

“Harmonic reduction using EBG structures”

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DECLARATION

I Deepti Chahar, hereby certify that the work which is being presented in this dissertation entitled "Harmonic Reduction using EBG structures" is an authentic record of my study carried out as requirement for the award of degree of ME (Electronics and Communication Engineering) at Thapar University, Patiala, under the supervision of "Dr. Rajesh Khanna" and "Mrs. Amanpreet Kaur".

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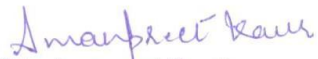
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ABSTRACT

Microstrip patch antennas are a class of planar antennas which have been researched and developed extensively in the past three decades. They are used in many applications in military and wireless communication systems. They have been an attractive choice in mobile and radio wireless communication. They have advantages of having a low profile, conformal, low cost, and robust and can be designed for dual polarization as well as multiple frequency applications. Out of the many feeding techniques for Microstrip antennas, proximity coupling is preferred because of advantage of high bandwidth, less spurious radiations, good suppression of higher order modes and better high frequency performance. In this technique, two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate. The Microstrip antennas have disadvantages of low efficiency, narrow bandwidth and surface wave losses. In the 1990s, researchers suggested that electromagnetic bandgap structures or EBG be introduced into the printed antenna substrate, which have the capability of removing unwanted substrate modes. EBG structures operating in the high frequency and the microwave frequency bands are periodic or quasi-periodic patterns which are created by inclusions in dielectric or magnetic materials. When these inclusions are in ground plane and are also periodic in nature, the structure so obtained is known as an EBG structure whereas if these are non periodic in nature, the structure is a defected ground structure or DGS.

The present work aims at the designing and implementation of a simple proximity coupled Microstrip antenna and its integration with EBG and DGS structures. With the use of EBG structure, the harmonics are considerably reduced and the return loss of antenna at resonant frequency is increased without affecting the radiation characteristics. Two different structures are studied one is a perforated EBG structure and the other is a single patch mushroom EBG structure. Also, the behaviour of DGS when used with single patch mushroom EBG structure is analysed. This results into multiple resonant frequencies, giving a triple band. The bandwidth of antenna is enhanced using a slot in the feedline and the ground plane.

A simple proximity coupled Microstrip antenna is designed to resonate at 1.52 GHz and the various parameters affecting the behaviour are studied such as patch width and feedline length.

A perforated EBG structure with a bandgap between 5-6 and 9-11GHz is used to reduce the harmonic radiation from a PCMA resonating at 3.6GHz. The return loss at fundamental frequency improves by 15dB.

A single patch mushroom EBG structure with a bandgap centred at 6.6GHz is used to reduce the third harmonic radiation from a PCMA resonating at 2.2GHz. The return loss at fundamental frequency improves by 15dB. The bandwidth of the conventional PCMA is enhanced by 73% with a slot in the feedline and the ground plane. Also, a DGS is used in PCMA with EBG which results in triple band and resonates at 1.43GHz, 2.61GHz and 3.17GHz.

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ABBREVIATIONS

MPA	Microstrip Patch Antenna
CST	Computer Simulation Technology
PCMA	Proximity Coupled Microstrip Antenna
WLAN	Wireless Local Area Network
EBG	Electromagnetic Bandgap
MEBG	Mushroom EBG
WiMax	Worldwide Interoperability for Microwave Access
VNA	Vector Network Analyzer
TMM	Transfer Matrix Method
FSS	Frequency Selective Surface

CHAPTER 1

INTRODUCTION

Microstrip patch antennas are a class of planar antennas which have been researched and developed extensively in the past three decades. They are used in many applications in military and wireless communication systems. They have been an attractive choice in mobile and radio wireless communication. This is because they have advantages of having a low profile, conformal, low cost, and robust and can be designed for dual polarization and multiple frequency applications. Microstrip antennas are fed by a number of methods which are mainly classified as contacting and non-contacting feeding methods. In the contacting method, the RF power is fed directly to the radiating patch using a connecting element such as a microstrip line. In the non-contacting method, electromagnetic field coupling is done to transfer power between the microstrip line and the radiating patch. The four most commonly used feeding techniques are the microstrip line, coaxial probe (both contacting schemes), aperture coupling and proximity coupling (both non-contacting schemes). [1]

1.1 Advantages of Proximity Coupled Feeding:

Out of all the feeding techniques for Microstrip antennas, proximity coupling is preferred because of advantage of high bandwidth, less spurious radiations, good suppression of higher order modes and better high frequency performance. In this technique, two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate. This feeding mechanism provides choices between two different dielectric media, one for the patch and other for the feed line in order to optimize the individual performances. Matching at the fundamental frequency is achieved by varying the length of feed line and patch overlap. [2]

1.2 Introduction of EBG with antenna:

The Microstrip antennas have disadvantages of low efficiency, narrow bandwidth and surface wave losses. In the 1990s, researchers suggested that electromagnetic bandgap structures or EBG structures be introduced into the printed antenna substrate, which have the capability of removing unwanted substrate modes. EBG structures operating in the high frequency and the microwave frequency bands are periodic or quasi-periodic patterns which are created by inclusions in dielectric or magnetic materials. The EBG structures are also referred to as high impedance surfaces, metallodielectric material, and

negative materials. These structures are broadly classified as metamaterials and are typically realized by periodic dielectric substrates and metallization patterns. Metamaterials exhibit novel electromagnetic features that may not occur in nature and they have led to a wide range of applications in the electromagnetic area. [3,4]

Recently, planar EBG surfaces have been proposed which exhibit distinctive electromagnetic properties with respect to incident electromagnetic waves. [5]

- i) When the incident wave is a surface wave ($k_x^2 + k_y^2 \geq k_0^2$), the structures show a frequency bandgap through which the surface wave cannot propagate for any incident angles and polarization states.
- ii) When the incident wave is a plane wave, the reflection coefficient of the structures is +1 at a certain frequency, which resembles a perfect magnetic conductor (PMC) that does not exist in nature.

In the above equations, k_x and k_y are the wavenumbers in the horizontal directions while k_0 is the free-space wavenumber. Various applications have been presented based on the above properties. For example, the surface wave bandgap has been utilized to enhance antenna gain, decrease back radiation, and reduce mutual coupling of Microstrip antennas and arrays. The in-phase reflection coefficient has been used to design transverse electromagnetic (TEM) waveguide and low profile wire and slot antennas. This EBG substrate has two most commonly used configurations namely the perforated and metallodielectric structures. The former consists of the periodic arrangement of air-columns. The effectiveness of the perforated structure relies on the high refractive index contrast between the air-columns and the relative permittivity of the dielectric material and the type of the lattice to use. For broadband and small volume mobile communication applications, the honeycomb-lattice was shown to be of good potential. However, unless the substrate has a high relative permittivity, it is more appropriate to employ the metallodielectric structures simply because they are usually easier to manufacture and have wide range of applications. They consist of periodic metalized elements etched usually on the same layer as the microstrip antenna with metal vias connecting the periodic patches on the ground. In most cases, vias are necessary to prevent waves with non-zero vertical electric field component to travel between patch array and the ground. [6]

1.3 Using DGS with Antenna

The EBG is an application of defected ground structures or DGS. DGS is an etched periodic or non-periodic cascaded configuration defect in ground of a planar transmission line (e.g., microstrip, coplanar and conductor backed coplanar wave guide) which disturbs the shield current distribution in the ground plane cause of the defect in the ground. This disturbance will change characteristics of a transmission line such as line capacitance and inductance. [7]

1.4 Need and Methods to reduce harmonics:

Microwave devices having active elements generate harmonic frequencies. In radio frequency front ends, the microwave devices and antenna are very closely placed, therefore if an antenna is not well isolated at these frequencies, those signals can be radiated and part of the power at resonant frequency is lost. It also results in interference with other radio systems. With a Microstrip patch antenna, active device integration is used to meet the requirements of modern wireless communication. Active patch antennas have non linear devices inside the antenna and they exhibit high level of harmonic radiations [8].

There are several methods which can be used for suppressing the harmonics. A photonic bandgap structure on the feeding line of a slot coupled Microstrip patch antenna was introduced by Itoh *et al* [9]. Defected ground structures (DGS) and compact resonant cell structure (CMRC) have been used to accomplish the mentioned aim [10,11]. The disadvantage in using these techniques is that the resonant cells and the periodic elements coplanarly load the feed line of the antenna or they are etched into the ground plane. This results in degradation of the antenna radiation characteristics. All these methods also suffer from spurious back radiation problems due to feeding line radiation related to discontinuities. Recently, there has been considerable research effort in the electromagnetic band gap (EBG) structure for antenna application to suppress the harmonic radiation and surface wave and thereby improve the radiation characteristics of the antenna to reduce the spurious radiation due to the corresponding patch modes in order to avoid the radiation of harmonic signals which are generated by non-linear devices at the amplifying stage.

1.5 Objective of the dissertation

- 1) Design, simulation and analysis of single band PCMA and its harmonics.
- 2) Design and simulation of proximity coupled Microstrip patch antenna operating at 3.6GHz employing perforated Electromagnetic Bandgap structure with reduced harmonics.
- 3) Design and simulation of proximity coupled Microstrip patch antenna operating at 2.2GHz employing MEBG structure with reduced harmonics.
- 4) Study the effect of DGS in both PCMA and in PCMA with EBG.

1.6 Dissertation Organization

The dissertation is divided into eight chapters.

Chapter 1 is dedicated to an overview of PCMA and different methods that can be used for harmonic reduction in antennas.

Chapter 2 is dedicated to basic principles and different parameters for designing of EBG and DGS structure.

Chapter 3 includes the literature survey on the proximity coupled antenna and also the researches done for bandwidth enhancement and Electromagnetic bandgap structure.

In Chapter 4, a single band antenna is designed and the effect of various physical parameters on the resonating frequency is studied.

In Chapter 5, the single band proximity coupled antenna is designed and then a perforated EBG is used in it to reduce the harmonic radiation.

In Chapter 6, a single band antenna with metallodielectric structure for reduced harmonic radiation and triple band antenna is designed with both EBG and DGS.

In Chapter 7, the antenna studied in Chapter 4 is fabricated and tested.

Chapter 8 is dedicated to the conclusion and the future scope.

CHAPTER 2

ELECTROMAGNETIC BANDGAP STRUCTURES

2.1 Introduction

The bringing forth of the electromagnetic band gap structure has actuated many new antennas applications. Two commonly used features are suppressing unwanted substrate modes and acting as an artificial magnetic ground plane. Nowadays most antennas are required to be small and broadband. Usually, to get small size and broadband operation patch antenna is fabricated on a thick piece of high permittivity substrate. There are two major disadvantages in this, first, higher is the relative permittivity of a material the more costly it would be. Second, unwanted substrate modes start to form and move towards the edges of the substrate which have a harmful effect on the antenna radiation pattern. There can be an increase in back radiation level, distortion in the main lobe and side lobes may appear.

In the 1990s, researches proposed that electromagnetic bandgap structure be introduced into the printed antenna substrate, which has the ability of removing unwanted substrate modes. This EBG substrate has two normally used configurations-the perforated and metallodielectric structures. The first one consists of the periodic arrangement of air-columns. The effectiveness of the perforated structure lies on the high refractive index contrast between the air-columns and the relative permittivity of the dielectric material and the type of the lattice used. However, unless the substrate has a high relative permittivity, it is more appropriate to use the metallodielectric structures because they are usually easy to manufacture and have a variety of applications. [12]

2.2 Formation of surface wave

As a patch antenna radiates, a portion of the total available power for direct radiation gets trapped along the surfaces of the substrate. This trapped electromagnetic energy leads to the forming of surface waves. In fact, the ratio of power that radiates into the substrate compared to the power that radiates into air is approximately ($\epsilon^{3/2}:1$). This is governed by the rules of total internal reflection, which states that any field line which is radiated into the substrate at angles greater than the critical angle are totally internally reflected at the top and bottom surfaces. This is illustrated in Figure 3.1. Therefore, for a substrate with dielectric constant $\epsilon = 10.2$, nearly 1/3 of the total radiated power is trapped in the substrate with critical angle of roughly 18.2 degrees.

Surface wave effects can be removed by using cavities or stacked substrate techniques. There are some drawback of it such as increasing the weight, thickness, and complexity of the microstrip antenna, thus deviating many of the advantages of using microstrip antennas. These complications prevent microstrip antennas from becoming the standard in the microwave telecommunications community.

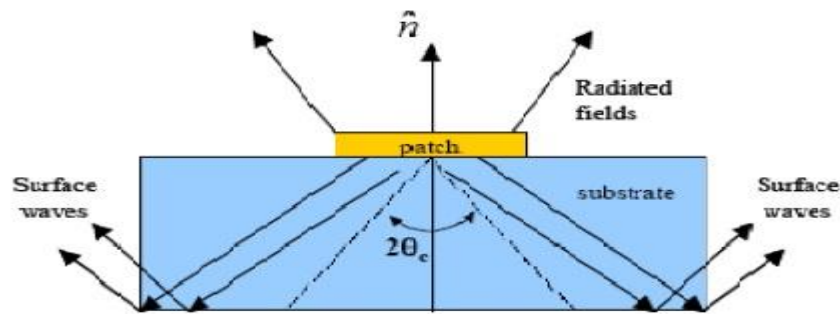


Figure 2.1: Field lines radiating from a patch antenna; illustrates the formation of surface waves. [12]

2.3 Perforated EBG structure

The first electromagnetic band gap (EBG) structure (previously termed Photonic band gap (PBG) conceptualized and manufactured was in 1991 by Eli Yablonovitch, then at Bell Communications Research in New Jersey. Yablonovitch constructed this crystal structure by mechanically drilling holes of a millimeter in diameter into a high dielectric constant material (perforated EBG structure) as shown in Figure 2.2. This patterned material became known as “Yablonovitch” prevented incident microwave signals from propagating in any direction along a unit sphere – in other words, it exhibited a 3-D band gap. This structure has now become the cornerstone for much of the researcher in this area with applications which are still in use today.

In most communication applications, however, the use of Yablonovitch is not practical. The three dimensional nature of the band gap rejects incident energy from all directions around a unit sphere, making it better suited as a high efficiency reflector or mirror. Instead, in a 2-D photonic crystal, the band gap exists only within a plane; therefore it allows propagation along one axis of the crystal only. This scenario is ideal for microstrip antenna designs, since the “rejection plane” can be in the plane of the patch which prevents surface wave’s formation. An example of a 2-D photonic crystal is a triangular lattice, as shown in Figure 2.2. [12]

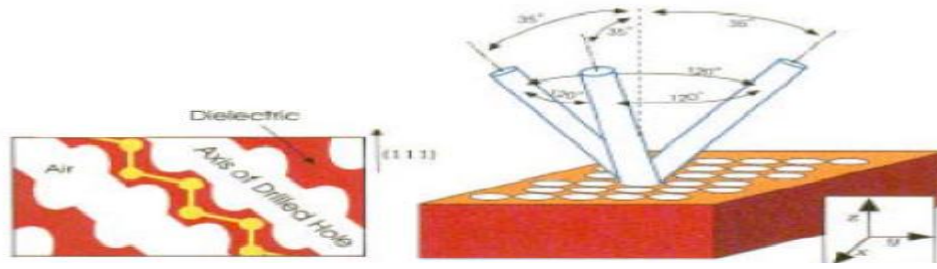


Figure 2.2 Technique used to fabricate the first 3D PC structure, the Yablonovite [12]

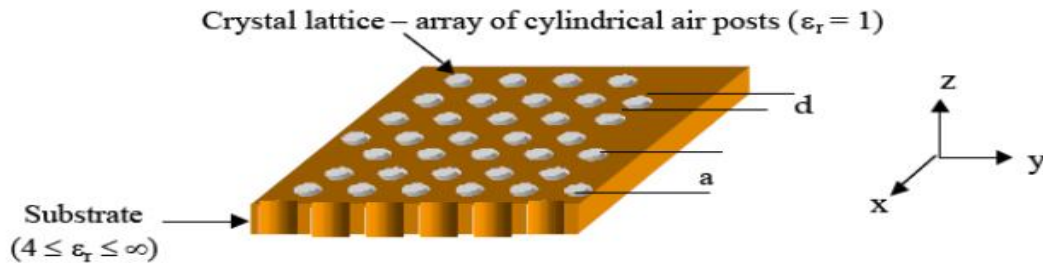


Figure 2.3 2D photonic crystal structure patterned with a triangular crystal lattice; the crystal lattice is of cylindrical air posts in a high dielectric substrate [12].

A photonic crystal essentially behaves much like a band-stop filter, which rejects the propagation of energy over a fixed band of frequencies. However, when a defect is introduced such that it destroys the periodicity in the crystal, an area to localize or “trap” electromagnetic energy is established. In this region, a pass-band response is created. This capability to confine and guide electromagnetic energy has several practical applications at microwave frequencies as filters, couplers, and especially antennas. This rather simple concept of placing defects in a photonic crystal structure introduces a new methodology in the design of microstrip (patch) antennas. The idea is to design a patch antenna on a 2D photonic crystal substrate, where the patch becomes the “defect” in the crystal structure, as shown in Figure 2.4. In this case, crystal arrays of cylindrical air holes are patterned into the dielectric substrate of the patch antenna.

By not patterning the area under the patch, a defect is established in the photonic crystal, localizing the EM fields. Surface waves along the XY plane of the patch (Figure 2.5) are prohibited from forming due to the periodicity of the photonic crystal in that plane. This prevention of surface waves improves operational bandwidth and directivity, all while reducing side lobes and coupling, which are common concerns in microstrip antenna designs.

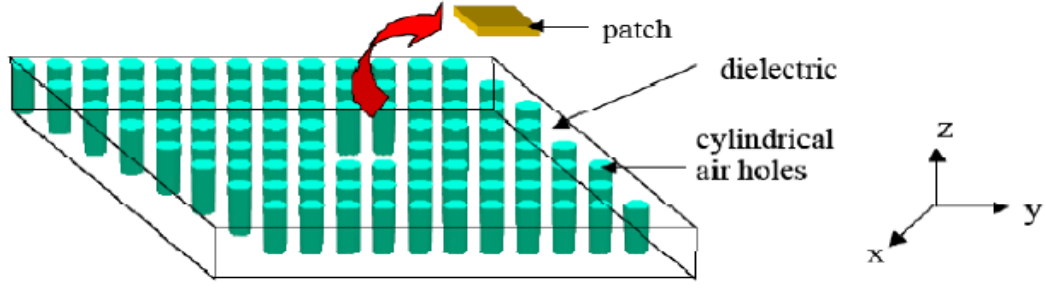


Figure 2.4 Illustration of a patch designed on a photonic crystal substrate; defect introduced in the area under the patch [12]

Although “photonic” refers to light, the principle of “band gap” applies to electromagnetic waves of all wavelengths. Consequently, there is a controversy in the microwave community about the use of the term “Photonic”, and the name Electromagnetic band gap (EBG) material or Electromagnetic crystal is being proposed. The main feature of these materials is the existence of a gap (stopband) in the frequency spectrum of propagating EM waves. This bandgap frequency depends on the permittivity of the dielectric inclusions or background used, the dimensions of the inclusions/defects, their periodicity and the incidence angle of electromagnetic waves [13].

The central frequency of the first stopband for a single period EBG can be determined roughly by the period ‘ a ’ using the formula :

$$f = \frac{c}{\sqrt{\epsilon_{eff}} \lambda_g} \quad (2.1)$$

where ‘ c ’ is the speed of light in free space and $\lambda_g = 2.a$ is the Bragg condition, where ‘ a ’ is the distance between the centres of two adjacent holes.

For a microstrip line with etched ground plane, the effective dielectric constant of the line is estimated as that of the line with unperturbed ground plane.

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12d/W}} \quad (2.2)$$

where ‘ d ’ and ‘ W ’ are the thickness of the substrate and the width of the line, respectively.

2.3.1 Bloch’s Theorem and Periodic Boundary Condition

Bloch studied wave propagation in three-dimensionally periodic media in 1928, followed by an extending theorem in one dimension by Floquet in 1883. In Bloch’s study, he proved that waves in such a medium can propagate without scattering, their behaviour is governed by a periodic envelop function multiplied by a plane wave. This means that, in a photonic crystal with periodic dielectric function:

$$\epsilon(\vec{r}) = \epsilon(\vec{r} + s_1 \vec{a}_1 + s_2 \vec{a}_2 + s_3 \vec{a}_3), \quad s_i = 0, \pm 1, \pm 2, \dots \quad (2.3)$$

where $\vec{a}_i$ ($i = 1, 2, 3$) are three primitive lattice vectors. For a crystal periodic in all three dimensions, the wave can be expressed in forms of combinations of plane waves and a periodic function:

$$\vec{H}(\vec{r}) = e^{i\vec{k}\vec{r}} \vec{u}(\vec{r}) \quad (2.4)$$

where $\vec{u}$ is a periodic envelope function. Equation 2.4 is commonly known as Bloch's theorem. It is known in solid-state physics as a Bloch State [8].

A simple example is shown in figure 2.5. The structure is repetitive in the y-direction, and invariant and infinite in the x-direction. So this structure has continuous translational symmetry in the x-direction and discrete translational symmetry in the y-direction. The unit cell is highlighted in the figure with a blue box. The primitive lattice vector in this case is $\vec{a} = a\hat{y}$.

According to Bloch's theorem, fields in these structures are in Bloch state

$$\vec{H}(\vec{r}) = e^{ik_x x} e^{ik_y y} \vec{u}_y(y, z) \quad (2.5)$$

where $\vec{u}(y, z)$ is a periodic function in y satisfying

$$\vec{u}(y + sa, z) = \vec{u}(y, z) \quad s_i = 0, \pm 1, \pm 2, \dots \quad (2.6)$$

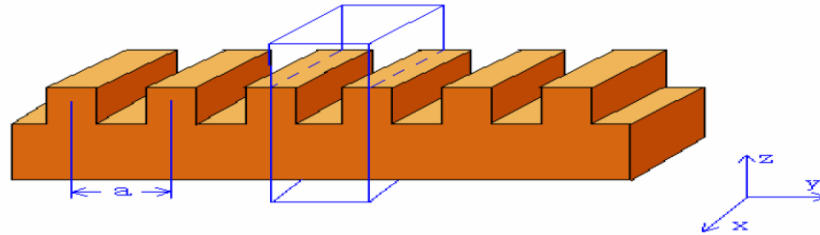


Figure 2.5 A dielectric configuration with discrete translational symmetry. (a is the lattice constant)[14]

According to equation (2.6), this state can be considered as a plane wave, modulated by a periodic function because of the periodic lattice. As a result, the field in Bloch's state can be studied by a so called unit cell approach, in which only elements in one unit cell are investigated and outside-cell elements are related and expressed using the following relationship:

$$\begin{aligned} \vec{H}(\vec{r} + sa\hat{y}) &= e^{ik_x x} e^{ik_y(y+sa)} \vec{u}_{k_y}(y+sa, z) \\ &= e^{ik_y sa} \vec{H}(\vec{r}) \end{aligned} \quad (2.7)$$

Equation (2.7) is used as the periodic boundary condition (PBC) in the study of the infinite EBG structures.

2.3.2 Brillouin Zone

A key fact about Bloch's states is that a Bloch state with wave vector k_y and a Bloch state with wave vector $k_y + mb$ are identical, where $b = 2\pi/a$ and m is an integer. That means

the mode frequencies are also periodic in k_y : $\omega(k_y) = \omega(k_y + mb)$. So we only need to consider k_y to exist in the range $-\pi/a < k_y \leq \pi/a$. This region of important, non redundant values of k_y is called the Brillouin zone.

Another example shown in figure 2.6 is made up of cylindrical elements periodically laid in a square lattice. Figure 2.6(a) shows the physical lattice, and the Brillouin Zone of the reciprocal lattice is plotted in figure 2.6(b). This structure shows not only a discrete translational symmetries along the x and y directions, but also rotation, mirror-reflection and inversion symmetry. It is shown that when these symmetries are shown in physical space, the reciprocal space (k space) shows the same kinds of symmetry. As a result, in the Brillouin zone shown in figure 2.6(b), every k-point included in it need not to be considered. Only a smallest region within the Brillouin zone for which the k vector are not related by symmetry need to be considered. That smallest region is termed as the **irreducible Brillouin zone**, shown in light blue colour; the rest of the Brillouin zone contains redundant copies of the irreducible zone.

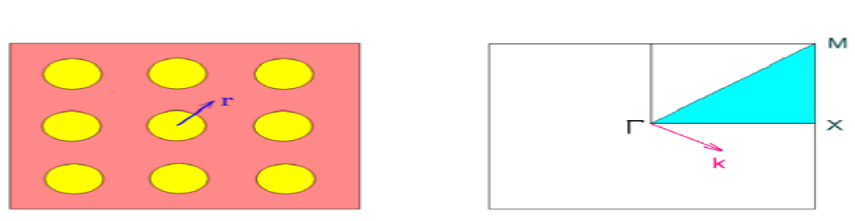


Figure 2.6: (a) The physical lattice of a EBG made using a square lattice. An arbitrary vector $\mathbf{r}$ is shown. (b) The Brillouin zone of the reciprocal lattice, centered at the origin (Γ). An arbitrary wave vector $\mathbf{k}$ is shown. The irreducible Brillouin zone is the light blue triangular wedge. [14]

2.3.3 Dispersion Diagram and Photonic Band Gap

With the knowledge of the irreducible Brillouin zone, the possible modes against the wave vector $\vec{k}$ can be plotted. This curve can be plotted in one dimension, two dimensions or three dimensions. These plots provide the dispersion relation and information on the flow of energy in an intuitive way. Figure 2.6 shows two examples of one-dimensional diagrams of one-dimensional EBG materials.

Figure 2.7(a) is the dispersion diagram for a uniform dielectric medium, to which a periodicity of ' a ' has been artificially assigned. It is known that in a uniform medium, the speed of light is reduced by the index of refraction. So the plot is just the light-line given by

$$\omega(\vec{k}) = c\vec{k}\sqrt{\epsilon} \quad (2.8)$$

Because the wavevector $\vec{k}$ repeats itself outside the Brillouin zone, the lines fold back into the zone when they reach the edges. The dashed lines show the folding effect of applying Bloch's theorem with an artificial periodicity a .

In figure 2.7(b), there is a gap in frequency between the upper and lower branches of the lines - a frequency gap in which no mode, regardless of $\vec{k}$, can propagate through the structure. This gap is called an electromagnetic band gap, which can be further classified as:

1. Complete Electromagnetic Band Gap: A complete photonic bandgap is a range of ω in which there are no propagating (real $\vec{k}$) solutions of Maxwell's equations for any $\vec{k}$, surrounded by propagating states above and below the gap.
2. Incomplete Electromagnetic Band Gap: This bandgap only exist over a subset of all possible wavevectors, polarizations, and/or symmetries.

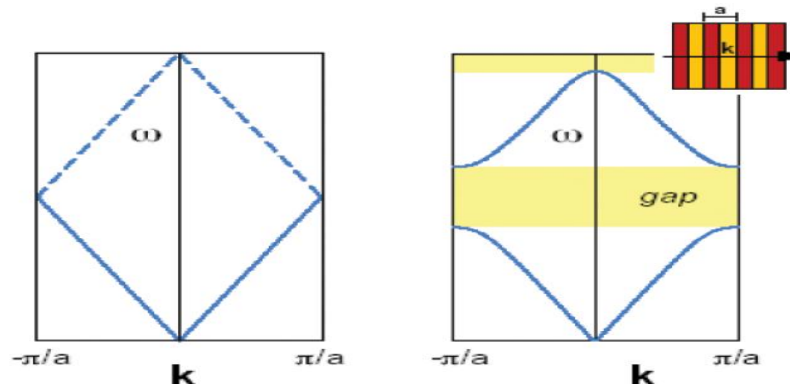


Figure 2.7 (a) Dispersion relation (band diagram), frequency ω versus wave number k of a uniform one-dimensional medium, (b) Schematic effect on the bands of a physical periodic dielectric variation (inset), where a gap has been opened by splitting the degeneracy at the $k = \pm\pi/a$. The right-up corner shows the physical lattice and the wave vector. a is the lattice constant [15].

2.3.4 An Overview of Numerical Methods for the Modelling of EBG's

Numerical methods are used to predict the performance of EBGs, either for the purpose of theoretical understanding of EBGs, or for the assistance of EBGs related designs. These numerical methods include the generalized Rayleigh Identity Method, the Korringa-Kohn-Rostoker (KKR) approach, the Plane Wave Expansion (PWE) method, the Transfer Matrix Method (TMM) [16,17], and the Finite-Difference Time-Domain (FDTD) method etc.

Modelling EBGs using the Transfer-Matrix Method

Pendry and MacKinnon introduced a complementary technique, *i.e.* the transfer-matrix method (TMM), of studying EBG structures in 1992. In the TMM, the total volume of the system is divided into small cells and the fields in each cell are coupled to those in the

neighbouring cells. Then the transfer matrix can be defined by relating the incident fields on one side of the EBG structure with the outgoing fields on the other side.

Expressing Maxwell's equations:

$$\nabla \times \vec{E} = -\partial \vec{B} / \partial t \quad \nabla \times \vec{H} = \partial \vec{D} / \partial t \quad (2.9)$$

in $(\vec{k}, \omega)$ space yields:

$$\vec{k} \times \vec{E} = \omega \vec{B}, \quad \vec{k} \times \vec{H} = -\omega \vec{D} \quad (2.10)$$

$$\text{Assuming that } \vec{D} = \epsilon \vec{E} = \epsilon_0 \epsilon_r \vec{E} \text{ and } \vec{B} = \mu \vec{H} = \mu_0 \mu_r \vec{H} \quad (2.11)$$

Equations (2.10) and (2.11) then become equations (2.12) and (2.13):

$$\begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \\ k_x & k_y & k_z \\ E_x & E_y & E_z \end{bmatrix} = \omega \mu \begin{bmatrix} H_x \hat{x} \\ H_y \hat{y} \\ H_z \hat{z} \end{bmatrix} \quad (2.12)$$

$$\begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \\ k_x & k_y & k_z \\ H_x & H_y & H_z \end{bmatrix} = -\omega \epsilon \begin{bmatrix} E_x \hat{x} \\ E_y \hat{y} \\ E_z \hat{z} \end{bmatrix} \quad (2.13)$$

Equation (2.12) yields:

$$(1/\omega \mu)(k_x E_y - k_y E_x) = H_z \quad (2.14)$$

and equation (2.13) yields:

$$k_y H_z - k_z H_y = -\omega \epsilon E_x \quad (2.15)$$

Substituting H_z in equation (2.12) with the expression in (2.15) yields:

$$k_y [(1/\omega \mu)(k_x E_y - k_y E_x)] - k_z H_y = -\omega \epsilon E_x \quad (2.16)$$

By making the substitution:

$$H' = i/a \omega \epsilon_0 H \quad (2.17)$$

then equation (2.18) can be obtained:

$$(iak_z)H'_y = (iak_y c^2 \mu_r^{-1} / a^2 \omega^2) [(iak_x)E_y - (iak_y)E_x] - \epsilon_r E_x \quad (2.18)$$

Applying the simple cubic mesh, the fields are defined by vectors a, b, c of length a in the $\hat{x}, \hat{y}, \hat{z}$ directions, respectively. Transforming equation (2.18) back into real space yields equation (2.19) from which the z components of the vectors are eliminated:

$$\begin{aligned} H'_y(r+c) &= -\epsilon_r(r+c)E_x(r+c) + H'_y(r) \\ &- (c^2 \mu_r^{-1} (r-b+c)/a^2 \omega^2) [E_y(r+a-b+c) - E_y(r-b+c) - E_x(r+c) + E_x(r-b+c)] \\ &+ (c^2 \mu_r^{-1} (r+c)/a^2 \omega^2) [E_y(r+a+c) - E_y(r+c) - E_x(r+b+c) + E_x(r+c)] \end{aligned} \quad (2.19)$$

Another three equations (2.20)-(2.22) can be obtained in a similar way:

$$\begin{aligned} H'_x(r+c) &= -\epsilon_r(r+c)E_y(r+c) + H'_x(r) \\ &- (c^2 \mu_r^{-1} (r-a+c)/a^2 \omega^2) [E_y(r+c) - E_y(r-a+c) - E_x(r-a+b+c) + E_x(r-a+c)] \\ &+ (c^2 \mu_r^{-1} (r+c)/a^2 \omega^2) [E_y(r+a+c) - E_y(r+c) - E_x(r+b+c) + E_x(r+c)] \end{aligned} \quad (2.20)$$

$$\begin{aligned}
E_x(r+c) &= +a^2\omega^2/c^2 \mu_r(r)H'_y(r) + E_x(r) \\
&+ \varepsilon_r^{-1}(r)[H'_y(r-a) - H'_y(r) - H'_x(r-b) + H'_x(r)] \\
&- \varepsilon_r^{-1}(r)[H'_y(r) - H'_y(r+a) - H'_x(r+a-b) + H'_x(r+a)]
\end{aligned} \tag{2.21}$$

$$\begin{aligned}
E_y(r+c) &= (-a^2\omega^2/c^2) \mu_r(r)H'_x(r) + E_y(r) \\
&+ \varepsilon_r^{-1}(r)[H'_y(r-a) - H'_y(r) - H'_x(r-b) + H'_x(r)] \\
&- \varepsilon_r^{-1}(r+b)[H'_y(r-a+b) - H'_y(r+b) - H'_x(r) + H'_x(r+b)]
\end{aligned} \tag{2.22}$$

Equations (2.19) and (2.20) express the H fields on the next plane of cells in terms of the E fields on the same plane, and the H fields on the previous plane. Equations (2.21) and (2.22) express the E fields on the next plane in terms of the E and H fields on the previous plane. Thus, given the x, y components of the E and H fields on one side of a dielectric structure, the x, y components of the E and H fields on the other side can be found by integrating throughout the structure. For a dielectric structure containing $(L \times L \times L)$ cells, the dimensions of the transfer matrix are $4L^2$.

The TMM has the advantage that the transmission coefficients and attenuation coefficients for incident electromagnetic waves of various frequencies can be obtained directly from the calculations. This method can also be efficiently used in cases when the PWE method fails or becomes too time consuming. In particular, when the dielectric function is frequency dependent, or when it has large imaginary values, Fourier expansion methods are not efficient. However, disordered systems and periodic systems with imperfections can be easily studied by the TMM method.

Using the TMM, the band property of an infinite periodic system can be calculated, but the main advantage of this method is the calculation of the transmission and reflection Coefficients for EM waves of various frequencies incident on a finite-thickness slab of the EBG material. In that case, the material is assumed to be periodic in the directions parallel to the interfaces.

2.4 Metallodielectric EBG

MEBG consists of periodic metalized elements etched usually on the same layer as the microstrip antenna with metal vias connecting the periodic patches on the ground. In most cases, vias are necessary to prevent waves with non-zero vertical electric field component to travel between patch array and the ground. It consists of two layer substrate with patch on the lower layer and a via connected to the ground. It is characterized by having high surface impedance. Although it is made of continuous metal, and conducts dc currents, it does not conduct ac currents within a forbidden frequency band. By incorporating a

special texture on a conducting surface, it is possible to alter its radio-frequency electromagnetic properties. In the limit where the period of the surface texture is much smaller than the wavelength, the structure can be described using an effective medium model, and its qualities can be summarized into a single parameter: the surface impedance. A smooth conducting sheet has low surface impedance, but with a specially designed geometry, a textured surface can have high surface impedance. The surface impedance is modeled as a parallel resonant circuit, which can be tuned to exhibit high impedance over a predetermined frequency band. The high-impedance surface can be considered as a kind of two-dimensional photonic crystal that prevents the propagation of radio-frequency surface currents within the bandgap.

We assign to the surface a sheet impedance equal to the impedance of a parallel resonant circuit, consisting of the sheet capacitance and the sheet inductance [18]:

$$Z = j\omega L / (1 - \omega^2 LC) \quad (2.23)$$

The surface is inductive at low frequencies, and capacitive at high frequencies. The impedance is very high near the resonance frequency, so a high impedance is obtained and the EBG does not support any surface waves, resulting in a frequency band gap.

$$\omega_o = 1/\sqrt{LC} \quad (2.24)$$

The high impedance surface also ensures that a plane wave will be reflected without the phase reversal that occurs on a perfect electric conductor (PEC).

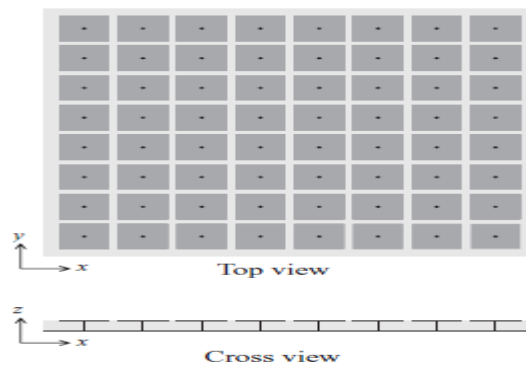


Figure 2.8 Geometry of a mushroom-like EBG structure [19]



Figure 2.9 LC Model for Mushroom like EBG structure (a) EBG Parameters (b) LC Model [19]

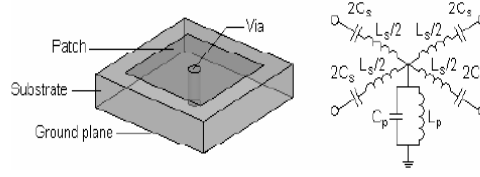


Figure 2.10 Equivalent circuit representation of single patch metallodielectric structure. [19]

The value of the capacitance is obtained by the fringing capacitance between neighboring co-planar metal plates. This can be done by conformal mapping. [16]

$$C = \frac{W\epsilon_o(1+\epsilon_r)}{\pi} \cosh^{-1}\left(\frac{W+g}{g}\right) \quad (2.25)$$

where W is the patch width and g , gap width. The inductance depends only on the thickness of the structure and the permeability:

$$L = \mu h \quad (2.26)$$

h - Substrate thickness

Substituting (2.25) and (2.26) into (2.23) and (2.24), the surface impedance and resonant frequency can be computed. Other characteristic parameters, such as the reflection phase, can also be derived accordingly. This LC model is easy to understand, but the static field approximations limit its accuracy.

2.4.1 Transmission line model for surface waves

Periodic transmission line method is another analytical model proposed to characterize EBG structures. For a 2-D EBG structure such as in figure 2.11, the impedance of each section is calculated using transmission line theory, and the whole structure is then cascaded together using the theory of periodic circuits. The figure depicts a transmission line model of EBG structures. Between two nodes of the periodic structure, there are two contributions (Z_p and X_C) to the total impedance. The centrally located shorting pin in Fig. 2.11 provides the inductive loading X_l of the resonator with the inductance value equal to [20]:

$$L = 2 \times 10^{-7} h \left[\ln\left(\frac{2h}{r}\right) + 0.5\left(\frac{2r}{h}\right) - 0.75 \right] \quad (2.27)$$

The impedance Z_p for each resonator section is calculated using the transmission line formula:

$$Z_p = Z_0 \frac{Z_1 + jZ_0 \tan(\beta_u l)}{Z_0 + jZ_1 \tan(\beta_u l)}, \quad (2.28)$$

where Z_0 is the characteristics impedance and β_u is the phase constant of the transmission line. The transmission line is approximated by a microstrip line whose line width and substrate properties are same as the mushroom-like EBG structure.

When the impedance of the resonator (Z_p) and the coupling capacitor (X_C) are known, the EBG structure can now be treated as a transmission line which is periodically loaded with a lumped impedance Z . The value of Z is then calculated from the parallel connection of Z_p and X_C .

The phase constant β for an infinite lossless periodic structure with a periodicity of a is as $\cos(\beta a) = \cos(\beta_u a) + j \frac{Z}{2Z_0} \sin(\beta_u a)$, (2.29) where Z is imaginary for a lossless resonator. At different frequencies, the corresponding propagation constant can be determined using (2.29) and then a dispersion diagram can be obtained.

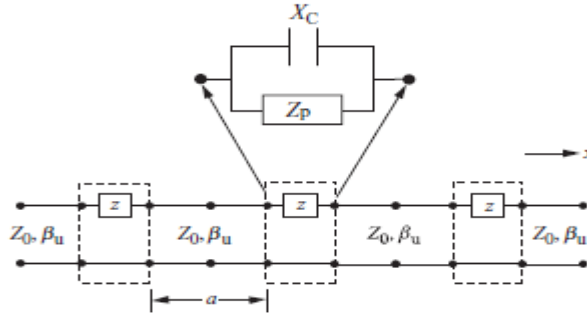


Figure 2.11 Transmission line model for surface waves [20]

2.4.2 Transmission line model for plane waves

To calculate the reflection phase of plane wave incidences at arbitrary incident angles and polarizations, a loaded transmission line model is established. The main idea is the decomposition of an EBG structure into a frequency selective surface (FSS) and a slab treated as a spacing medium between the FSS and the ground plane. When vertical vias are present in the mushroom-like EBG, the medium is treated as a so-called wire medium. The EBG surface impedance Z_s results from two parts: the FSS grid impedance Z_g and the slab impedance Z_d . The value of Z_s is calculated from the parallel connection of Z_g and Z_d :

$$Z_s = \frac{Z_g Z_d}{Z_g + Z_d} \quad , \quad (2.30)$$

The reflection coefficient is then computed as:

$$\Gamma^{TE} = \frac{Z_s \cos \theta - \eta_0}{Z_s \cos \theta + \eta_0} \quad , \quad (2.31)$$

For TM is given as:

$$\Gamma^{TM} = \frac{Z_s - \eta_0 \cos \theta}{Z_s + \eta_0 \cos \theta}, \quad (2.32)$$

where η_0 is the free space wave impedance and θ is the incident angle. The resonant frequency for the zero degree reflection phase has to satisfy:

$$X_g(\omega_0) + X_d(\omega_0) = 0, \quad (2.33)$$

where $X_g = \text{Im}(Z_g)$ and $X_d = \text{Im}(Z_d)$

As a metal backed wire medium, its impedance Z_d can be derived analytically. In most interesting cases ($k_d h \ll 1$), both TM and TE impedances are practically equal to [21]:

$$Z_d^{TE, TM} \approx j\omega\mu_0 h \quad (2.34)$$

When vertical vias are absent, the TE impedance remains unchanged, but the TM impedance strongly depends on the incidence angle:

$$Z_d^{TM} \approx j\omega\mu_0 h \cos^2 \theta \quad (2.35)$$

The grid impedance Z_g of the FSS depends on specific geometry used in the design. For an array of patches, its values are calculated as the following:

$$Z_g^{TE}(\omega, \theta) = \frac{Z_g(\omega, 0)}{\cos^2 \theta}, Z_g^{TM}(\omega, \theta) = Z_g(\omega, 0) \quad (2.36)$$

$$Z_g(\omega, 0) = \frac{1}{j\omega C_g}, C_g = \frac{(1+\epsilon_r)\epsilon_0 a}{\pi} \log\left(\frac{2a}{\pi g}\right) \quad (2.37)$$

2.4.3 Parametric study of Mushroom-like EBG structure

Physical dimensions of an EBG structure determine its electromagnetic properties. For a mushroom-like EBG structure, there are four main parameters that affect its performance namely, patch width W , gap width g , substrate thickness h , and substrate permittivity ϵ_r . The vias' radius r has a trivial effect because it is very thin compared to the operating wavelength.

1) Patch Width Effect

Patch width plays an important role in determining the resonant frequency. While studying the effect of the EBG patch width, other parameters such as the gap width, substrate permittivity, and substrate thickness are kept the same. It is observed that when the patch width is increased, the resonant frequency for 0° reflection phase decreases. Also the slope of the curve becomes steep near the resonance, which indicates a narrow bandwidth. This phenomenon can be explained using the lumped LC model. According to (2.25), a wider patch width leads to a larger capacitance C . Thus, the frequency reduces and the bandwidth becomes narrow.

2) Gap Width Effect

The gap width g controls the coupling between EBG patch units. Hence, a variation in the gap width also affects the frequency band of the EBG surface. The patch width, substrate permittivity, and substrate thickness are kept the same. It is noticed that the variation of the gap width has the opposite effect to the patch width. When the gap width is increased, the resonant frequency increases. Meanwhile, the slope of the curve becomes flat near the resonance, which indicates a wide bandwidth. According to the lumped LC model, increasing the gap width will decrease the value of the capacitance C . Thus, both the resonant frequency and the bandwidth increases.

3) Substrate Thickness Effect

The bandwidth changes in the same way as the resonant frequency. When the frequency decreases, the bandwidth also becomes narrower. By adjusting the substrate thickness h we can decrease the frequency while still increasing the bandwidth. For analysing the substrate thickness effect the patch width, gap width, and substrate permittivity are kept the same. The substrate thickness is always kept small compared to the wavelength because a thin EBG surface is preferred in practical applications. If the substrate thickness is increased, the frequency decreases. This is similar to the effect of the patch width. This can be also explained from the LC model. When the substrate thickness is increased, the equivalent inductance L increases. Thus, the frequency reduces but the bandwidth increases.

4) Substrate Permittivity Effect

Relative permittivity (ϵ_r) of a substrate, also called the dielectric constant, is another effective parameter used to control the frequency behaviour. When air is used as the substrate, the EBG surface has the highest resonant frequency and largest bandwidth. When the permittivity is increased, the resonant frequency decreases, so does the bandwidth. Thus, we can always use a high dielectric constant substrate to reduce the EBG cell size. The price paid, however, is the narrow bandwidth. This effect is similar to a microstrip patch antenna design.

2.5 Defected Ground Structures

Recently, there has been an increasing interest in the use of DGSs for performance enhancement of microstrip antennas and arrays. They are realized by etching of a simple shape defect from the ground plane of the microstrip antenna. The shape may vary from a simple geometry to a complicated one. Due to its resonant behaviour, the DGS may be

compared to the LC parallel resonator, i.e., the equivalent circuit of the DGS consists of an inductance and a capacitance in parallel to itself [22, 23].

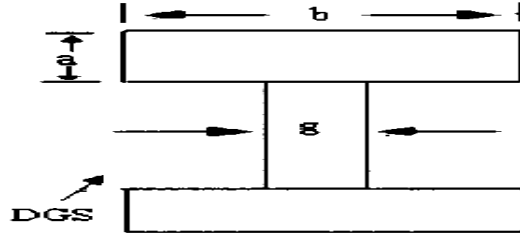


Figure 2.12 Dumbbell shaped DGS

It is the simple and mostly used dumbbell shaped DGS which is etched in the ground plane below the microstrip line, in which both the areas ($a \& b$) and slot gap (g) play very important roles for finding the resonance behavior of the DGS.

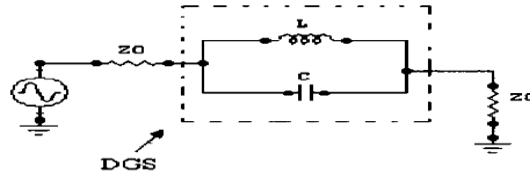


Figure 2.13 The equivalent circuit of the DGS as a parallel combination of Inductance (L) and Capacitance (C)

The head areas ($a \& b$) are very useful for the variation in the inductance (L), and slot (g) produces the capacitance (C). The L and C may be calculated from the formulae given below [24].

$$L = 1 / 4\pi^2 f_0^2 C \quad (2.38)$$

$$C = \frac{f_c}{2Z_o} \cdot \frac{1}{2\pi\sqrt{f_o^2 - f_c^2}} \quad (2.39)$$

In this work, the conventional proximity coupled Microstrip antenna having the EBG structure is placed around the patch antenna. Harmonic reduction is achieved using different EBG structures such as perforated EBG as well as single patch MEBG structures. The proposed design is evaluated using the CST Microwave Studio and the effectiveness of the design is compared with the conventional microstrip antenna. The study shows the possibility of controlling the second harmonic resonance matching by varying the length of the feeding line. On the other hand, the suppression of the third harmonic is achieved by using a resonator. Besides the interference due to other frequencies can also be reduced using this resonator. When a DGS is etched off from the ground plane, it results in multiple resonant frequencies.

CHAPTER 3

LITERATURE SURVEY

This chapter gives an idea about the evolution of proximity coupled Microstrip antennas and various developments in the past in the field of Microstrip antennas which includes bandwidth enhancement, widebanding and multibanding of Microstrip antennas for growing needs of today's wireless communication.

Georg Splitt and Marat Davidovitz in July 1990: presented graphical guidelines for design of electromagnetically coupled square and circular microstrip antennas. Substrates composed of two different dielectric layers were considered. The analysis was extended to electrically thick substrates. Material parameters are selected based on resonant frequency and the bandwidth. Patch dimension and the optimal position of the feedline were obtained from the provided graphs. The design data were computed by applying the method of moments in the spectral domain to solve the integral equation for the currents on the patch and portion of the microstrip feed line. The integral equation was formulated using the appropriate dyadic Green function for the grounded multilayered slab. [25]

David Sinchez-Heminez and Ian D. Robertson in 1995: found that wider bandwidth can be accomplished by employing a thick substrate with low dielectric constant; yet, there is a limit on the maximum usable thickness of the substrate so that surface waves will not be radiated. Dual frequency operation can be obtained by using multilayer structures. An adjustable air gap between the substrate and the ground plane in order to tune the resonant frequency of a microstrip patch antenna has also been carried out. [26]

C. H. Chan, Y. X. Yu and K. M. Luk in 1998: established that for improving the inherently narrow bandwidth of a microstrip antenna, it is very effective to use an electrically thick substrate. Proximity coupling offers the advantage of low cross polarization (typically 25dB) because of no spurious radiation from a perpendicular probe. The microstrip-line feed above a slotted ground plane has been found to be excellent for exciting the electrically thick microstrip antenna. [27]

Rod B. Waterhouse in 1999: presented a method for the performance of stacked patches incorporating a high and low dielectric constant material. Such a printed antenna is applicable for cases where photonic and microwave devices need to be directly integrated with the antenna. Two circular polarization (CP) configurations were presented and experimentally verified. [28]

Yasushi Horii and Makoto Tsutsumi in January 1999: presented a single microstrip patch antenna having two-dimensional photonic bandgap (PBG) in the ground and the effectiveness of the PBG structure for the suppression of the resonance at the harmonic frequencies of the antenna. Experimental results indicated that the radiation patterns at the harmonic frequencies can be drastically diminished comparing with the normal microstrip patch antenna without the PBG structure. For instance, the radiation to the forward of the PBG antenna is suppressed at more than 15 dB at the third harmonic frequency. But at the same time, the radiation pattern of the PBG antenna became almost bidirectional, which showed that the PBG circles were radiating substantially which improved by adjusting the circle size. [29]

Dan Sievenpiper, Lijun Zhang, Romulo F. Jimenez Broas, Nicholas G. Alexopolous, and Eli Yablonovitch in November 1999: developed a metallic electromagnetic structure that was characterized by having high surface impedance. Although it was made of continuous metal, and conducted dc currents, it did not conduct ac currents within a forbidden frequency band. Unlike normal conductors, this new surface did not support propagating surface waves, and its image currents were not phase reversed. The geometry was analogous to a corrugated metal surface in which the corrugations had been folded up into lumped-circuit elements, and distributed in a two-dimensional lattice. The surface could be described using solid-state band theory concepts, even though the periodicity was much less than the free-space wavelength. [30]

Yong-Xin Guo, Chi-Lun Mak, Kwai-Man Luk and Kai-Fong Lee in February 2001: employed the finite-difference time-domain (FDTD) method to analyze L-probe proximity-fed rectangular patch antennas. [31]

Y. J. Sung and Y.-S. Kim in May 2005: presented a paper on impedance matching and harmonic suppression of microstrip antennas since microstrip antennas inherently have a

high input impedance at resonant frequency. Two one-dimensional (1-D) photonic bandgap (PBG) structures, namely, the defected ground structure (DGS) and the compact microstrip resonant cell (CMRC), were applied to the feed line of microstrip antennas. The characteristic impedance of the microstrip line was controlled by the additional effective inductance of the PBG structure. Without any matching circuits, microstrip antennas could be easily fed by a simple $50\ \Omega$ microstrip line with a PBG structure at the operating frequency. The second harmonic of the proposed antennas was properly suppressed compared to a conventional antenna. [32]

Wayne S. T. Rowe and Rod B. Waterhouse in 2006: investigated the parameters that control the impedance and radiation performance of proximity coupled stacked microstrip patch radiators. In particular we explore the relationship required between the dielectric layers to achieve broadband behaviour and also how the dimensions of the stacked radiators and the relative location of the feed can influence the impedance response. Bandwidths in excess of 20% can be achieved with careful layer design. [33]

Yijun Zhou, Chi-Chih Chen, and John L. Volakis in January 2007: a novel proximity-fed stacked patch antenna was presented to cover the GPS band, namely L5 (1176 MHz, available after 2007) together with the L1 and L2 bands (1575 and 1227 MHz). High permittivity dielectric material was used to minimize the antenna size down to $1.2'' \times 1.2''$. Quadrature phase feeding was employed to ensure RHCP radiation, with a broadside gain of 2 dBi. With its reduced size, the presented antenna could be used within a GPS antenna array or other tri-band GPS applications. [34]

Jing Liang and Hung-Yu David Yang in June 2007 investigated- Radiation characteristics of a microstrip patch over an electromagnetic bandgap (EBG) substrate. This paper focused on a mushroom-type EBG structure, although the design is applicable to various EBG profiles. The patch antenna was modeled as a half-wavelength resonator of an EBG-loaded microstrip transmission line. Through a full-wave eigenmode analysis of a microstrip line on an EBG structure, it was found that the resonant patch did not see a high-impedance surface (HIS), but rather it was coupled to the EBG structure as an open cavity resonator. Due to strong near-field coupling, the propagation characteristics including the bandgap zones were very different with or without the patch cover. [35]

T. Archevapanich, J. Nakasuwan, B. Purahong, N. Anantrasirichai, O. Sangaroon in February 2008: designed a slot antenna having a rectangular U-strip slot to achieve desirable two frequency bands. The three configurations of slot antenna fed by microstrip line which have the same size are presented for desirable frequency and bandwidth. The slot antenna fed by microstrip line is design for dual band by using U-strip and improvement by etching dual U-slot in the U-strip. Finally, the slot antenna with dual U-strip and dual U-slot is introduced for dual band coverage standard of IEEE 802.11b/g, IEEE 802.11j ,IEEE 802.11a and WiMAX of IEEE802.16d. [36]

Luis Inclán-Sánchez, José-Luis Vázquez-Roy, and Eva Rajo-Iglesias in April 2008: presented a new method to enhance the isolation between two ports in a dual-frequency proximity coupled patch antenna was presented. The dual polarized patch antenna had a multilayer substrate configuration to achieve a compact design. In addition, two periodic structures had been included under the two feeding lines to have stopband behaviour in the other frequency port. These electromagnetic bandgap (EBG) filters were realized by introducing mushroom type resonators underneath the antenna feeding lines. Measurements show that the isolation between the feeding ports could be improved by selecting a suitable size for the resonators. [37]

Qiu-Rong Zheng, Yun-Qi Fu, and Nai-Chang Yuan in June 2008: presented a compact electromagnetic band-gap (EBG) structure in a spiral shape which significantly enlarged the capacitance between neighbouring elements. It was proved that the size of the spiral structure is only 30.9% of the conventional EBG structure. Two applications including patch antenna with the spiral EBG structure and a double-element microstrip antenna array with low mutual coupling were considered. A gain improvement over 3 dB and a significant reduction of cross polarization in H-plane were obtained. A 6 dB reduction of mutual coupling was also achieved in a double-element EBG microstrip antenna array. [38]

Jung-Woo Baik, Sang-Min Han, , Chandong Jeong, Jichai Jeong, and Young-Sik Kim in October 2008: proposed two bandpass filters (BPFs) for ultra-wideband (UWB) applications proposed using the uniplanar compact– electromagnetic bandgap (UC–EBG) and the foliated UC–EBG (FUC–EBG) structures for size reduction. The sizes of the UWB BPFs were reduced by 20~22% compared to the conventional one with the

microstrip multiple-mode resonator (MMR). Both EBG structures were shown to cause a slow-wave effect, which was required for compactness and the characteristic impedance Z close to 50 ohms which is needed for wideband match. [39]

Francisco Medina, Francisco Mesa and Ricardo Marqués in December 2008-used simple concepts from the theory of frequency-selective surfaces, waveguides, and transmission lines to explain extraordinary transmission for both thin and thick periodically perforated perfect conductor screens. It was shown that a simple transmission-line equivalent circuit satisfactorily accounted for extraordinary transmission, explaining all of the details of the observed transmission spectra, and easily gave predictions on many features of the phenomenon. Although the equivalent circuit was developed for perfect conductor screens, its extension to dielectric perforated slabs and/or penetrable conductors at optical frequencies was almost straightforward. The circuit model also predicted extraordinary transmission in nonperiodic systems for which this phenomenon had not been reported. [40]

Kasra Payandehjoo and Ramesh Abhari in 2009: investigated the effect of mutual coupling on the operation of a multiantenna system. Radiation pattern, input impedance, gain, and efficiency of a slot antenna in proximity of another slot antenna were studied through simulations. A mushroom-type electromagnetic band-gap (EBG) structure was designed to isolate the antennas and reduce the influence of coupling on radiation characteristics. Two multiantenna prototypes were fabricated and experimentally evaluated. Measurement results confirmed the improvement of isolation between the antennas by 28 dB at the radiation frequency of 5.2 GHz when the EBG reflector was utilized. In addition, the diversity gain of the two prototypes were measured using a reverberation chamber demonstrating an increase of 3.3 dB in the combined received power for 99% of transmission trials when the EBG structure was added in the substrate of the multiantenna system.[41]

Dan Sun and Lizhi You in April 2010: presented a method to optimize impedance matching through narrow cavity backed configuration. [42]

Sang il Kwak, Dong-Uk Sim, and Jong Hwa Kwon in May 2011 proposed- an optimized multilayer planar inverted-F antenna (PIFA) with an electromagnetic bandgap

(EBG) at personal communication services band for specific absorption rate (SAR) reduction. The EBG structure, which had bandgap capability and acted as a perfect magnetic conductor surface, could suppress surface waves and reduce undesired radiation from an antenna. Thus, the EBG structure was capable of preventing electromagnetic (EM) fields being emitted in the direction of the human head. [43]

Amit A. Deshmukh, M. Parulekar, S. Kadam and Ameya Kadam In 2011: found that the commonly used technique to realize broadband microstrip antenna was by cutting the slots at an appropriate position inside the patch. The bandwidth of an E-shaped microstrip antenna was further increased by cutting the pair of rectangular slots on one of its edge. This increase in bandwidth was due to another mode introduced by additional pair of slots. The slot affects the resonance frequency of higher order mode, which along with modes of E-shaped patch, realize higher bandwidth. This antenna gave a larger BW of 47% with broadside radiation pattern with a peak gain of approximately 10 dBi. The Ψ -shaped MSA realised by cutting the additional pair of slots inside the E-shaped MSA and gave larger BW. [44]

Dan Sun, Wenbin Dou, Lizhi You, Xuequan Yan, and Rong Shen in 2011: presented a broadband cavity-backed proximity-coupled stacked microstrip antenna. Due to the interaction of the two stacked patches, two associated resonances are produced. Unlike conventional proximity-coupled or cavity-backed microstrip antennas, the lower patch and the cavity of this antenna produced the coupled resonances. These devised methods made the antenna act at multiple resonances, conducting to a broadband impedance matching. A bandwidth over one octave was obtained. [45]

Thomas, M.; Roy and J.S. Gupta in February 2011: designed a small wideband antenna to work at 5GHz band WLAN. Using multilayered proximity coupling, bandwidth was improved. An inclined slot loaded PCMA was studied. When the slot is inclined at an angle of 45 with respect to feedline just below the center of the patch, best results are obtained. The area of the patch is reduced by 65%. [46]

Lin Peng, Cheng-li Ruan, and Jiang Xiong in September 2012: proposed an electromagnetic band-gap (EBG) structure with a compact size and multi-band-gaps. The EBG (denoted as DAU-EBG) was formed by etching dual U-shaped slots symmetrically

with respect to one axis of the edge-located vias mushroom-type EBG (ELV-EBG). As the surface current paths of the DAU-EBG were prolonged by the etched U slots, the size of our proposed DAU-EBG was only 25.9% of the conventional mushroom-type EBG (CMT-EBG) and 37.3% of the ELV-EBG. Due to the asymmetry introduced by the dual U slots, different band-gap properties in X- and Y-directions were obtained. Three band-gaps and two band-gaps were achieved in X- and Y-directions, respectively. [47]

Wei Zhang, Chang-Hong Liang, Tong-Hao Ding, Bian Wu: investigated mushroom-like EBG structures with different number of vias. Theories to analyze the parameter ratio relations between the two-via structure and the one-via structure were presented. After validating the correctness they used the direct transmission method to derive the characteristics of the structures. Then the two-via EBG structure was cascaded with the one-via EBG structure showing that the band-gap of the cascaded structure almost covered the bands of the two structures with different number of vias, which validated the fact that the bandwidth of the multi-via cascaded structure can be broadened effectively. [48]

S. A-sa, P. Krachodnok, and R. Wongsan in 2012: introduced a compact EBG resonator antenna to improve directivity. The antenna was composed of two back-to-back folded dipoles as a feed for a resonator antenna and reflective walls. The single-resonant metallic EBG as a superstrate was designed. A highly directive radiation pattern was created due to angle-dependent attenuation of resonator antenna coupling to free space. It is successful to direction gain of 15.1 dB because of the qualifications of reflective walls. The antenna with a high gain can be used for equipments for wireless communication. [49]

M. S. Alam, K. M. Yeh, M. T. Islam, N. Misran and A. M. Hasbi in 2012: proposed a compact microstrip antenna for 5.4 GHz WLAN/HIPERLAN applications, which achieved a bandwidth of 230 MHz and peak gain of 3.6 dB at 5.4 GHz. The antenna was incorporated with an electromagnetic bandgap structure that was comprised of a 3x3 array of N-like shape unit. The EBG antenna gave a wider bandwidth of 320 MHz, better return loss and improved gain up to 5.46 dB. There is an enhancement of antenna performance with the effectiveness of the proposed EBG structure. [50]

Research Gaps:

From the above literature review, it is clear that:

- In a proximity-coupled microstrip antenna, when a laminate used is too thick for the antenna layer, the coupling will be decreased. And it is hard to achieve broadband impedance matching. A method to optimize impedance matching through narrow cavity backed configuration. Bandwidth beyond 40% can be achieved using either slots on patch or ground plane.
- With an efficient proximity coupled microstrip patch antenna designed at 2.45 GHz, the length of the feeding line penetration and a simple rectangular slot etched in radiation element were used to reject the 2nd and 3rd harmonic frequencies. This application can be used for designing rectangular antennas for wireless power transmission. The frequency range can be increased by using either S or U slots. Also other methods such as EBG structures can be used for this purpose.
- In a strip loaded and slotted patch antenna for wireless applications, a new broadband planar impedance matching scheme was achieved by using a simple rectangular metal strip on a slotted microstrip antenna. It exhibited a good radiation characteristics but with moderate gain. The gain for this antenna can be further increased by using stacked patch configuration.

Problem Definition:

- A proximity coupled Microstrip antenna is to be designed and study of its various parameters. Finally, the results of simulation are verified by fabricating the antenna resonating at 1.52GHz.
- Harmonic reduction is to be done using different EBG structures.
- Multibanding using DGS and bandwidth enhancement using slots on feedline and ground plane is also to be accomplished.

CHAPTER 4

DESIGN OF PROXIMITY COUPLED MICROSTRIP ANTENNA AND STUDY OF ITS VARIOUS PARAMETERS

In this chapter a circularly polarized Rectangular Microstrip antenna with a low-profile, small-size, and light weight is designed for satellite communication resonating at 1.52GHz. The circularly polarized microstrip antennas are classified as single fed type or dual-fed type depending on the number of feed points necessary to excite the circularly polarized waves. The single-fed type has the advantage of not requiring an external circular polarizer such as the 90-degree hybrid.

4.1 Theoretical design

The first step in designing the microstrip patch antenna is to employ the following formulas as an outline for the design procedures. [51]

i) Width of patch:

$$W = \frac{c}{2f_0} \left(\frac{\epsilon_r + 1}{2} \right)^{1/2}, \quad (3.1)$$

where;

c - free space velocity of light, 3×10^8 m/s

f_0 - frequency of operation

ϵ_r - dielectric constant

ii) Effective dielectric constant (ϵ_{eff}):

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2}, \quad (3.2)$$

where;

h - height of dielectric substrate

W - width of the patch

iii) Effective length (L_{eff}):

$$L_{eff} = \frac{c}{2f_0} \sqrt{\epsilon_{eff}} \quad (3.3)$$

iv) Patch length extension (ΔL):

$$\Delta L = 0.412h \frac{(\epsilon_{reff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{reff} - 0.258) \left(\frac{W}{h} + 0.8 \right)} \quad (3.4)$$

v) Actual length of patch (L):

$$L_{eff} = L + 2\Delta L \quad (3.5)$$

4.2 Antenna configuration:

The rectangular patch antenna and the microstrip line are formed of substrates with a dielectric constant 2.6, and thicknesses h and t , respectively. The length of the patch antenna is L_p , and the width is W_p , L_o is the offset length from the center of the rectangular patch antenna to the center of the microstrip line. The characteristic impedance of the microstrip line is 50 ohms. S is the distance between the edge of the patch antenna and the edge of the microstrip line.

The microstrip antenna is made up of rectangular radiating patch having width W_p of 58 mm and length L_p of 56mm is printed on the first substrate. The substrate is made up of copper clad material having dielectric constant of 2.6 and height h of 1.6mm. The width of the microstrip feed line W_s is 8mm and the length of the offset from the center of the rectangular patch antenna to the center of the microstrip feed line is L_o which is of the dimensions of 30.04mm. The length of the feed line from the center of the microstrip patch antenna towards the length of the substrate is S having dimensions of 19.8mm. The feed line is placed on the upper side of the second substrate. The proposed proximity feed rectangular patch antenna design is shown in fig 4.1. The return loss of the antenna can be improved by increasing the length and width of the feed line. The graph shifts towards left by increasing the length and width of the patch. By shifting the feedline to the left that is offset from the center of the rectangular patch the impedance of the antenna varies.

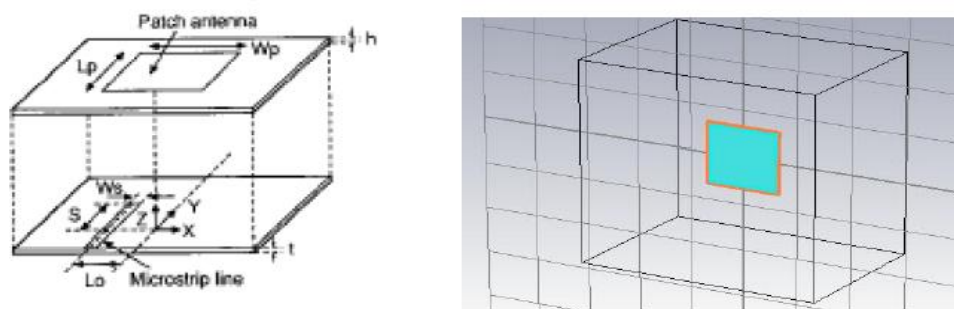


Figure 4.1 Proposed antenna configuration [52] and Designed Antenna

4.3 Simulation results:

The proposed antenna shows good return loss approximately -28dB and good impedance of approximately 52.09 ohms and resonates at 1.52GHz. Figure 4.2 shows the measured impedance and return loss for the proximity-coupled rectangular patch antenna.

Return loss:

The return loss (RL) is the parameter which indicates the amount of power that is lost to the load and does not return as a reflection. The RL is defined as:

$$RL = -20\log_{10}|\hat{\Gamma}| \quad [51]$$

For the perfect matching between the transmitter and antenna $\hat{\Gamma} = 0$ and RL is infinity which means no power is reflected back, while $\hat{\Gamma} = 1$ has an RL = 0, which implies that all the incident power is reflected. In practical applications, the applicable VSWR of 2 is acceptable corresponds to an RL of -9.5 dB or 11% power reflection. A return loss of -28dB is obtained at the resonant frequency of 1.52GHz with a bandwidth of 100MHz.

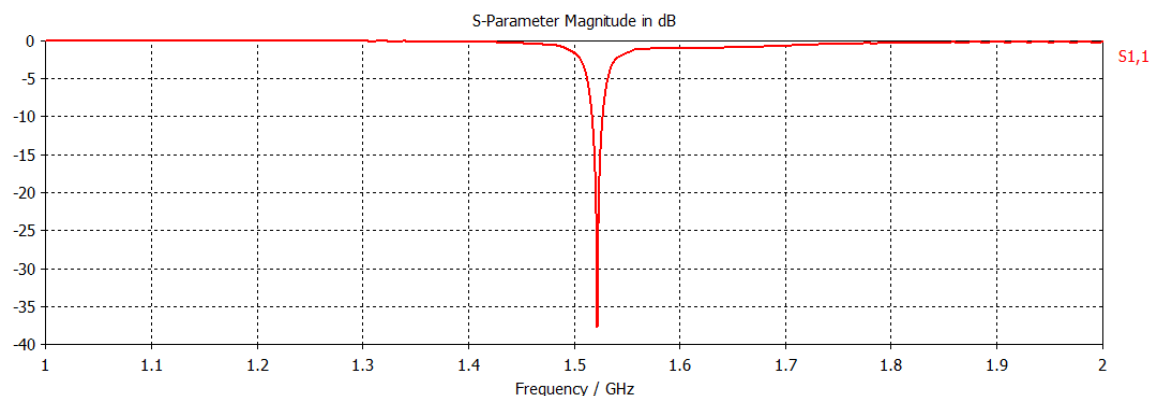


Figure 4.2 Return Loss (dB) vs Frequency curve

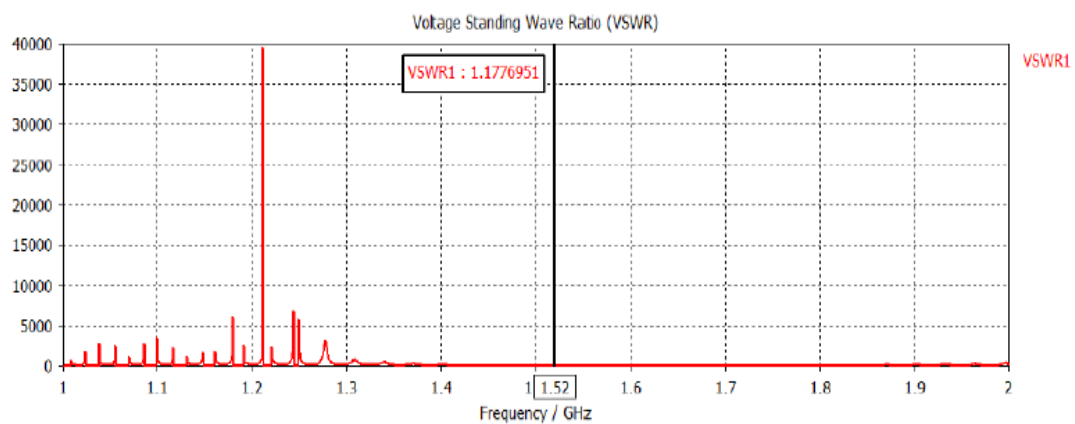


Figure 4.3 Figure showing VSWR at different frequencies

Directivity:

Directivity of an antenna defined as “the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. In mathematical form, it can be written as

$$D = U/U_0 = 4\pi U/P_{rad} \quad [51]$$

If the direction is not specified, it implies the direction of maximum radiation intensity.

Directivity is dimensionless.

U = radiation intensity (W/unit solid angle)

U_0 = radiation intensity of isotropic source (W/unit solid angle)

P_{rad} = total radiated power (W)

A maximum directivity of 6.113 dBi is obtained in the direction of theta equal to two degrees as is indicated by the red part in the figure 4.4.

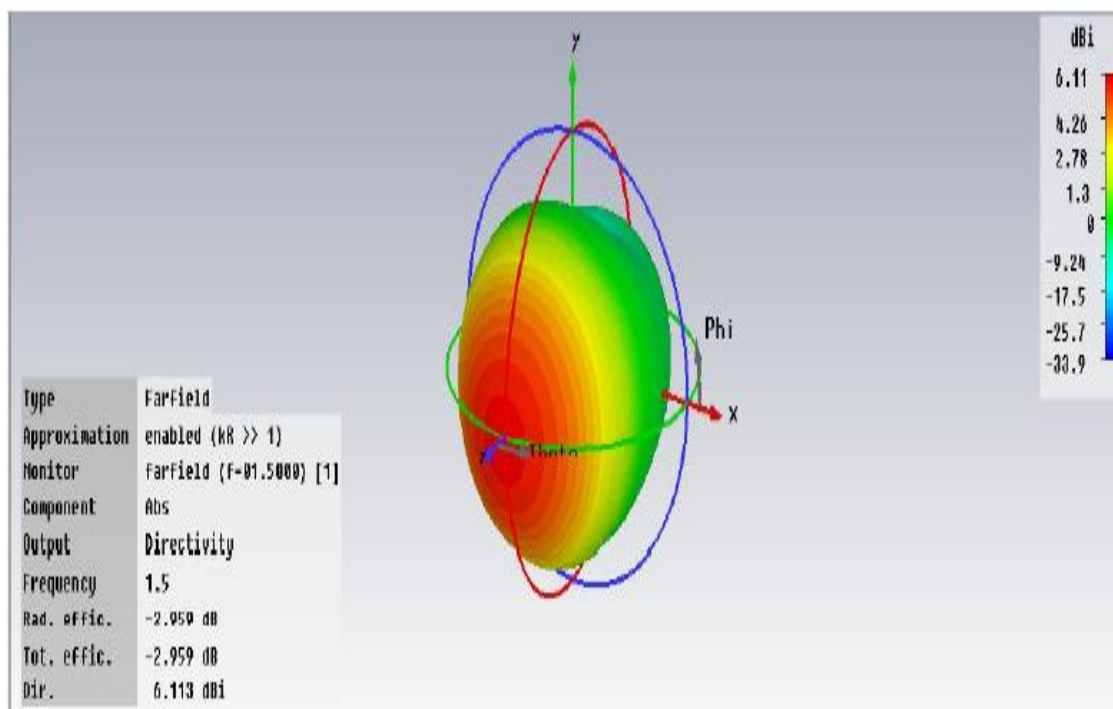


Figure 4.4 Directivity of the designed antenna

Radiation pattern:

In the field of antenna design the term radiation pattern (or antenna pattern or far-field pattern) refers to the directional (angular) dependence of the strength of the radio waves from the antenna. Directivity is 6.1 dBi in the direction of theta equal to 2.0 degrees with a side lobe level of -6.4dB and beam width of 90.6 degrees as is indicated by the E-plane pattern in figure 4.5.

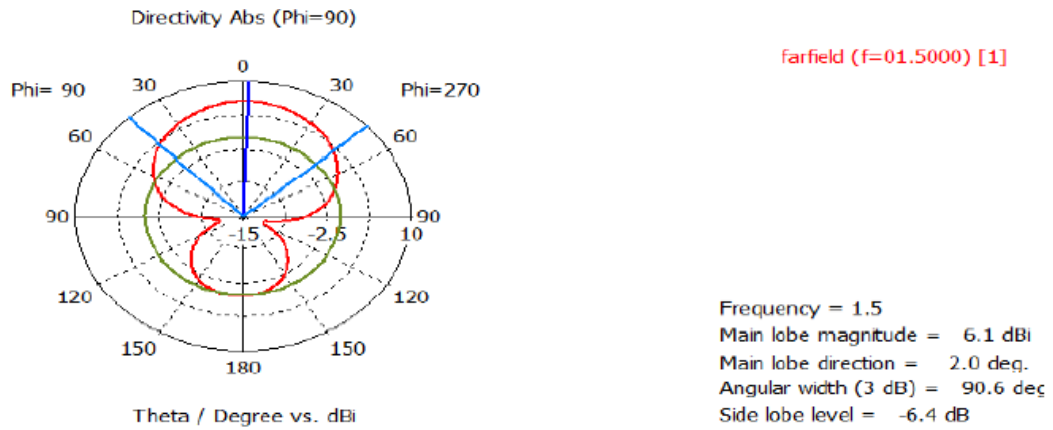


Figure 4.5 Radiation Pattern of the designed antenna

Parametric study of proposed antenna:

In the final optimised design; the return loss can be improved by increasing the length or width of the microstrip feed line but increasing the length of the feed line the impedance of the antenna decreases. Shifting the feedline to the left upto a certain point improves the return loss but increases the input impedance. Shifting the feeding line to the right of the optimum point increases the return loss and decrease the input impedance.

The effect of varying the patch width is studied. As the patch width is increased both the return loss and the resonant frequency decreases.

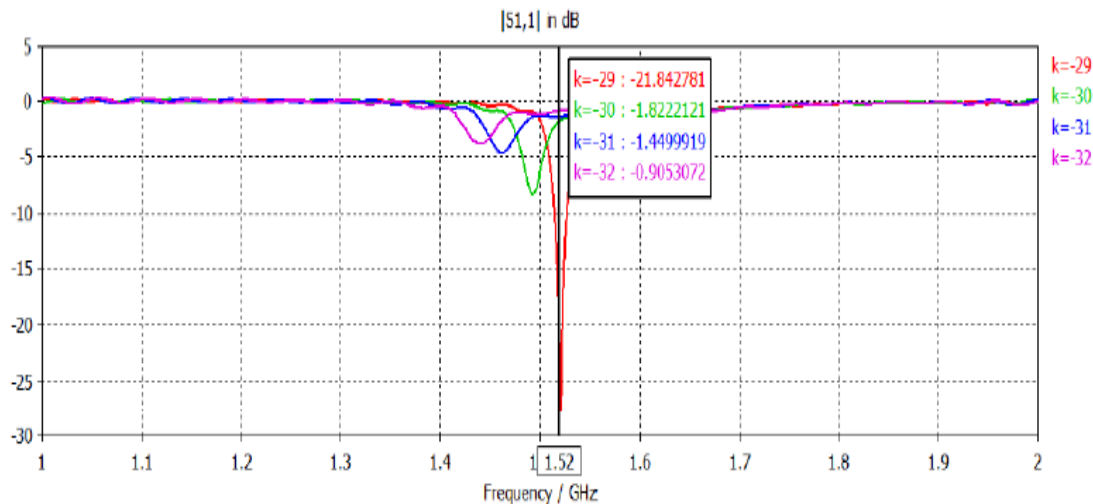


Figure 4.6 Effect of patch width variation on return loss and resonant frequency

4.4 Analysis:

- From the above results it is concluded that: The return loss can be improved by increasing the length or width of the microstrip feed line but increasing the length of the feed line the impedance of the antenna decreases. Shifting the feedline to the left upto a certain point improves the return loss but increases the input

impedence. Shifting the feeding line to the right of the optimum point increases the return loss and decrease the input impedance.

- The designed 1.52 GHz microstrip antenna is employed for Global Positioning System based applications with required bandwidth. This antenna can be fabricated using Photolithography or Printed Circuit Board Fabrication Technique and can be tested in an echoic chamber.

CHAPTER 5

HARMONIC REDUCTION USING PERFORATED EBG STRUCTURE

In this chapter, harmonic reduction is done using perforated EBG structure. Firstly, a conventional PCMA is designed then EBG is used along with this structure to reduce the harmonics.

5.1 Conventional proximity coupled microstrip antenna design

In order to identify and verify the improvement for electromagnetic band gap (EBG) structure in Microstrip antenna, the conventional Microstrip antenna was first designed. This conventional Microstrip antenna is designed using transmission line model and the perforated EBG is designed using the formulas given in section 2.3. The conventional Microstrip antenna so designed resonates at 3.6GHz but has strong third harmonics at $3f_0$. The perforated EBG is then designed to have a bandgap between 5-6GHz and 9-11GHz. This perforated EBG is used as an upper substrate when used along with PCMA. This eliminates the harmonic radiation.

5.1.1 PCMA design

The first step in designing the patch antenna is by employing the formulas in section 4.1.

5.1.2 Design Specifications

The antenna is designed to operate at frequency 3.6 GHz. For this design, two layers of the FR4 dielectric material ($\epsilon_r = 4.4$) with dielectric loss tangent ($\tan \delta$) of 0.019 and height of substrate (h) 1.6mm were used. The feed point is located at the distance 13.35 mm away from the centre of the patch. A rectangular patch is placed on top of the upper substrate.

Frequency (f_r)	3.6 GHz
Dielectric Constant of both substrates(ϵ_r)	4.4
Height of upper and lower substrate	1.6mm
Feeding Method	Proximity Coupling
Shape	Rectangular

Table 5.1 Design Parameters for conventional Microstrip antenna

5.1.3 Designed Antenna Configuration:

Patch Length	17.1mm
Patch Width	23.16mm
Feed line Length	13.35mm
Feed line Width	5.55mm

Table 5.2 Designed antenna specifications

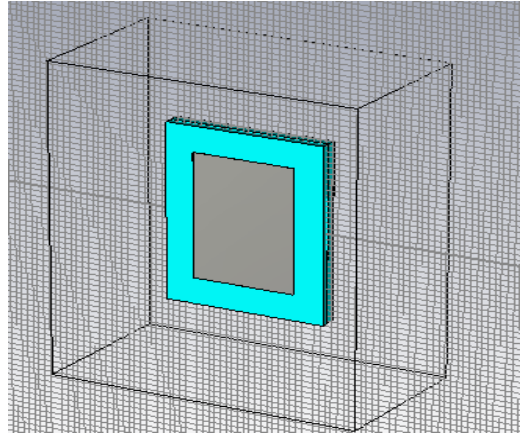


Figure 5.1 Designed Antenna

5.1.4. Return Loss: S1, 1 parameter for the designed antenna is as:

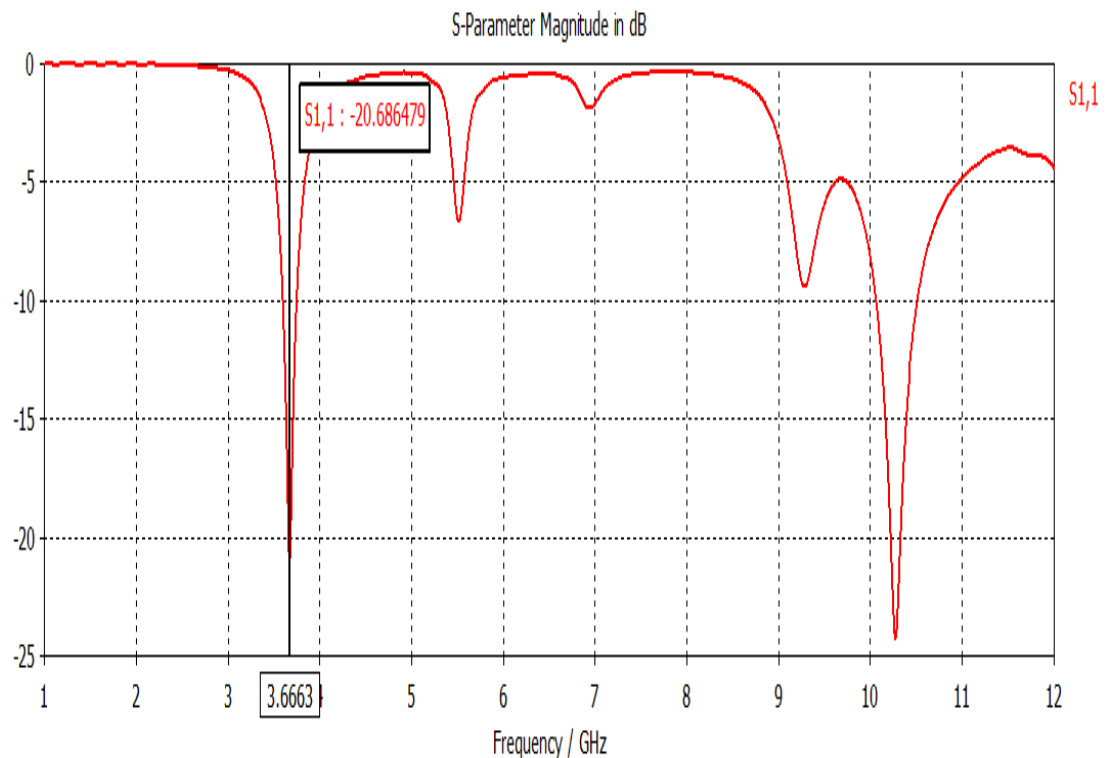


Figure 5.2 S1, 1 parameter of designed antenna

The antenna resonates at 3.6GHz with a return loss of -21dB and a bandwidth of 100MHz at this frequency. The designed antenna experiences strong harmonic radiation due to the presence of third harmonics. The effect of a perforated EBG structure on the third harmonics is studied by designing it at the harmonic frequency.

5.2 Electromagnetic bandgap structure design:

Application of the Electromagnetic Bandgap structure around the conventional antenna suppresses the harmonic radiation present as well as the surface wave and improves the radiation performance of the antenna.

The EBG structure is designed to have a band gap centred at the third harmonics. Using equations 2.1 and 2.2, putting the central frequency desired on the right hand side of equation 2.1 and using the value of effective dielectric constant calculated from equation 2.2, the period is determined. EBG is then repeated to get the desired bandgap. Here it is designed to have a bandgap between 10.4GHz as well as 5.5GHz to suppress the radiation at these frequencies.

Band Gap center frequency(f_r)	5.5GHz and 10.4 GHz
Dielectric Constant of substrate(ϵ_r)	4.4
Height of substrate	1.6mm
Shape	Rectangular

Table 5.3 Design Parameters (EBG)

A square shaped structure 16mm is designed to have a period of $a=12\text{mm}$. A cylinder with inner radius zero and outer radius equal to 6mm is cut from it. The structure is repeated 10 times to meet the desired specifications.

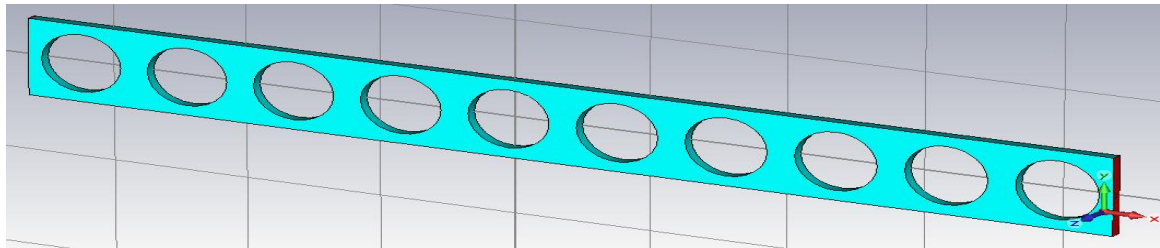


Figure 5.3 Designed Perforated EBG

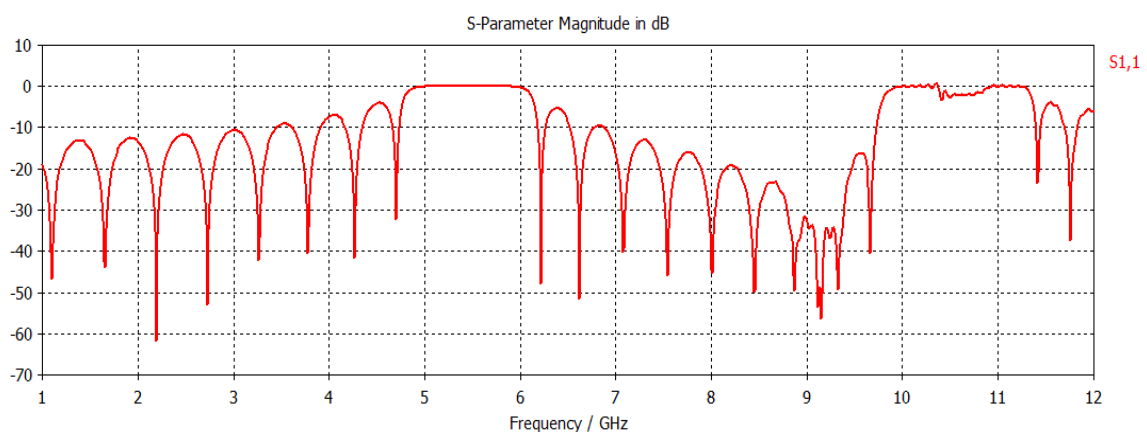


Figure 5.4 S1, 1 parameters of EBG

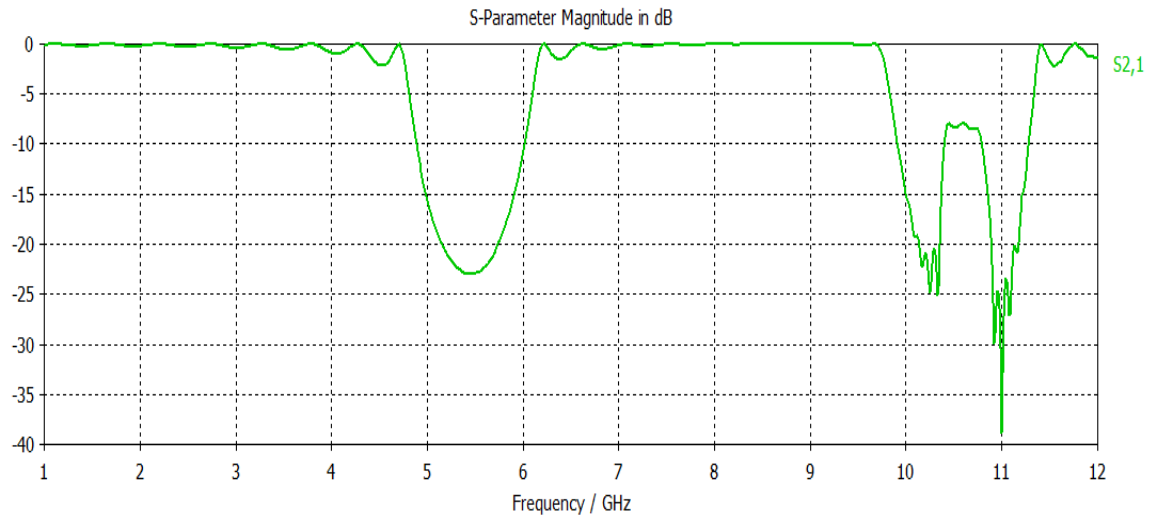


Figure 5.5 S2, 1 parameters of EBG

From the S1, 1 and S2, 1 parameters it is clear that the designed EBG structure has band gap between 5-6 and 9-11GHz as desired. This designed EBG structure is then used as an upper substrate and patch is placed over it to reduce the harmonics obtained from conventional antenna design.

5.3 Microstrip antenna with EBG structure

This design is basically the conventional proximity coupled Microstrip antenna with the designed EBG structure placed below the patch (E- plane). The parameters are same as discussed in the conventional Microstrip antenna and the EBG structure section.

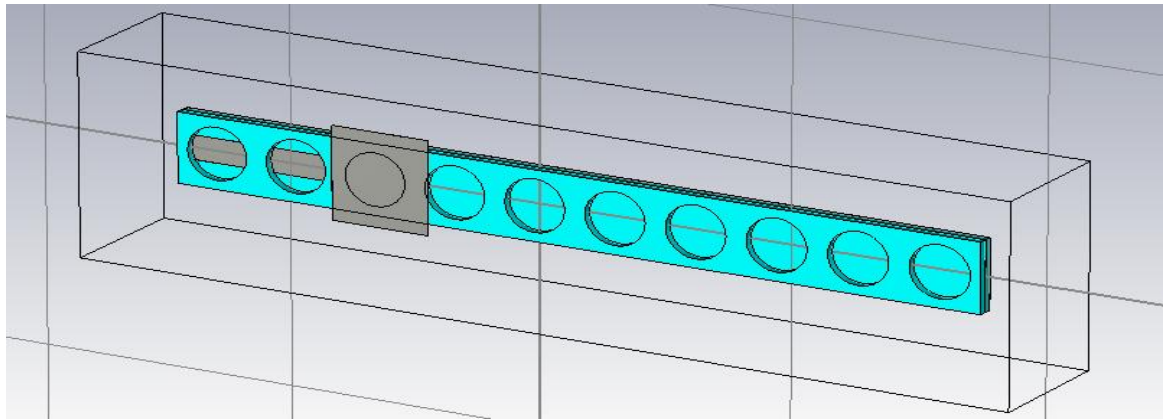


Figure 5.6 Proximity coupled Microstrip antenna with EBG

Centre Frequency(f_r)	3.6 GHz
Dielectric Constant of upper EBG substrate(ϵ_r)	4.4
Dielectric Constant of lower substrate(ϵ_r)	4.4
Height of both substrate	1.6mm

Feed line Inset distance	9.2mm
Feed Line width	5.5mm

Table 5.4 Design parameters of Microstrip antenna with EBG

5.3.1 Designed Antenna Configuration:

The feed line length and width remain the same but the patch length is increased slightly by 2.6 mm and patch width is decreased by 1.96 mm. Thus the patch area remains approximately the same. To obtain the desired characteristics, feedline length and width also remain the same.

Patch Length	19.40mm
Patch Width	21.20mm
Feedline Length	13.35mm
Feedline Width	5.55mm

Table 5.5 Design specifications of Microstrip antenna with EBG

5.3.2 Return Loss of PCMA with EBG:

From the return loss curve, it is clear that the return loss at the fundamental frequency is improved by 15dB whereas the level of harmonics is reduced by 20dB, bandwidth of antenna with EBG remaining the same as that of conventional PCMA that is 100MHz.

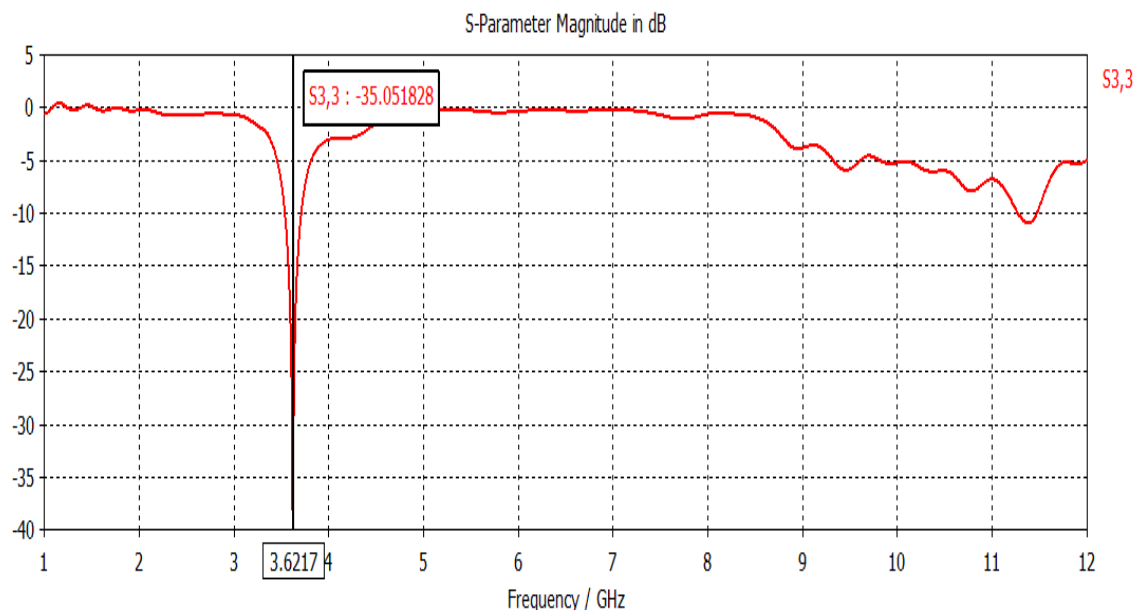


Figure 5.7 S1, 1 parameters of Microstrip antenna with EBG substrate

5.4 Analysis

- A conventional Microstrip antenna experiencing harmonic radiation due to the frequency component present at 10.4GHz can be improved by employing a perforated EBG as upper substrate in the design of proximity coupled Microstrip

antenna, thereby suppressing harmonic radiation without affecting the radiation characteristics of antenna and thereby reducing gain at harmonic frequency by 20dB.

- The patch area in both conventional PCMA and in the PCMA with EBG remains the same though the patch length is slightly increased and the patch width is slightly decreased.
- There is a variation in the harmonic level as the inset distance of feedline is varied. The harmonics increase as the feed line length is increased beyond the optimum point.
- Though the radiation properties are not affected but the size of antenna due to perforated EBG is greatly enhanced. To overcome this, mushroom EBG can be used as discussed in subsequent chapters.

CHAPTER 6

BANDWIDTH ENHANCEMENT, HARMONIC REDUCTION AND MULTIBANDING

In this chapter, a conventional PCMA is designed which is then used along with a single patch MEBG structure to get a reduced harmonics design. Using a dumbbell DGS in this design results into a multiband antenna resonating at three frequencies.

6.1 Conventional proximity coupled microstrip antenna design

The theoretical designing procedure for conventional Microstrip antenna is same as shown in 4.1.

6.1.1 Design Specifications

The antenna is designed to operate at frequency 2.2 GHz. For this design, the FR4 dielectric material ($\epsilon_r = 4.5$) with dielectric loss tangent ($\tan\delta$) of 0.015 and height of substrate (h) 1.5mm is used as a lower substrate. The Rohacell dielectric material ($\epsilon_r = 1.07$) with dielectric loss tangent ($\tan\delta$) of 0.0002 at 2GHz and height of substrate (h) 2mm is used as an upper substrate. The feed point is located at the distance 50mm away from the centre of the patch.

Frequency (f_r)	2.2 GHz
Feeding Method	Proximity Coupling
Shape of patch	Square

Table 6.1 Design Parameters for conventional Microstrip antenna

6.1.2 Designed Antenna Configuration:

A square patch of 50×50mm is used and the dielectric used is of 100×100mm. For optimum matching in order to reduce the second and third harmonics, length of feedline is varied.

Patch Length	50mm
Patch Width	50mm
Feedline Length from patch	29mm
Feedline Width	4mm

Table 6.2 Designed antenna specifications

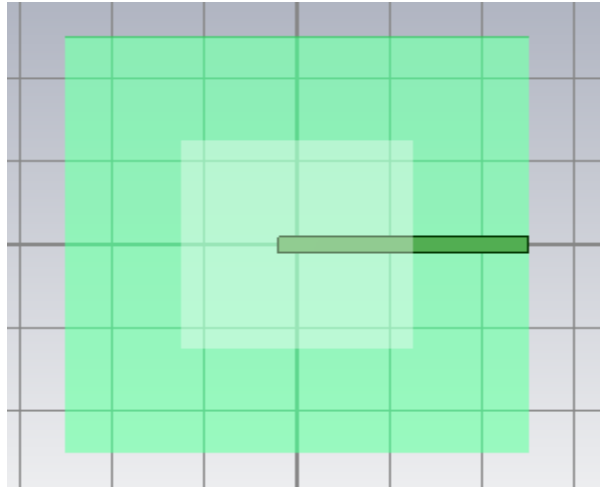


Figure 6.1 Designed Antenna

6.1.3 Return Loss:

$S_{1,1}$ parameter for the designed antenna is as:

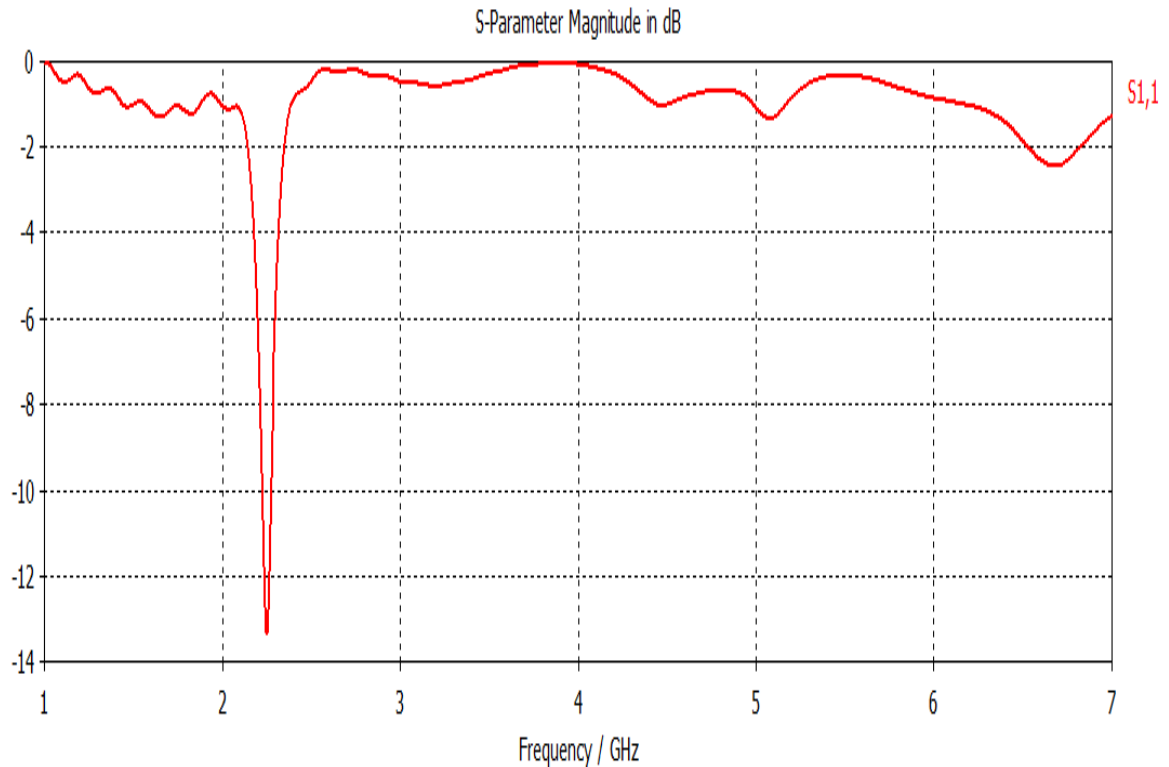


Figure 6.2 $S_{1,1}$ parameter of designed antenna

At the fundamental frequency of 2.2GHz the return loss is -13.5dB with a bandwidth of 49MHz. The designed antenna experiences harmonic radiation due to the presence of second and third harmonics. Second harmonics is reduced with Feed line-patch overlap length (L). Third Harmonics is eliminated using a compact EBG resonator (mushroom type) which consists of a patch with a grounded via. The effect of a mushroom EBG structure on the harmonics is studied by designing it at the harmonic frequency.

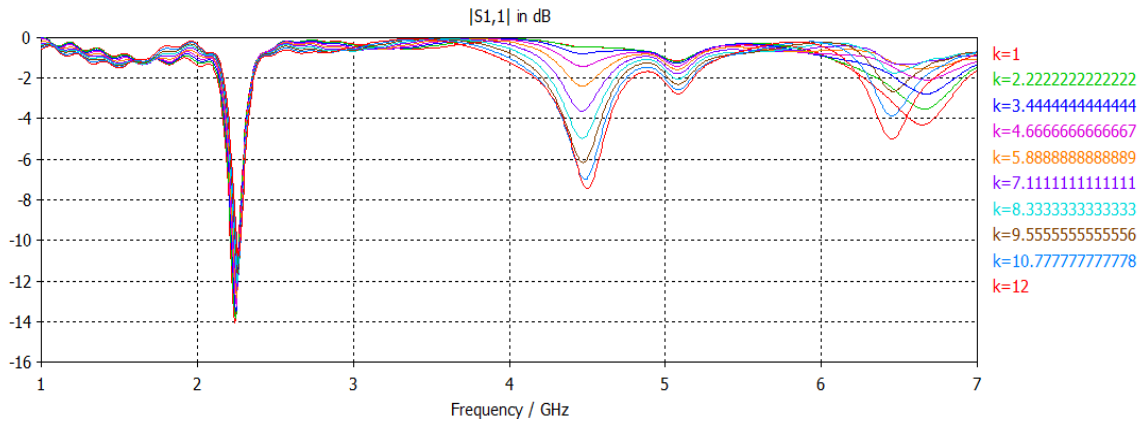


Figure 6.3 Effect of harmonics with variation in feedline length (25+k) mm

From the figure it is clear that as the length of the feedline is increased the effect of the harmonics becomes more prominent. At feedline and patch overlap length of 29mm, optimum matching is obtained with -2 dB and -3 dB return loss at second and third harmonics respectively.

6.1.4 Radiation Pattern

From polar plot view of the gain, it can be seen that at a frequency of 2.2GHz, gain is 8.9 dB, radiation pattern obtained is with main lobe directed at an angle of 0.0 degree, having angular beam width of 72.8 degree. The magnitude of the main lobe is 8.9dB with a side lobe level of -22.8dB as is indicated by the E-Plane pattern in figure 6.1.4.

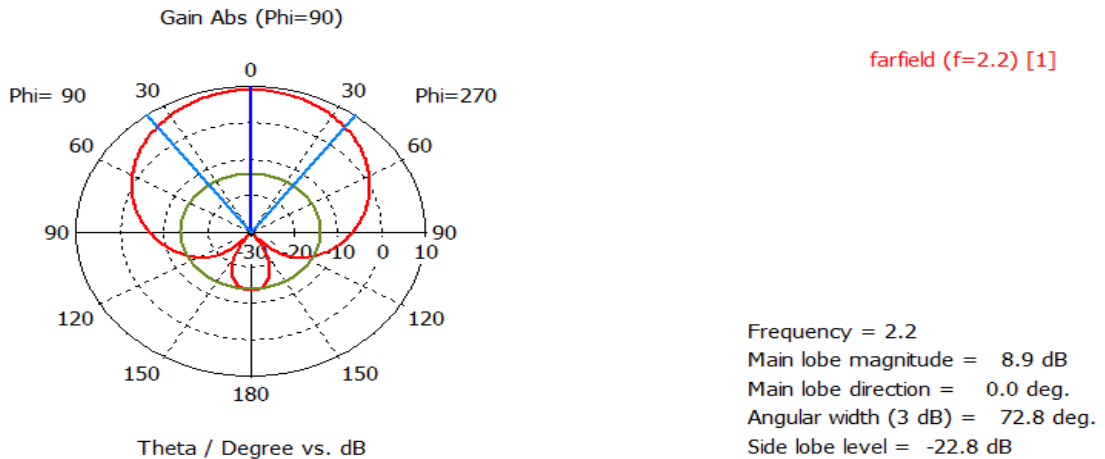


Figure 6.4 Gain Plot (polar)

6.2 Conventional PCMA with a slot in feedline and ground plane:

In this proximity coupled antenna a narrow slot is cut in the microstrip feed line. The slot is located at a position, which is approximately $\lambda/4$ from the other end of input feed. Another narrow slot is located in the ground plane, which is below the feed line, at the same position as the slot in the microstrip feed line. Its dimensions are slightly greater

than the dimensions of the slot in the feed line. The centers of both slots must be at the same location for maximum coupling. The patch is located above the feed in such a way that the center of patch is almost exactly above the center of slot or slightly offset for maximum coupling. This offset is less than 1.5 mm.

Slot	Length of slot	Width of slot
Feedline	4.5	3.6
Ground Plane	15	4

Table 6.3 Characteristics of slot in feedline and ground plane

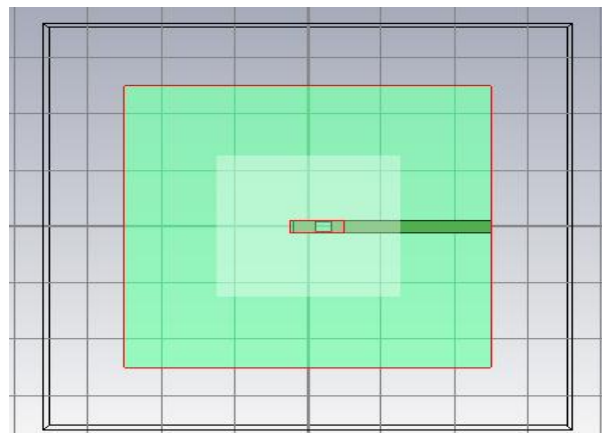


Figure 6.5 PCMA with a slot in feedline and ground plane

6.2.1 Return Loss:

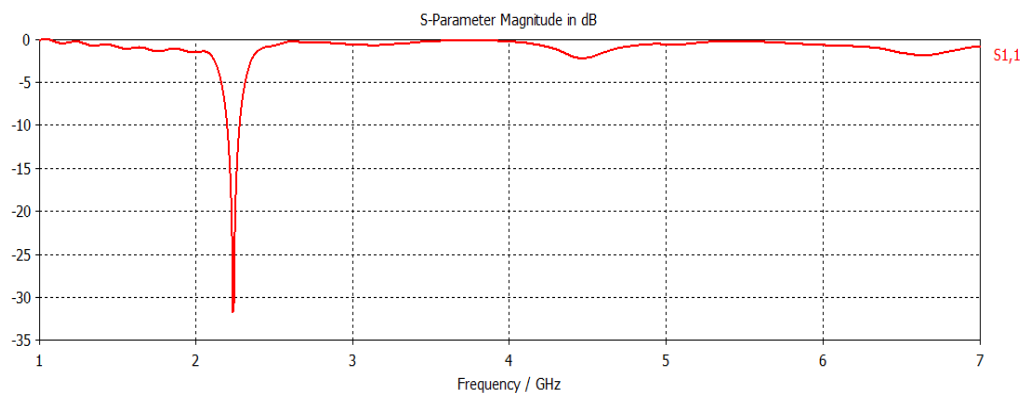


Figure 6.6 Return loss curve with a slot in feedline and ground plane

From the return loss curve, it is clear that the return loss as well as the impedance bandwidth has improved by 16 dB and 73% respectively if we cut a slot in both the feedline and the ground plane. The bandwidth now is 85GHz and hence is approximately double than reference structure while the level of harmonics still remains the same.

6.3 Electromagnetic bandgap structure design:

Application of the Electromagnetic Bandgap structure around the conventional antenna suppresses the harmonic radiation present as well as the surface wave and improves the radiation performance of the antenna.

The EBG structure is designed to have a band gap centred at the third harmonics that is 6.6GHz to suppress the radiation at these frequencies.

Band Gap center frequency(f_r)	6.6GHz
Dielectric Constant of both substrates (ϵ_r)	4.5
Height of lower substrate	0.5 mm
Height of upper substrate	1.5 mm
Shape	Square

Table 6.4 Design Parameters (EBG)

A square shaped structure 100×100 mm is designed with a single patch MEBG. This mushroom type element works as a resonator, which makes a short circuit between the transmission line and the ground plane at resonance. The increase in the resonator metallization size causes a reduction in the resonant frequency. Resonator with patch size length 2.75 mm and width 6 mm is used with the Microstrip line width of 18.28 mm. A detailed numerical characterization of the stopband position and bandwidth with the geometrical parameters of the resonator has been presented in [16].

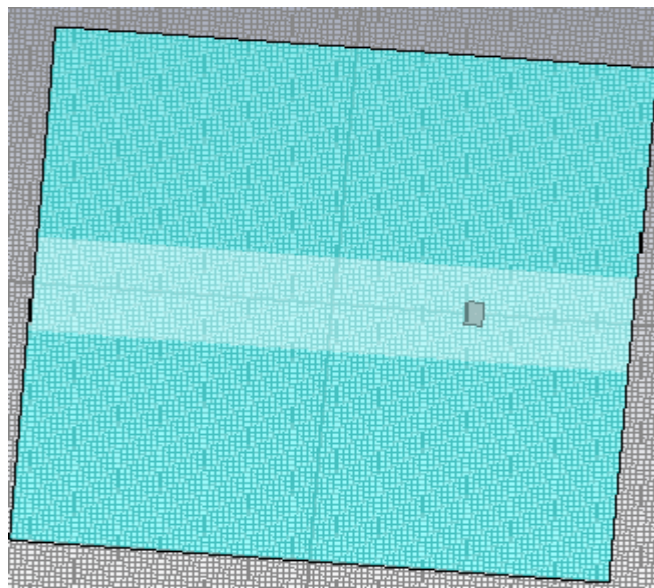


Figure 6.7 Designed Single patch mushroom EBG

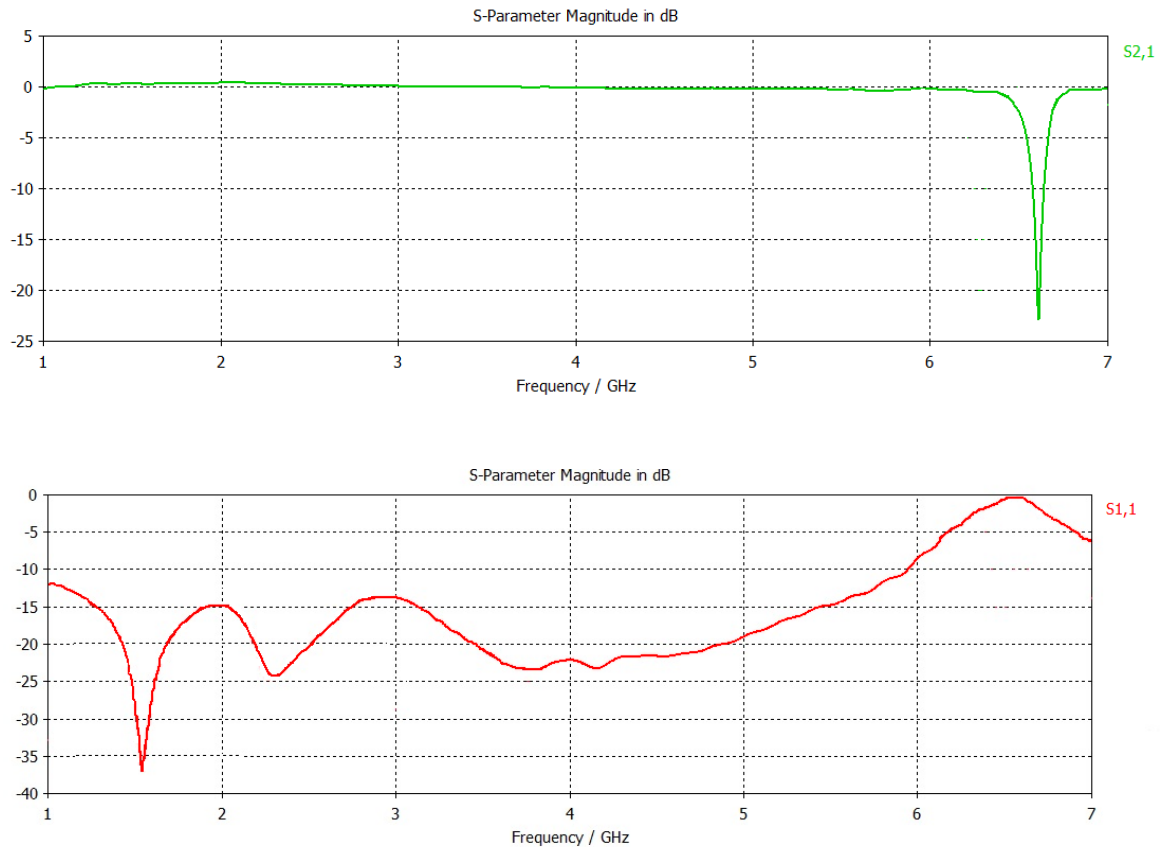


Figure 6.8 S1, 1 and S2, 1 parameters of EBG

The single patch mushroom EBG has a bandgap centred at 6.6GHz. The EBG is designed at a lower frequency since there is a shift in the frequency when the antenna is placed over the EBG structure, the centre frequency of the bandgap shifts by a certain amount.

6.4 Microstrip antenna with EBG structure

This design is basically the conventional proximity coupled Microstrip antenna with the designed EBG structure placed below the patch (E- plane). The parameters are same as discussed in the conventional Microstrip antenna and the EBG structure section.

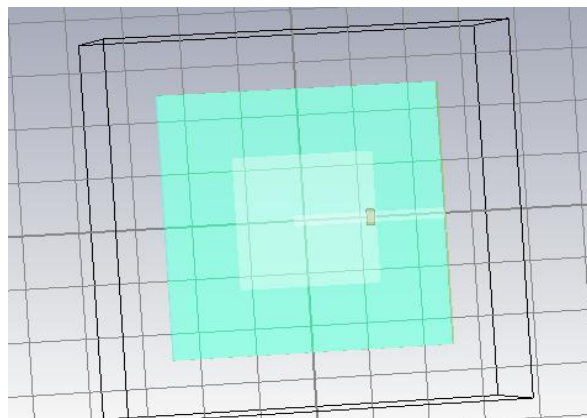


Figure 6.9 Proximity coupled Microstrip antenna with single patch MEBG

Layer	Thickness	ϵ_r	Material	Tan δ
1 (lowest)	0.5	4.5	FR4	0.015 (1GHz)
2 (Middle)	1.5	4.5	FR4	0.015 (1GHz)
3 (Upper)	2	1.05	Rohacell 51	0.0002(2.5GHz)

Table 6.4 Characteristics of substrates

Between the layers 1 and 2 is placed the smaller patch having dimensions 2.75×6 mm. A via connects the centre of patch to the ground plane. The antenna's radiating patch is placed on top of the uppermost substrate.

6.4.1 Designed Antenna Configuration:

Patch Length	50 mm
Patch Width	50 mm
Feedline Length	29 mm
Feedline Width	4 mm

Table 6.5 Design specifications of Microstrip antenna with EBG

6.4.2 Return Loss:

The return loss curve clearly states that there is no change in the fundamental frequency when the antenna is placed over the mushroom EBG. The fundamental frequency is 2.2GHz but the harmonics are reduced to a level as low as -0.5dB. The bandwidth of antenna is same as conventional PCMA that is 49MHz.

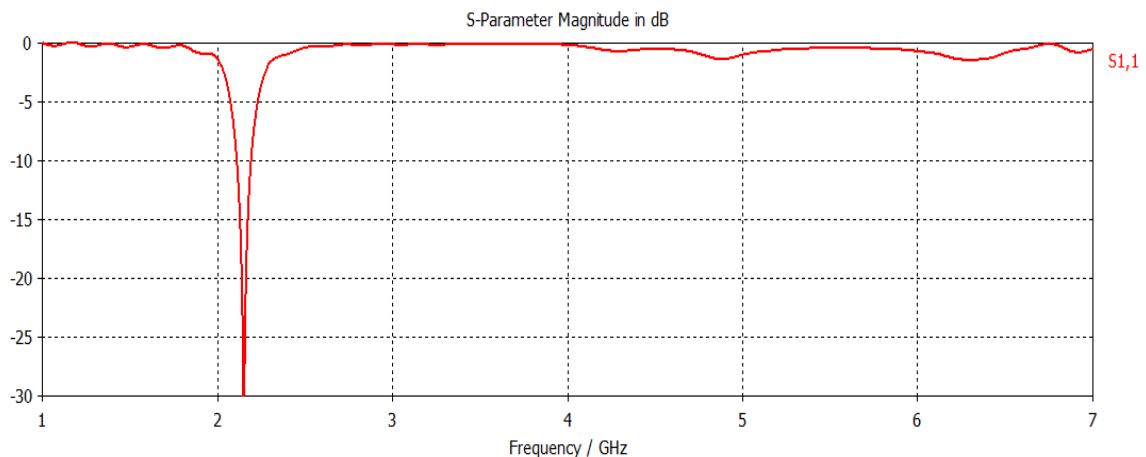


Figure 6.10 S1, 1 parameters of Microstrip antenna with EBG substrate

6.4.3 Radiation Pattern

From polar plot view of the gain, it can be seen that at a frequency of 2.2GHz, gain is 8.3 dB, radiation pattern obtained is with main lobe directed at an angle of 0.0 degree, having angular beam width of 73.8 degree. The magnitude of the main lobe is 8.3dB with a side lobe level of -24dB. There is a very little change in the radiation characteristics of PCMA and PCMA with EBG as can be seen with the E-Plane pattern of PCMA with EBG. Gain has reduced by 0.6dB whereas the side lobe level is reduced by 2dB.

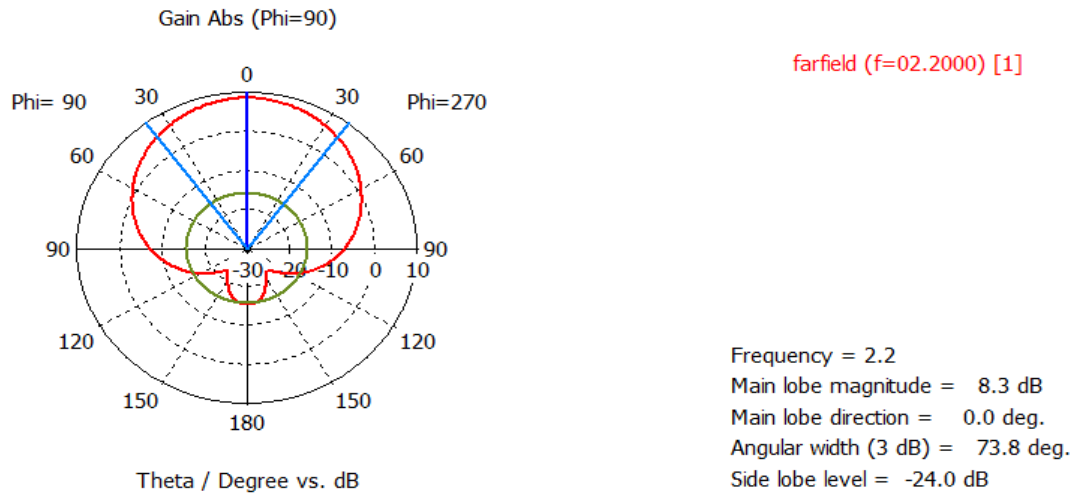


Figure 6.11 Farfield characteristics of antenna with EBG

6.5 Effect of using DGS with conventional PCMA and in PCMA with EBG:

6.5.1 PCMA with dumbbell DGS

A PCMA with dumbbell DGS as in fig 6.12.

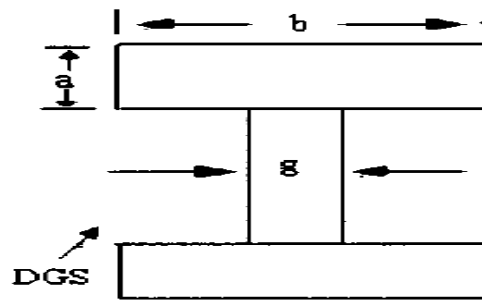


Figure 6.12 Dumbbell DGS

The parameters a , g and b are varied to get the optimised results, where ' b ', the length ' a ', the width of the longer arm of dumbbell and ' g ' is the length of the smaller arm. It is observed in all cases that the harmonics are more pronounced between 4 to 6GHz. As the parameter ' b ' is varied, there is a shift in the resonant frequency to the right as can be seen from figure 6.14. With the variation in parameter ' g ', the return loss at fundamental frequency of 1.495 and 2.6GHz is decreased as in figure 6.15.

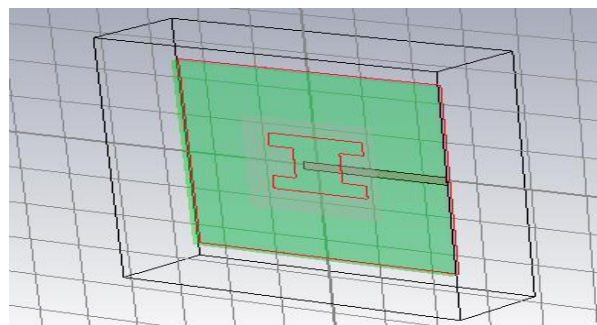


Figure 6.13 PCMA with dumbbell DGS

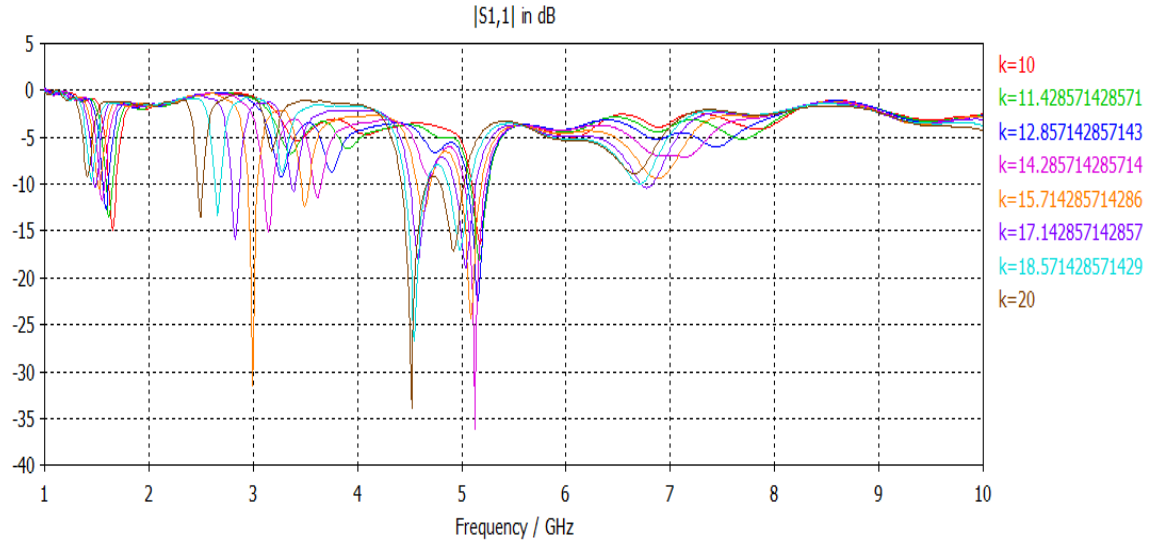


Figure 6.14 Variation in return loss with 'b'

The figure shows return loss curves when 'b' is varied from 20 to 40mm where $b = -k$ to k . The resonant frequency shifts to right as 'b' is decreased where the minimum return loss is observed at a frequency of 3GHz. Also the level of harmonics remains the same for any change in 'b'.

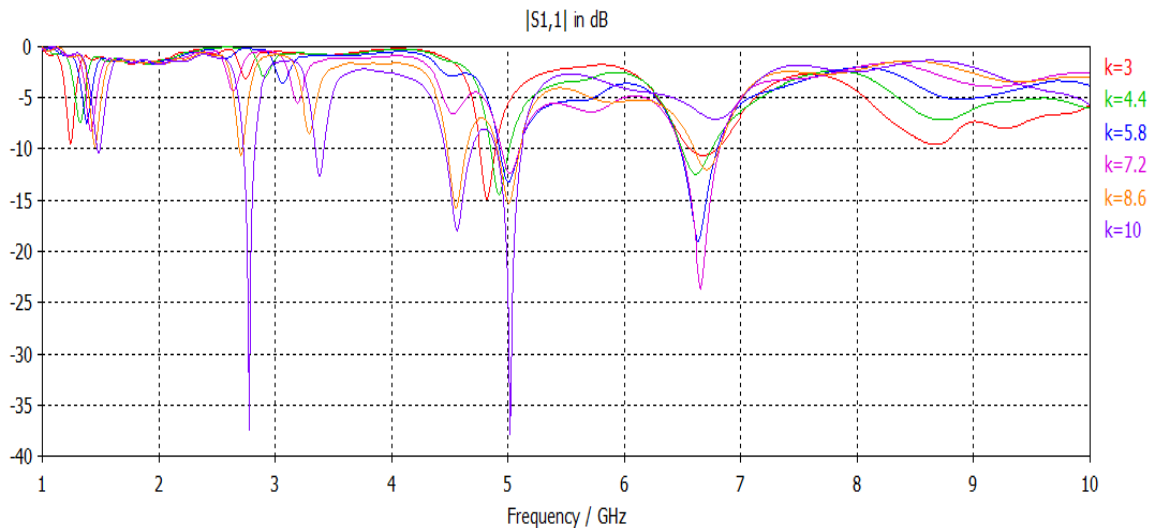


Figure 6.15 Variation in return loss with 'g'

The figure shows return loss curve when 'g' is varied from 6 to 20 mm where $g = -k$ to k . It is observed that as 'g' is increased, the return loss at fundamental frequencies is improved however with an equal increase in level of harmonics also. EBG is then designed so as to reduce the harmonics at these frequencies and also to improve gain at resonant frequencies.

6.5.2 Using DGS in PCMA with EBG

A dumbbell shaped DGS similar to the one in 6.12 is made in ground plane of PCMA with EBG structure similar to the one in 6.3. Resonator with patch size 9×6 mm is used.

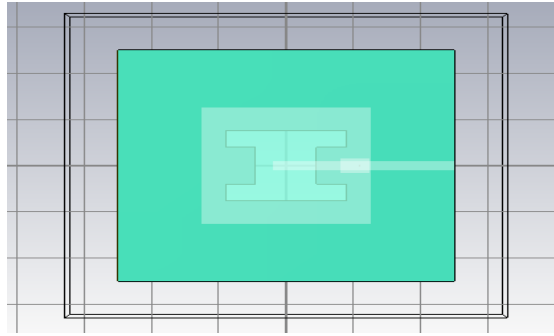


Figure 6.16 Designed antenna

With the introduction of dumbbell shaped DGS in the PCMA-EBG antenna, a triple band antenna is obtained with return loss as shown in figure 6.17. The return loss at 1.43GHz is -26dB, at 2.61GHz is -38dB and at 3.17GHz is -36dB with a bandwidth of 80MHz at all frequencies. The return loss at resonant frequencies which were present due to DGS in PCMA is now improved with introduction of EBG in PCMA.

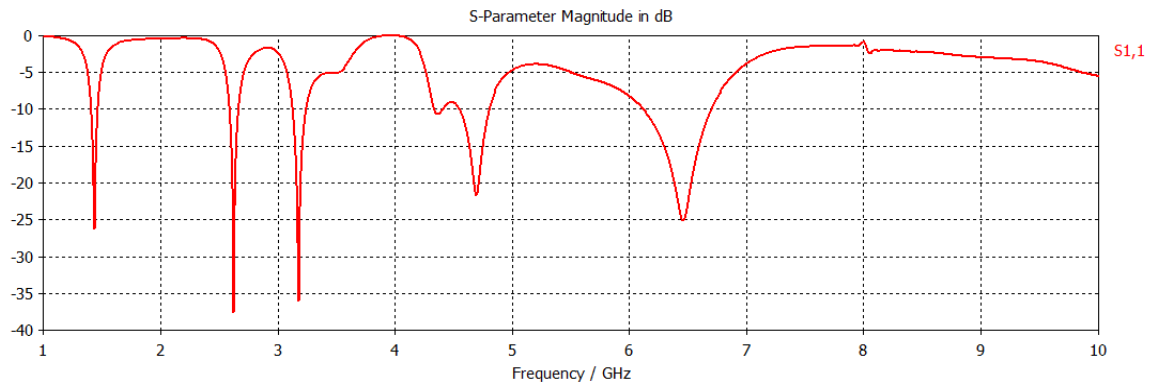


Figure 6.17 S1, 1 parameter for multiband antenna with DGS

a	b	g
7mm	36mm	18mm

Table 6.6 Parameters of DGS

6.5.3 VSWR at resonant frequencies

The VSWR range at all the desired frequencies is between 1 and 1.30. VSWR at 1.43GHz is found to be 1.26. VSWR at 2.61GHz is found to be 1.12. VSWR at 3.17 GHz is found to be 1.04.

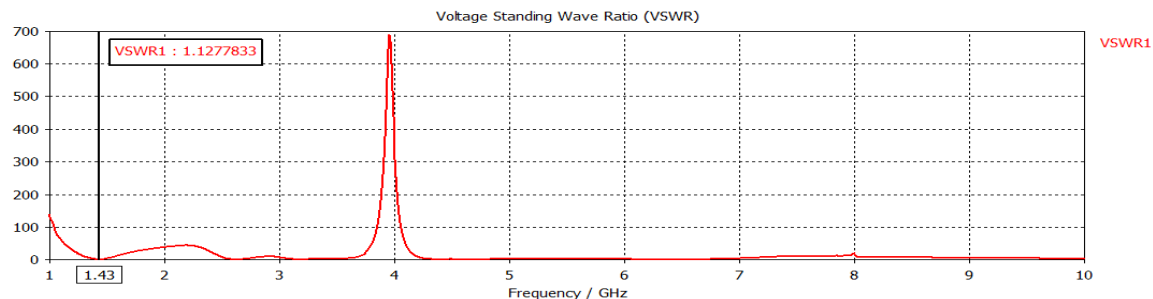


Figure 6.18 VSWR at 1.43 GHz

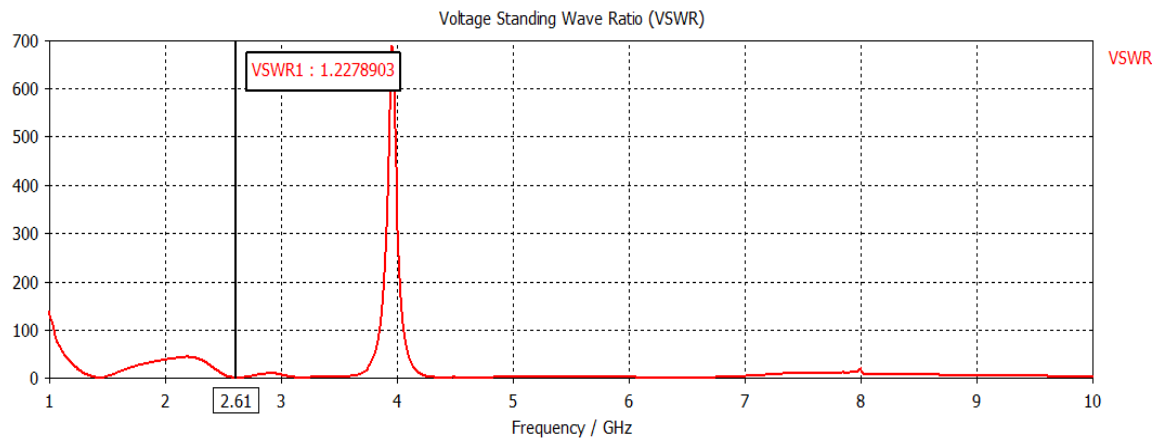


Figure 6.19 VSWR at 2.61GHz

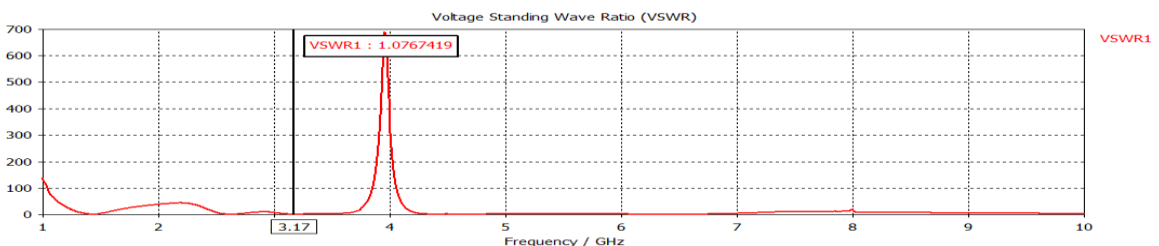


Figure 6.20 VSWR at 3.17 GHz

6.6 Radiation Pattern

The polar plots for farfield characteristics at triple band frequencies is shown as below:

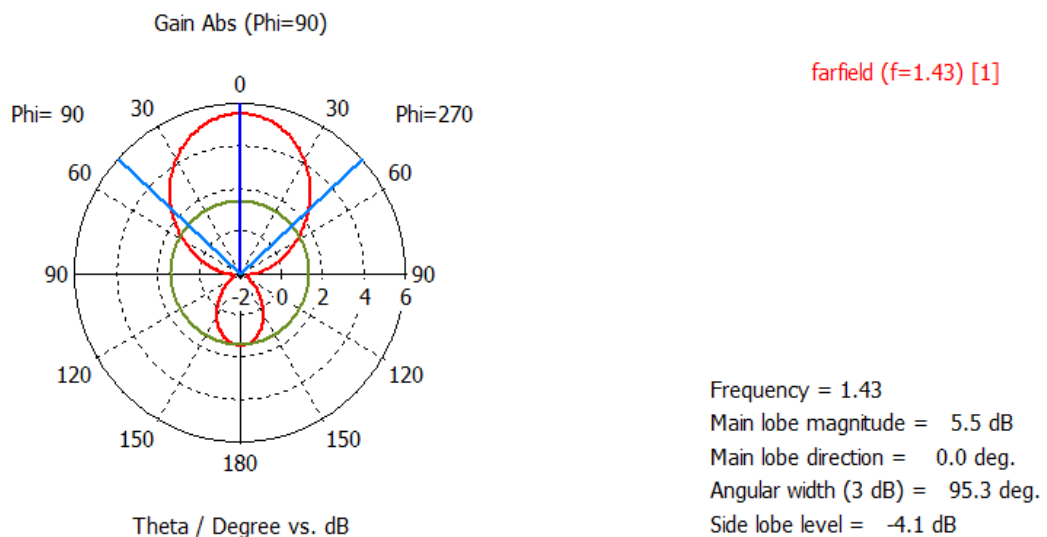
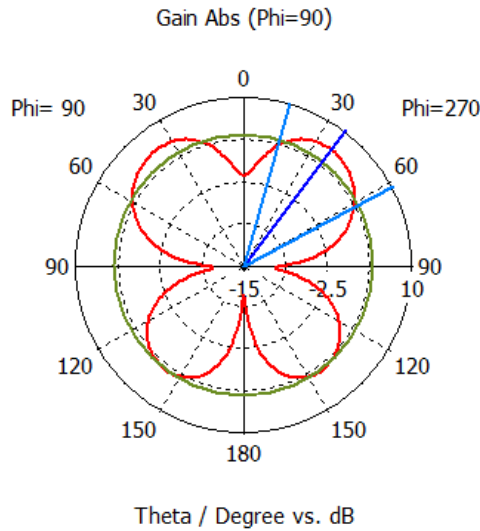


Figure 6.21 E-plane pattern at 1.43 GHz

Highest gain is found to be 5.476dB in the direction of theta equal to zero with an angular width of 95.3 degrees and a side lobe level of -4.1dB.

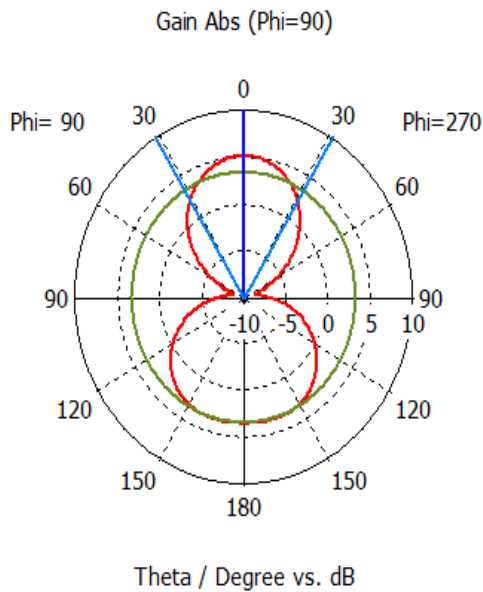


farfield (f=2.61) [1]

Frequency = 2.61
Main lobe magnitude = 6.5 dB
Main lobe direction = 37.0 deg.
Angular width (3 dB) = 46.3 deg.
Side lobe level = -2.2 dB

Figure 6.22 E-plane pattern at 2.61GHz

Highest gain is 6.464dB in the direction of theta 37 degrees and Phi=90 and 270 degrees with an angular width of 46.3 degrees. Another front lobe is there which is diametrically opposite and identical to the main lobe. There are two back lobes each having an angular width of 20 degrees. Hence, the antenna radiation pattern is identical to that of omnidirectional antenna.



farfield (f=3.17) [1]

Frequency = 3.17
Main lobe magnitude = 5.1 dB
Main lobe direction = 0.0 deg.
Angular width (3 dB) = 63.2 deg.
Side lobe level = -1.7 dB

Figure 6.23 E-plane pattern at 3.17 GHz

Highest gain is found to be 5.121dB in the direction of theta equal to zero with an angular width of 63.2 degrees. There is back lobe in the direction of theta equal to 180 degrees, with an angular width of 120 degrees. These two side lobes allow bidirectional communication.

6.7 Analysis

- A conventional Microstrip antenna experiencing harmonic radiation due to the frequency component present at 4.4GHz and 6.6 GHz can be improved by varying the feedline length to reduce the second harmonics and designing a resonator that is a single patch MEBG for eliminating the third harmonics component. The application of both the tuning length technique and the use of a resonator element can mitigate the 2nd and 3rd harmonic radiation in this type of antenna. 3rd harmonic is suppressed by 8dB and second harmonics by 5dB.
- The radiation pattern at fundamental frequency is not significantly affected by the proposed modifications. The mechanisms proposed in the new antenna do not reduce the antenna gain and hence, the efficiency at the operating frequency.
- Since the resonator is small and it is placed under the patch metallization, a compact design is achieved, given that no extra surface is needed to introduce the filtering cell. Also this resonator does not cause back radiation problems. Consequently, the simplicity of this compact low harmonics design has potential application in active microstrip antennas for communications systems.
- The level of harmonics can be reduced using the tuning length technique and the bandwidth can be then improved by 73% using a slot in the feedline and the ground plane as compared to ordinary proximity coupled antenna.
- Using an EBG and DGS with simple proximity coupled antenna, a compact triple band antenna with reduced harmonics is obtained. The designed triple band antenna can be used for satellite applications. The 1.4GHz band is used to provide supplementary mobile downlink, 2.6GHz band is used for mobile broadcasting and 3.1 GHz band for mobile WiMax applications. With a gain of 5.476dB at 1.43, 6.464dB at 2.61 and 5.121dB at 3.17, this antenna can be used in MIMO applications.

CHAPTER 7

FABRICATION AND TESTING OF SINGLE BAND MSA

This chapter describes the entire procedure for fabrication of a microstrip patch antenna. A single band antenna is fabricated which is also designed and simulated in chapter 4.

7.1 Simulated Results of the Antennas at 1.52GHz

The simulated result of the Microstrip antenna resonating at 1.52GHz as discussed in chapter 4 has been discussed below:

- **Single Band Antenna at 1.52GHz:** The dimensions of the antenna are given below in the table 7.1

Patch Length	56mm
Patch Width	58mm
Feedline Length from patch	8mm
Feedline Width	34.8mm

Table 7.1 Design specifications of antenna at 1.52GHz

For this design, the copper clad material with $\epsilon_r = 2.6$ with height of 1.6mm is used as both upper as well as lower substrate. The feed point is offset from the centre of the patch by 30.4mm.

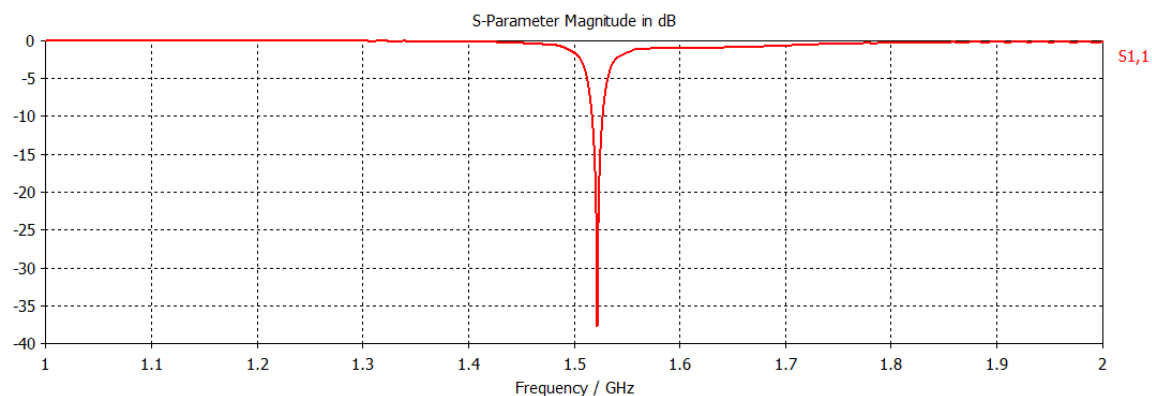


Figure 7.1 Return loss curve of simulated antenna

7.2 Fabrication process:

There are various steps followed when we fabricate an antenna.

- 1.) Brush the PCB.
- 2.) Cut PCB into the required size.
- 3.) Dip PCB in the photo-resist and dry it in oven.
- 4.) Draft the layers of antenna on a transparent sheet.
- 5.) Take photo of the layers on the negative by using a camera.

- 6.) Develop negative for each layer.
- 7.) Put negative on PCB and expose to Ultra Violet radiations.
- 8.) Develop image on PCB by photo-resist developer.
- 9.) Etching of PCB.

Final Design is now ready.

7.3 Fabricated antenna at frequency 1.52 GHz

Below is the fabricated antenna. Figure 7.2 shows the simple single band antenna at 1.52GHz.



Figure 7.2 Fabricated antenna at 1.52 GHz

7.4 Testing of Antennas on VNA:

A proximity coupled single band microstrip patch antenna at 1.52GHz for mobile satellite application was designed using CST2010 studio (software). But practically, antenna has been tested using VNA model no: E5071C, frequency range is 9KHz-8.5GHz and is shown in figure 7.3.

7.5 Comparison of simulated and tested results

It is found that the resonant frequency is shifted by 40GHz. Though the bandwidth found is the same as that of simulated results that is 80GHz. The resonant frequency now is 1.56GHz and return loss is also reduced by 15dB.

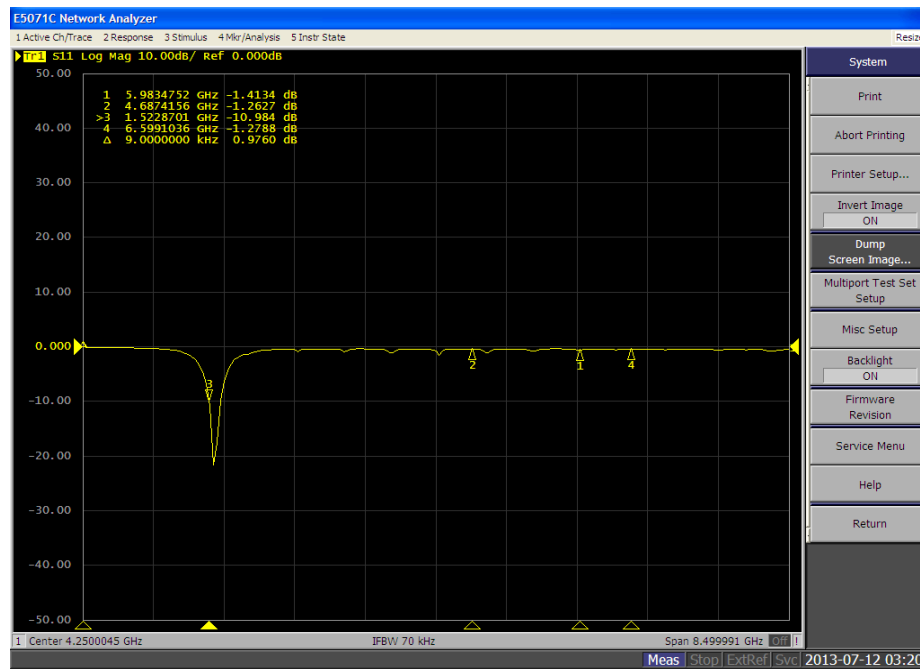


Figure 7.3 Tested results at 1.56GHz.

7.6 Analysis

The fabrication and the testing of the single band antenna is done and it is observed that there occur some shifts in the results of simulated and fabricated antennas.

CHAPTER 8

CONCLUSION AND FUTURE SCOPE

8.1 Conclusion

- In this dissertation, firstly a simple rectangular proximity coupled Microstrip antenna was designed which resonates at a frequency of 1.522GHz and provides a bandwidth of 100MHz. Different physical parameters such as patch width and feedline length were analysed and various antenna parameters like operating frequency, input impedance, VSWR, Bandwidth, Return loss, directivity and gain were determined for each antenna configuration. A return loss of -37.5dB at the resonant frequency of 1.52GHz with a bandwidth of 100MHz at the resonant frequency and a directivity of 6.113 dBi with a beam width of 90.6 degrees is obtained. This can be used for GPS applications. This antenna is also fabricated and tested to verify the simulated results. There is a slight shift in the resonant frequency of fabricated antenna due to soldering issues, imperfect connector and VNA accuracy problems.

Effects of Parameter variation:

In the final optimised design; the return loss can be improved by increasing the length or width of the microstrip feed line but increasing the length of the feed line the impedance of the antenna decreases. Shifting the feedline to the left upto a certain point improves the return loss but increases the input impedance. Shifting the feeding line to the right of the optimum point increases the return loss and decrease the input impedance.

Parameter Varied	Value of parameter varied	Effect of parameter varied
Patch Width	K=29 K=30 K=31 K=32	As the patch width is increased both the return loss and the resonant frequency decreases. An optimum value of -28dB is obtained with a patch width of 29mm.

Table 8.1 Effect of Parameter variation

- Harmonic reduction is achieved with a perforated EBG structure which reduced the harmonics from a simple PCMA by 20dB and also improves the return loss at the fundamental frequency by 15dB without any change in the radiation characteristics of the antenna. The antenna designed at 3.6 GHz can be used for WLAN applications with a reduced harmonics design. The second harmonics is reduced by feedline length adjustment and for reducing the third harmonics is reduced using an EBG structure. The patch area in both conventional PCMA and in PCMA with EBG remains the same.
- Harmonic reduction is achieved with a single patch mushroom EBG resonator structure with a bandgap centred at 6.6GHz which reduced the harmonics from a simple PCMA resonating at 2.2GHz by 8dB and also improves the return loss at the fundamental frequency by 15dB with a little change in the radiation characteristics of the antenna. The antenna designed at 2.2 GHz can be used for mobile satellite applications with a reduced harmonics design. The level of harmonics can be reduced using the tuning length technique and the bandwidth can be then improved by 73% using a slot in the feedline and the ground plane as compared to ordinary proximity coupled antenna.

Using an EBG and DGS with simple proximity coupled antenna, a compact triple band antenna is obtained. The designed triple band antenna can be used for satellite applications. The 1.4GHz band is used to provide supplementary mobile downlink, 2.6GHz band is used for mobile broadcasting and 3.1 GHz band for mobile WiMax applications. With a gain of 5.476dB at 1.43, 6.464dB at 2.61 and 5.121dB at 3.17, this antenna can be used in MIMO applications.

8.2 Future Scope

The antennas designed in this thesis can be used for applications such as mobile satellite applications, WLAN, WiMax, mobile broadcasting and MIMO applications. In the future, antennas can be designed for:

- 1) **Metamaterials:** A metamaterial is a metallic or semiconductor substance whose properties depend on its inter-atomic structure rather than on the composition of the atoms themselves. Certain metamaterials bend visible light rays in the opposite sense from traditional refractive media. Some metamaterials also exhibit such behaviour at Infrared wavelengths. These materials can be used for Surface

Absorption Rate or (SAR) reduction. SAR is a measure of the rate at which energy is absorbed by the body when exposed to a radio frequency (RF) electromagnetic field; although, it can also refer to absorption of other forms of energy by tissue, including ultrasound. It is defined as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg). SAR is usually averaged either over the whole body, or over a small sample volume.

- 2) **Split-ring resonator structure (SRS):** A split-ring resonator (SRR) is a component of a Negative index metamaterial (NIM), also known as Double negative metamaterials (DNG) or Left-handed medium (LHM). SRRs are also used for research in Terahertz metamaterials, Acoustic metamaterials, and Metamaterial antennas. A single cell SRS has a pair of enclosed loops with splits in them at opposite ends. The loops are made of nonmagnetic metal like copper and have a small gap between them. The loops can be concentric, or square, and gapped as needed.

List of publications:

- 1) Deepti Chahar, Amanpreet Kaur, Rajesh Khanna, “ Multiband Proximity Coupled Microstrip Patch Antenna with EBG and DGS Leading to Reduced Harmonic Radiation”, *International Journal of Advanced Research in Computing and Communication Engineering*, vol. 2, Iss. 6, June 2013.
- 2) Deepti Chahar, Amanpreet Kaur, Rajesh Khanna, “Controlling Harmonics Using Feedline Length and Improving Bandwidth with a slot in Feedline and Ground Plane”, International Conference on Electronics, Communication and Information Technology, Thapar University, October 4th-5th, 2013. (Accepted)

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