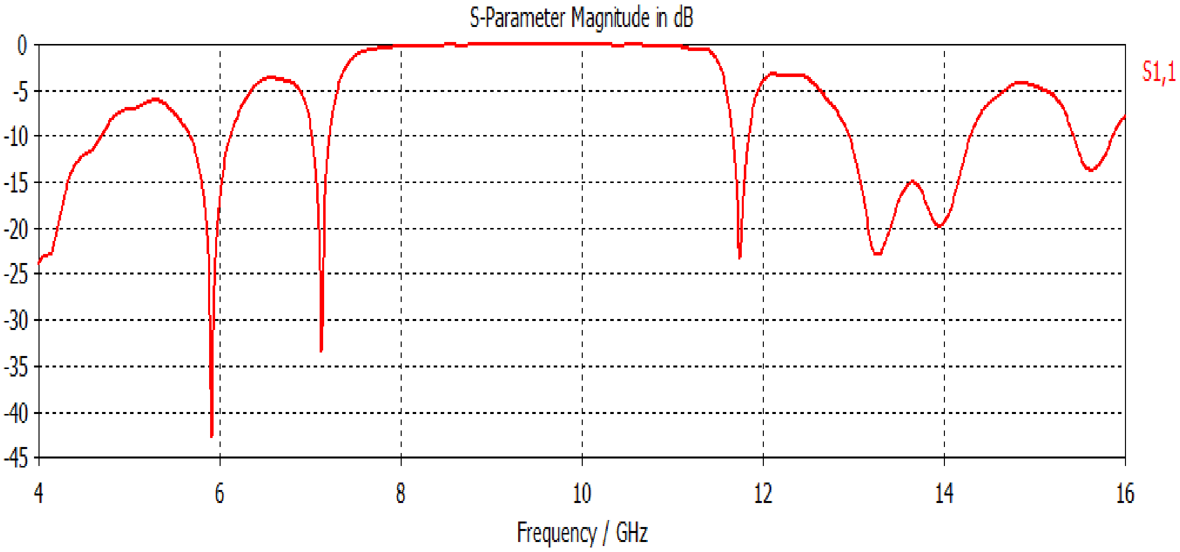


Figure 5.3 Return loss (S11) of uniform EBG band stop filter structure

Table 5.2 Simulated results of EBG based bandstop filter

Parameters		Square Tapered EBG based Band Stop Filter
10-dB bandwidth (GHz)		3.75
Ripple level (dB)	Lower	3.34
	Higher	4.75
Attenuation (dB)		>24
Side lobe Level (dB)	Lower	>3
	Higher	>2

5.2 TAPERING TECHNIQUES

It has been examined in [13] that tapering techniques are capable of minimizing the ripples present in the passband. In some techniques tapering is done by using tapering functions such as Hamming and Hanning tapering functions. Tapering is also done by adopting low sidelobe level array technique. It includes Dolph-TsChebyshev array also called Chebyshev array and Binomial array.

In case of 1-D planar EBG structure when there is an etching of single column of square in its ground plane square side calculated by s=2*r where r is the radius of the circle and is calculated by using a tapering function $T(y_k)$ as

$$a_k=a_c * T(y_k) \tag{5.6}$$

it is further deduced by

$$a_k=a_c * c_k \tag{5.7}$$

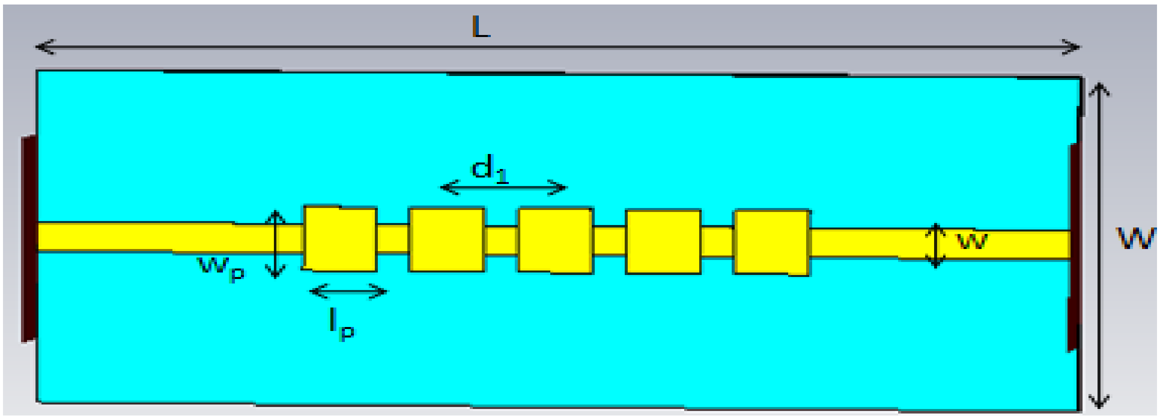
here k is an integer which varies its value from 1 to p/2 where p is an even number and it varies from 1 to (p+1) where p is odd number. a_k defines the radius of *k*th circle and a_c

defines the radius center circle. Here y_k defines the distance from center of the square to that of the *k*th square form by *k*th circle.

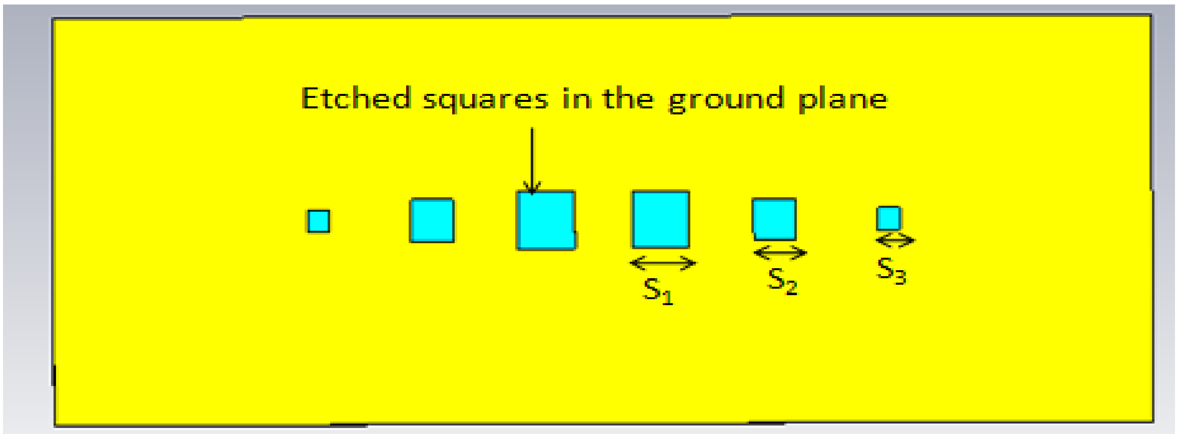
5.3 TAPERING TECHNIQUE USED TO DESIGN EBG BASED BANDSTOP FILTER

5.3.1 Design of Chebyshev Square Tapered EBG Based Band Stop Filter

Figure 5.4 (a) and (b) shows the top and bottom view of Chebyshev square tapered EBG based bandstop filter. In this the bottom layer is different from the above filter in the respect that here Chebyshev tapered etched squares are inserted in the ground plane.



(a)



(b)

Figure 5.4 Chebyshev square tapered EBG bandstop filter structure (a) Top view (b) Bottom view

Table 5.3 gives the complete description of all dimensions used to design the Chebyshev squared tapered EBG bandstop filter. Table 5.4 gives the sides of square calculated by the radius of the respective circle.

Table 5.3 Dimension of Chebyshev square tapered EBG band stop filter structure

Substrate Used	Fr4
Dielectric constant (‘ε_r’)	4.7
Substrate height (‘h’)	1.6 mm
Length ‘L’	70 mm
Width ‘W’	35 mm
Frequency range	4-16 Ghz
Center frequency	10 Ghz
Side of square on front plane ‘l_p’ and ‘w_p’	5 mm

Table 5.4 Sides of squares calculated by using Chebyshev function

Radius of incircle to the square	**Side of Square formed by radius of incircle (2*r)**
R1=1.82	S1=3.64
R2=1.33	S2=2.66
R3=0.71	S3=1.42

5.3.2 Simulated Result of Chebyshev Square Tapered EBG Based Band Stop Filter

To authenticate the above analysis the design is made on CST microwave studio software. Figure 5.5 shows the insertion loss (S12) and Figure 5.6 shows the return loss (S11) of the proposed Chebyshev squared tapered EBG band stop filter. Table 5.5 gives the values of simulated result of the above proposed filter.

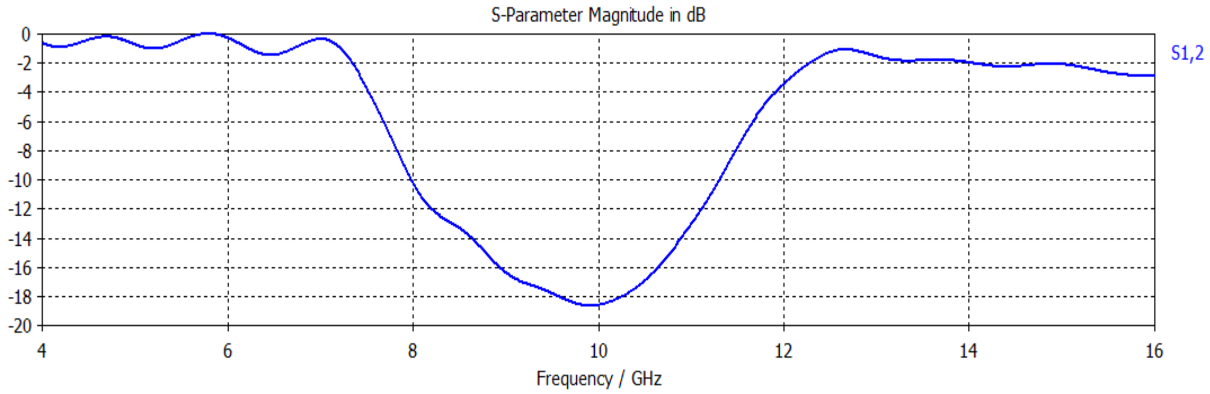


Figure 5.5 Simulated Insertion loss (S12) of Chebyshev square tapered EBG bandstop filter

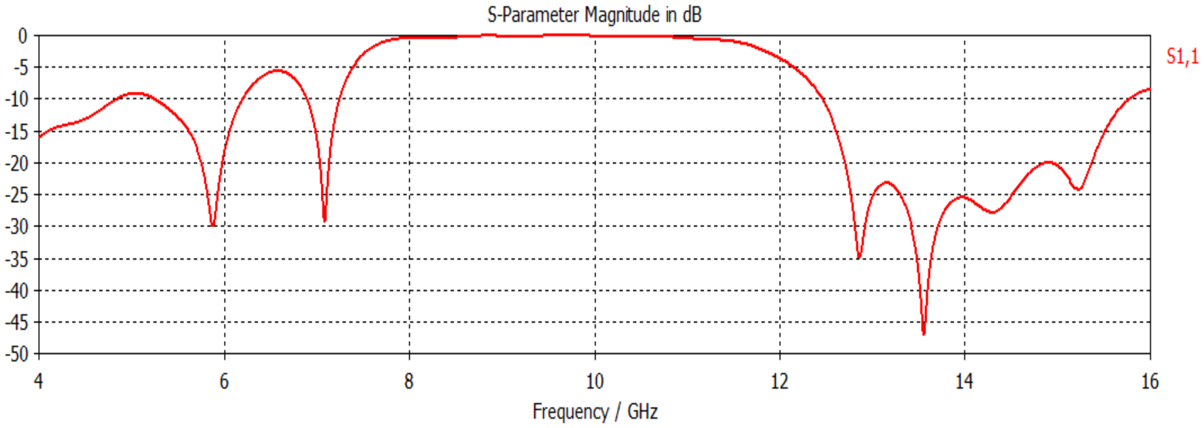


Figure 5.6 Simulated return loss (S11) of Chebyshev square tapered EBG bandstop filter

Table 5.5 Simulated results of Chebyshev squared tapered EBG bandstop filter

Paramteres		**Square Chebyshev Tapered Band Stop Filter**
10-dB bandwidth (GHz)		3.57
Ripple level (dB)	Lower	1.85
	Higher	2.12
Attenuation (dB)		>15
Side lobe Level (dB)	Lower	>4

	Higher	>22

5.3.3 Fabrication and Testing of Chebyshev Square Tapered EBG based Bandstop Filter

The fabrication of Chebyshev square tapered ground plane band stop filter is done by using Fr4 as its substrate which is two sided copper plated. The fabrication of the filters is shown and its results are discussed in the subsequent sections. The results of fabricated filter are checked on vector analyser. In the last the measured and simulated results are compared with each other and the results are further tabulated together.

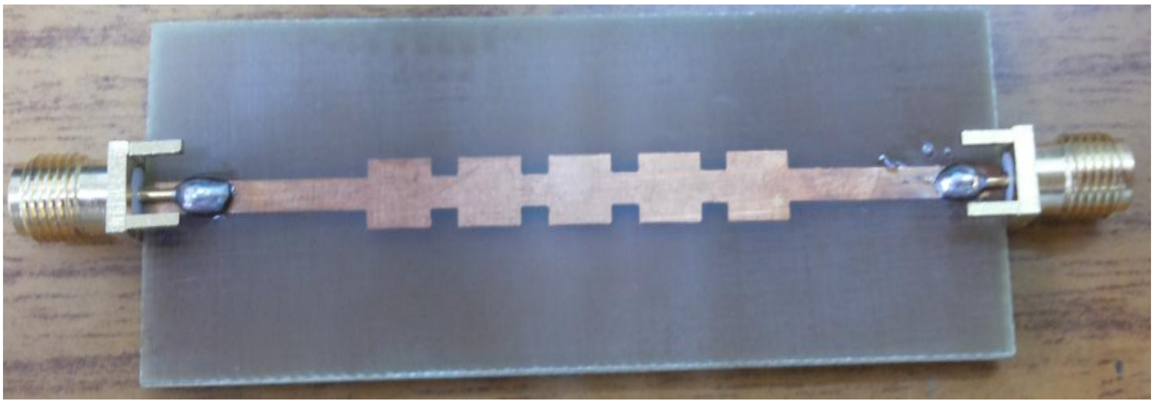


Figure 5.7 Top view of Chebyshev square tapered EBG bandstop filter

The fabrication of Chebyshev tapered squares in ground plane is shown in figure 5.7 and 5.8. The structures are highly compact with 70 mm by 26 mm as its dimension.

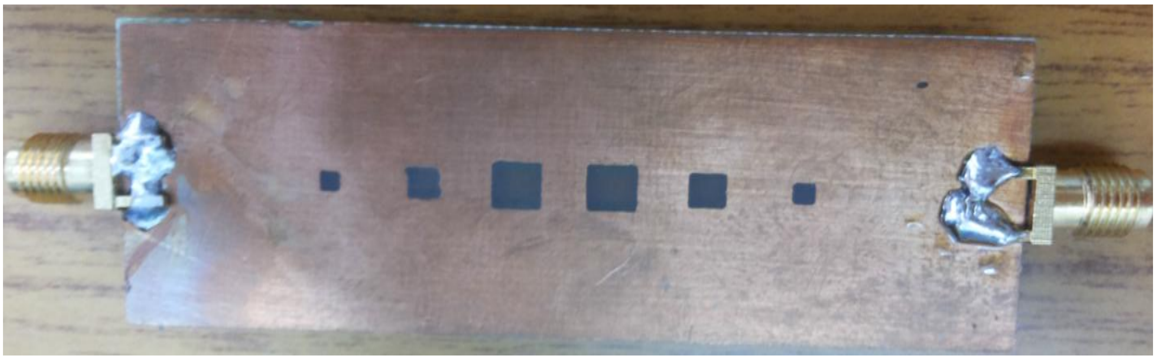


Figure 5.8 Bottom view of Chebyshev square tapered EBG bandstop filter

5.3.4 Comparison of Measured and Simulated Result of Chebyshev Square Tapered EBG Bandstop Filter Structure

A comparison of measured and simulated result of Chebyshev square tapered EBG bandstop filter are combined together on one scale by using matlab 2010 software.

Figure 5.9 gives the comparison of measured and simulated result of S21 parameters for Chebyshev square tapered EBG bandstop filter structure.

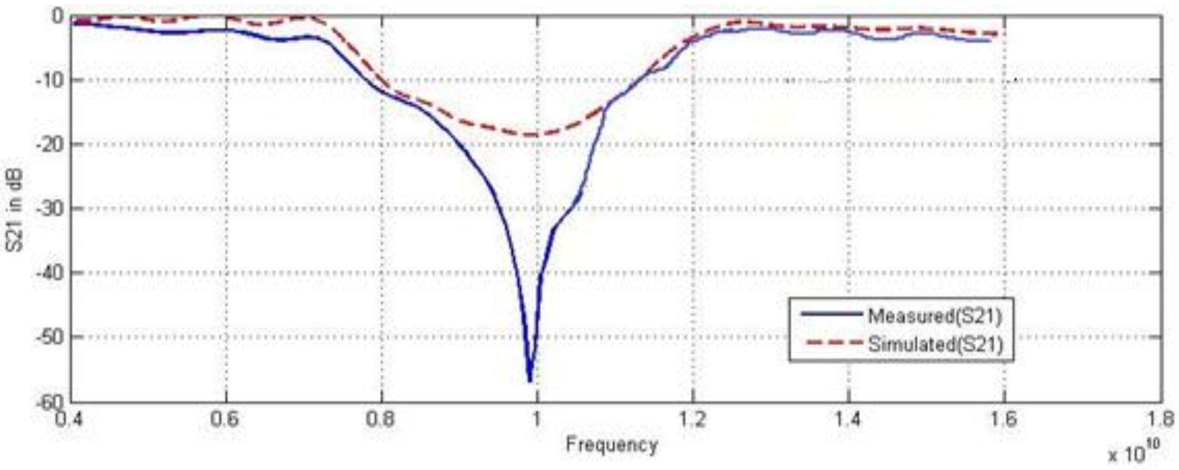


Figure 5.9 Comparison of measured and simulated result of S21 parameters for Chebyshev square tapered EBG bandstop filter structure.

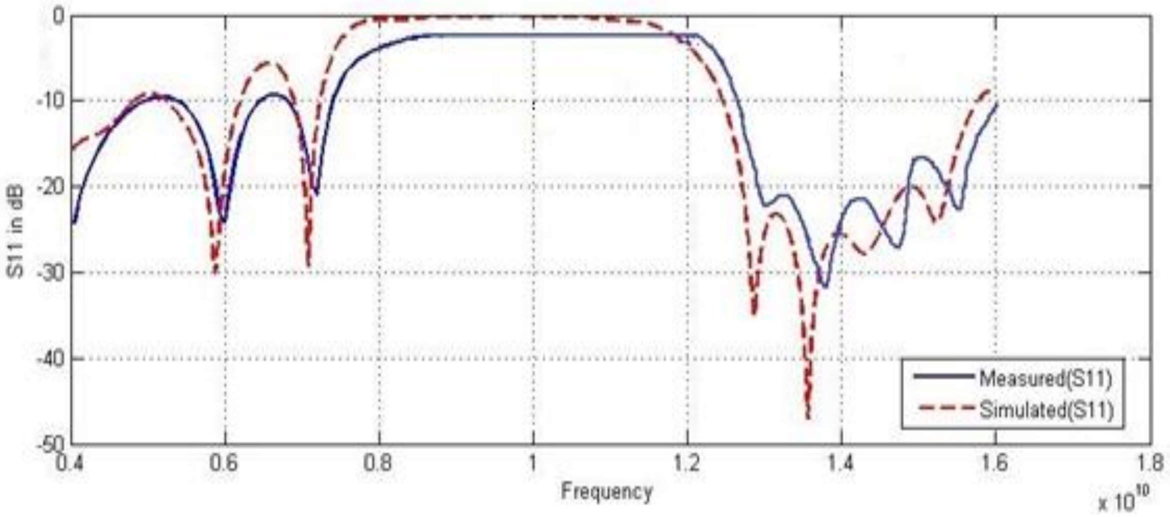


Figure 5.10 Comparison of measured and simulated result of S11 parameters for Chebyshev square tapered EBG band stop filter structure.

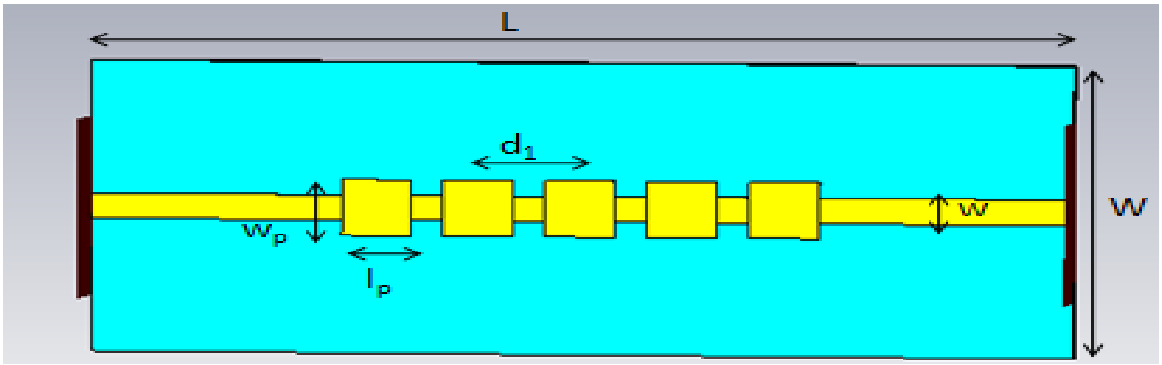
Figure 5.10 gives the comparison of measured and simulated result of S11 parameters for Chebyshev square tapered EBG bandstop filter structure. Table 5.6 gives the comparison between the simulated and measured results of the Chebyshev square tapered EBG band stop filter.

Table 5.6 Comparison of measured and simulated results of Chebyshev square tapered EBG Bandstop filter

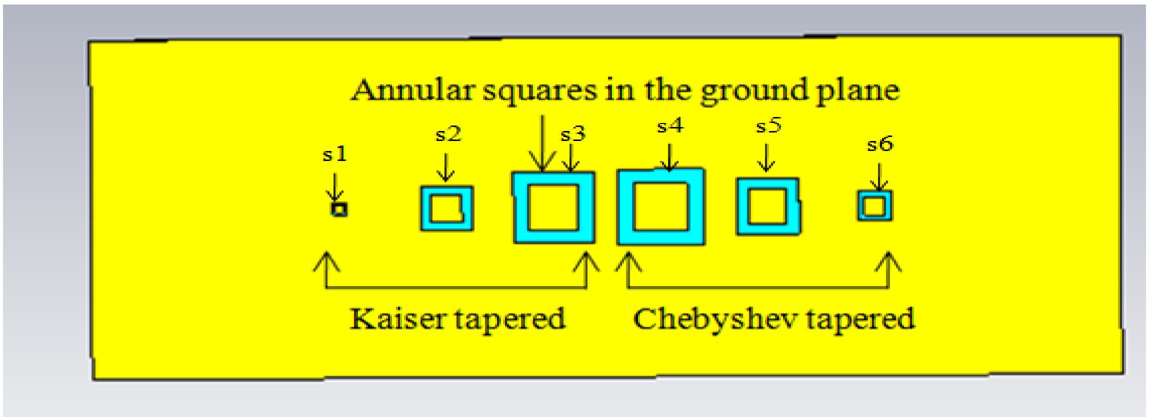
Parameters	Measured Results	Simulated Results
10-dB Bandwidth (Ghz)	3.57	3.62
Ripple level (lower) (dB)	1.85	2.93
Ripple level (higher) (dB)	2.12	3
Resonate frequency (Ghz)	10	9.67
Sidelobe level (lower) (dB)	>4 dB	>8 dB
Sidelobe level (higher) (dB)	>22 dB	>20 dB
Attenuation (dB)	>15 dB	>55 dB

5.3.5 Design of Annular Chebyshev and Kaiser Square Tapered EBG Band stop Filter

The design of annular Chebyshev and Kaiser square tapered EBG band stop filter structure is shown in figure 5.11.



(a)



(b)

Figure 5.11 Annular Chebyshev and Kaiser square tapered EBG bandstop filter structure (a) Top view (b) Bottom view

Figure 5.11 (a) gives the top view of the filter structure and 5.11 (b) gives the bottom view of the proposed filter structure.

The table 5.7 gives the complete description of dimensions for annular Chebyshev and Kaiser square tapered EBG bandstop filter. 5.8 and table 5.9 gives the complete description of radius of circle from which the square is generated with aspect ratio 0.25 and 0.4 respectively.

The figure shown above describes the top view same as the above mentioned design but has a different bottom view of the ground plane. Here the left three squares are Kaiser tapered and right three squares are Chebyshev tapered annular squares.

Table 5.7 Dimension of annular tapered ground plane C-EBG band stop filter structure

Substrate Used	Fr4
Dielectric constant (ε_r)	4.7
Substrate height (h)	1.6 mm
Length ‘L’	70 mm

Width ‘W’	35 mm
Frequency range	4-16 Ghz
Center frequency	10 Ghz
Side of square on front plane l_p and w_p	5 mm

Table 5.8 Sides of inner patched squares in the ground plane with aspect ratio 0.25

Kaiser Tapered		**Chebyshev Tapered**	
Left three squares(mm)		**Right three squares(mm)**	
s1	0.58	s4	3.64
s2	2.12	s5	2.66
s3	3.42	s6	1.42

Table 5.9 Sides of outer etched squares in the ground plane with aspect ratio 0.40

Kaiser Tapered		**Chebyshev Tapered**	
Left three squares(mm)		**Right three squares(mm)**	
s1	0.92	s4	5.82
s2	3.38	s5	4.25
s3	5.47	s6	2.27

5.3.6 Simulated Results of Annular Chebyshev and Kaiser Square Tapered EBG Band Stop Filter

The figure 5.12 and 5.13 shown below gives the simulated results of insertion loss (S12) and return loss (S11) for annular tapered band stop filter with aspect ratio as 0.4 for outer etched square and 0.25 for inner patch square. Table 5.10 shows the values of parameters of simulated result.

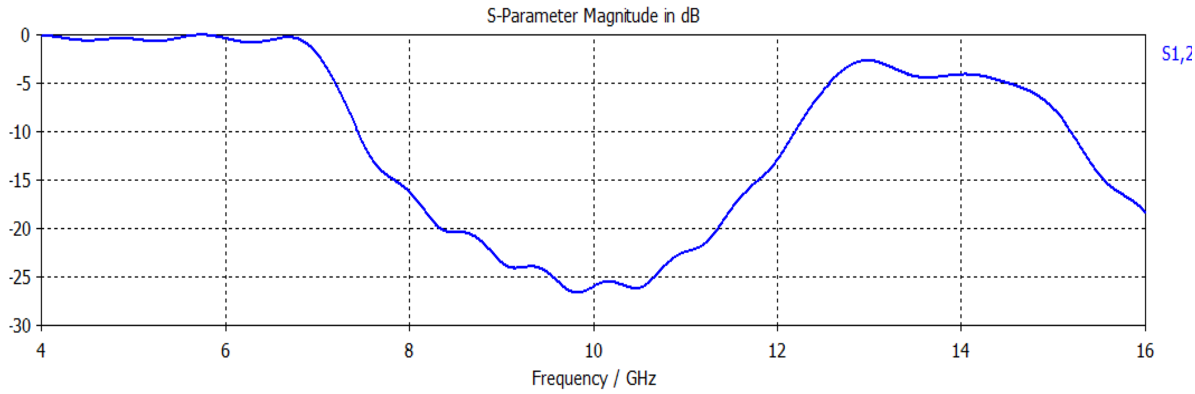


Figure 5.12 Simulated result of insertion loss (S12) for annular tapered structure

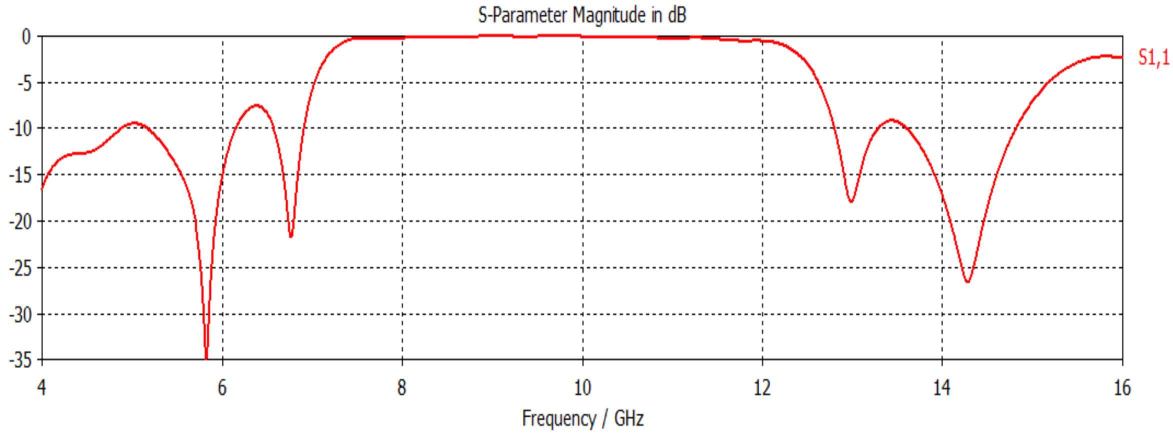


Figure 5.13 Simulated result of return loss (S11) for annular tapered structure

Table 5.10 Simulated results of Square annular tapered bandstop filter

Paramteres		**Square Annular Tapered Band Stop Filter**
10-dB bandwidth (GHz)		5.25
Ripple level (dB)	Lower	0.74
	Higher	4.88
Attenuation (dB)		> 26
Side lobe Level (dB)	Lower	>6
	Higher	>9

5.3.7 Fabrication and Testing of Annular Chebyshev and Kaiser Square Tapered EBG Band Stop Filter

The fabrication of annular square tapered ground plane band stop filter is done by using Fr4 as its substrate which is two sided copper plated. The fabrication of the filters is shown and its results are discussed in the subsequent sections. The results of fabricated filter are checked on vector analyzer. In the last the measured and simulated results are compared with each other and the results are further tabulated together. The fabrication of annular tapered squares in ground plane bandstop filter is shown in figure 5.14 and 5.15.

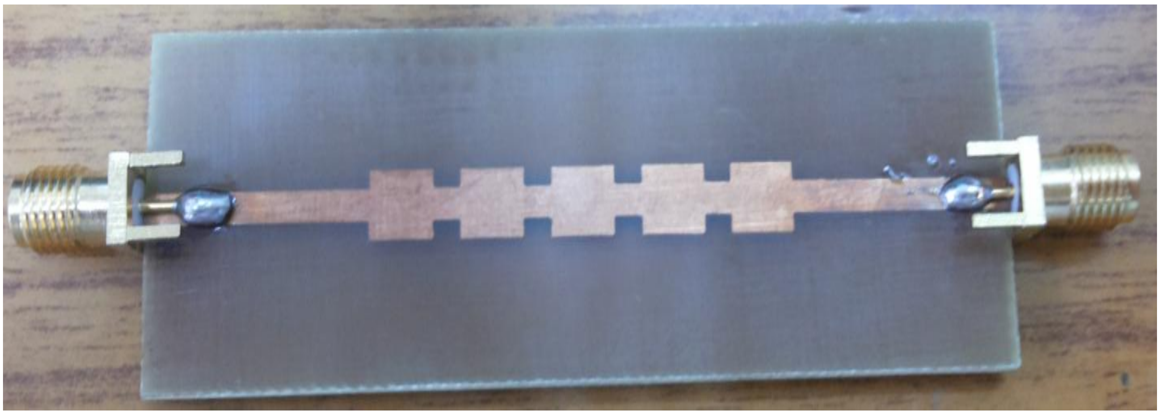


Figure 5.14 Top view of annular square tapered EBG band stop filter

Figure 5.15 Bottom view of annular square tapered EBG band stop filter

5.3.8 Comparison of Measured And Simulated Result of Annular Square Tapered EBG Bandstop Filter Structure

In this section a comparison of the measured and simulated result of anular square tapered

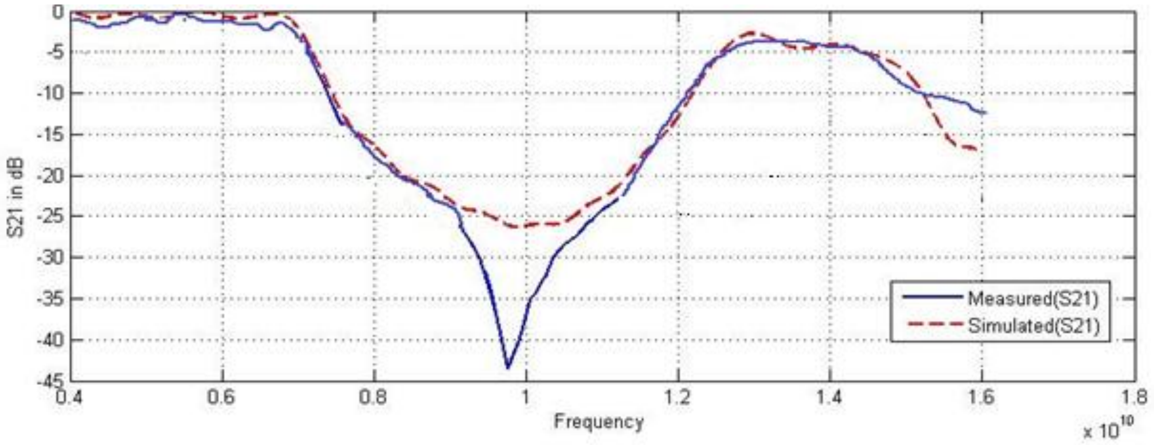


Figure 5.16 Comparison of measured and simulated result of S21 parameters for annular square tapered bandstop filter structure.

EBG band stop filter is discussed. The measured and simulated graphs are combined together on one scale by using matlab 2010 software.

Figure 5.16 gives the comparison of measured and simulated result of S21 parameters for annular square tapered bandstop filter structure.

Figure 5.17 gives the comparison of measured and simulated result of S11 parameters for annular square tapered EBG bandstop filter structure. Table 5.11 gives the comparison between the parameters calculated by the simulated and measured result for the above discussed bandstop filter.

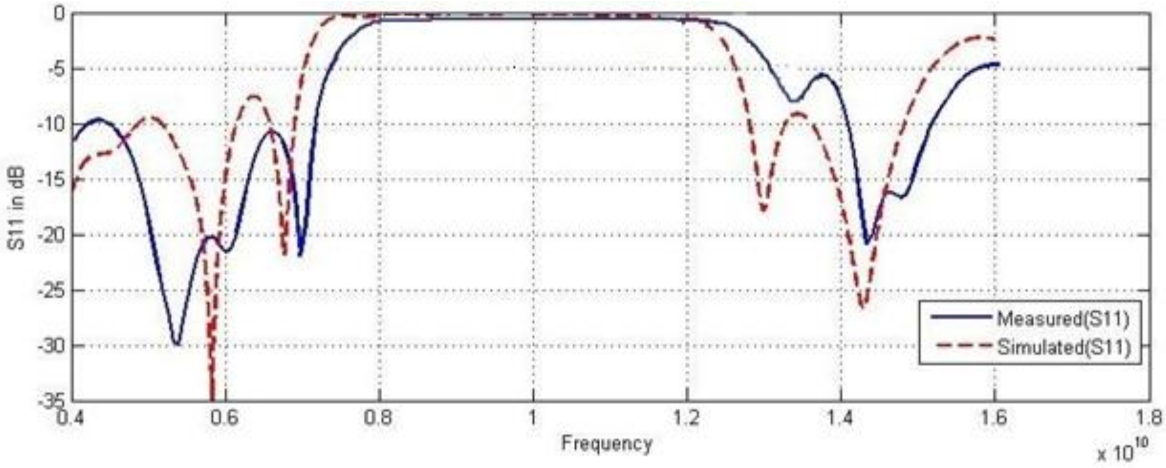


Figure 5.17 Comparison of measured and simulated result of S21 parameters for annular square tapered EBG bandstop filter structure.

Table 5.11 Comparison between the measured and simulated result of annular square tapered EBG bandstop filter

Parameters	**Measured Results**	**Simulated Results**
10-dB Bandwidth (Ghz)	5.25	5.17
Ripple level (lower) (dB)	0.74	1.12
Ripple level (higher) (dB)	4.88	4.2
Resonate frequency (Ghz)	10	9.13
Sidelobe level (lower) (dB)	>6 dB	>10 dB
Sidelobe level (higher) (dB)	>9 dB	>5 dB
Attenuation (dB)	>26 dB	>42 dB

5.3.9 Conclusion

In this chapter, a new design and physical realization of a bandstop filter with wide band width is designed. The proposed squared Chebyshev tapered and annular squared ground tapered bandstop filter gives a 10-dB bandwidth of 3.57 GHz and 5.25 GHz respectively. The fabricated and simulated results differ due to the SMA connector losses. A comparison between two designs is presented in table 5.12.

Table 5.12 Comparison of Chebyshev tapered and annular Chebyshev and Kaiser square tapered EBG bandstop filter structure

Parameters	**Chebyshev tapered band stop filter**	**Annular Chebyshev and Kaiser tapered bandstop filter**
10-dB bandwidth (Ghz)	3.57	5.25
Ripple level (lower) (dB)	1.85	0.74
Ripple level (higher) (dB)	2.12	4.88
Sidelobe level (lower) (dB)	>4 dB	>6 dB

Sidelobe level (higher) (dB)	>22 dB	>9 dB
Attenuation (dB)	>15 dB	>26 dB

The two tapering techniques Kaiser and Chebyshev together result in low ripple level in the passband with an increase in the bandwidth thus gives rise to good performance in the passband. The filters are simple to fabricate. The tested results are well coordinated with the simulated results. The design results in a good band stop filter with elevated characteristics in both stopband and passband.

Chapter 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The main objective of the entire thesis was to design an EBG based microwave filter with an improved passband and stopband characteristics. Initially in this thesis the designs are made by using single plane electromagnetic bandgap structure. A low pass filter is designed in chapter 4 with square etches introduced in the ground plane instead of circular patches in [10]. The square patches improved the bandwidth the passband and stopband characteristics. It also improved the bandwidth of filter structure.

From the chapter 4 it was concluded that by employing the square etches instead of circular etches in the ground plane, some cases the bandwidth is improved and in other cases the modification of the design is done by employing the tapering technique on the square etches in order to improve the other filter characteristics such as ripple level in passband and attenuation of stopband etc.

In chapter 5 a band-stop filter is designed and this includes the main part of the thesis work. Many researchers have design a bandstop filter using circular etches in the ground plane. The bandstop filter design is modified by introducing the square patches in the ground plane instead of circular patches. It was concluded that although the performance of bandstop filter is improvised by adopting the square patches in the ground plane but at the cost of increase in the ripple level content in the passband characteristics.

Further the modified bandstop filter with annular square patches etched in the ground plane is discussed and designed with an improved performance of bandstop filter two tapering techniques one Chebyshev and other Kaiser are employed together and it increased the bandwidth of the filter as compared to the filter employing only one tapering technique.

Thus it was concluded that in order to achieve the low ripple level in the passband with improved bandwidth the annular tapering is necessarily adopted. The two window function achieves two important characteristics of any filter when used together.

The proposed bandstop filter (annular Chebyshev and Kaiser and only Chebyshev) were fabricated and tested by using vector network analyser. All the results were in good agreement with the simulated results using CST 2010 software the results are compared with each other by using matlab2010.

The proposed squared Chebyshev tapered and annular Chebyshev and Kaiser squared tapered EBG bandstop filter gives a 10-dB bandwidth of 3.57GHz and 5.25 GHz respectively. The fabricated and simulated results differ due to the SMA connector losses. A comparison between two designs is presented in table 6.1.

Table 6.1 Comparison of Chebyshev tapered and annular Chebyshev and Kaiser square tapered EBG bandstop filter structure

Parameters	Chebyshev tapered band stop filter	Annular Chebyshev and Kaiser tapered bandstop filter
10-dB bandwidth (Ghz)	3.57	5.25
Ripple level (lower) (dB)	1.85	0.74
Ripple level (higher) (dB)	2.12	4.88
Sidelobe level (lower) (dB)	>4 dB	>6 dB
Sidelobe level (higher) (dB)	>22 dB	>9 dB
Attenuation (dB)	>15 dB	>26 dB

The two tapering techniques Kaiser and Chebyshev together result in low ripple level in the passband with an increase in the bandwidth thus gives rise to good performance in the passband. The filters are simple to fabricate. The tested results are well coordinated with the simulated results. The design results in a good band stop filter with elevated characteristics in both stopband and passband.

Below gives the conclusion of the bandwidth and ripple level of passband of bandstop filter:

- Higher bandwith upto 5.25 Ghz was achieved
- Filter allowed to operate in the X-band region
- Low ripple level of 0.82 dB was achieved using annular square structure
- Better passband and stopband characteristics

6.2 FUTURE SCOPE

Annular square tapered EBG filter showed a wide application to satisfy the needs of designing filter structure.

  - The proposed 1-D EBG configuration will be further employed in other application for compact microwave circuits. It will be used as reflectors in the design of resonators or for the coupling elimination of close microstrip lines.
  - The annular square tapered structure has wide application in amplifiers, resonators, reflectors, planar antennas, filters and in many Ghz frequency applications.
  - In this thesis only two tapering techniques Chebyshev and Kaiser are used, further in future other tapering techniques such as Hanning, Hamming, Binomial and Gaussian tapering techniques can be used to etch the ground plane.
  - Squares in the ground plane can be replaced by pentagon, hexagon or any other polygon to design a new type of filter.
  - EBG techniques can also be used in the designing of band pass and high pass filter.
- EBG can also be used in radar engineering so as to provide a transmitter and receiver isolation. By using such isolation structure, surface waves are suppressed by employing EBG structure in the radars which also minimizes the interference between two closely space antennas. Figure 6.1 shows the Transmit-Receive isolation in radar with the metal walls. Figure 6.2 shows the Transmit-Receive isolation in radar with EBG walls.

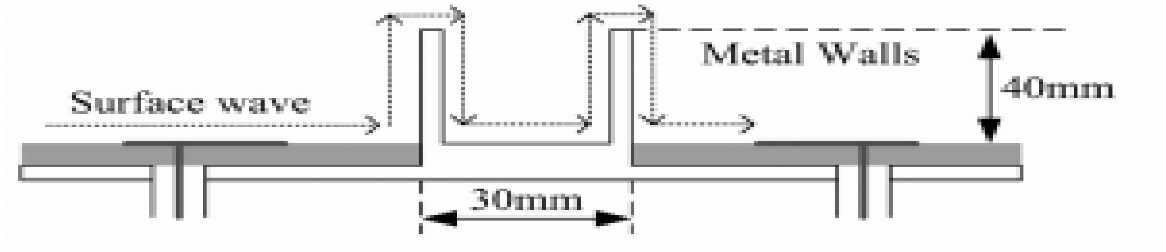


Figure 6.1 Transmit-Receive Isolation in Radar with Metal walls

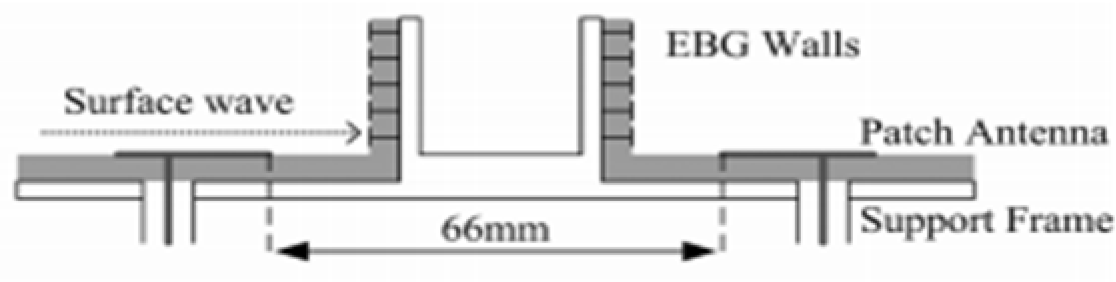


Figure 6.2 Transmit-Receive Isolation in radar with EBG walls

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