CHAPTER -3
Electromagnetic BandGap Structures

3.1 Introduction and Historical Background

Electromagnetic bandgap materials are one of the most rapidly advancing materials in the electromagnetic arena. They have ability to persuade the propagation of electromagnetic waves to a level that was not possible earlier [1]. Electromagnetic Band Gap (EBG) structures produced a wide variety of design alternatives for researchers working in the area of microwave and photonics. Focus is now towards on finding real applications combined with detailed modelling. Due to the incredible potential of EBGs, there are plethoras of applications in which they can be used. New companies have also started to exploit the commercial potential of this technology [2].

Due to their unique properties, EBG materials are very popular in scientific society. *Generally, EBG structures are defined as artificial periodic structures that avert or assist the propagation of electromagnetic waves in a specified band of frequencies for all incident angles and all polarization states* [3]. EBG structures are always used as a part of microwave devices in order to improve the performance of devices especially to improve the radiation/gain patterns and to decrease the noise /losses in transmissions. EBG structures are also known as high impedance surface due to their ability to suppress the surface wave at certain operational frequencies. In recent years, there has been rapid increase in utilization of Electromagnetic bandgap (EBG) structures in electromagnetic and antenna community [4] [5].

The EBG terminology is based on the total internal reflection, phenomenon of Photonic crystal in optics, which is realized by periodic structures [19]. EBG Structures are popularly known as photonic crystals that are artificially synthesized crystals which control light completely [6]. The EBG structure is originated from the two papers published by Eli Yablonovitch and Sajeev John in 1987 [8] [9]. In the 1980's Yoblonovitch stated that this PBG, produced by periodic variation in the refractive index of the structure, can be very useful as it can be used to eliminate the spontaneous emission of photons at certain frequency bands. The motivation after this was that the performance of semiconductor lasers, hetero junction bipolar transistor, and solar cells was limited by spontaneous emission, but in characteristically different way. Yablonovitch introduced band gap which can control radiation of light arbitrarily induced, and John presented band gap which can ponder light waves into focus. They used the idea of capitalizing on the Bragg condition to construct materials that block all incoming light of a particular wavelength (the Bragg's condition is met when the planes of a crystal are situated such that each plane reflects a little of the incoming light) [8].

In 1987, Yablonovitch published the first physical review letter discussing how to establish three dimensional periodic variation using PBG crystals. He fabricated the crystal structure by mechanically drilling holes of diameter in millimetre into a high dielectric constant material as shown in Figure 3.2. This patterned material, which is known as “Yablonovitch” prohibited incident microwave signals from propagating in any direction; it manifested 3-D Band Gap.

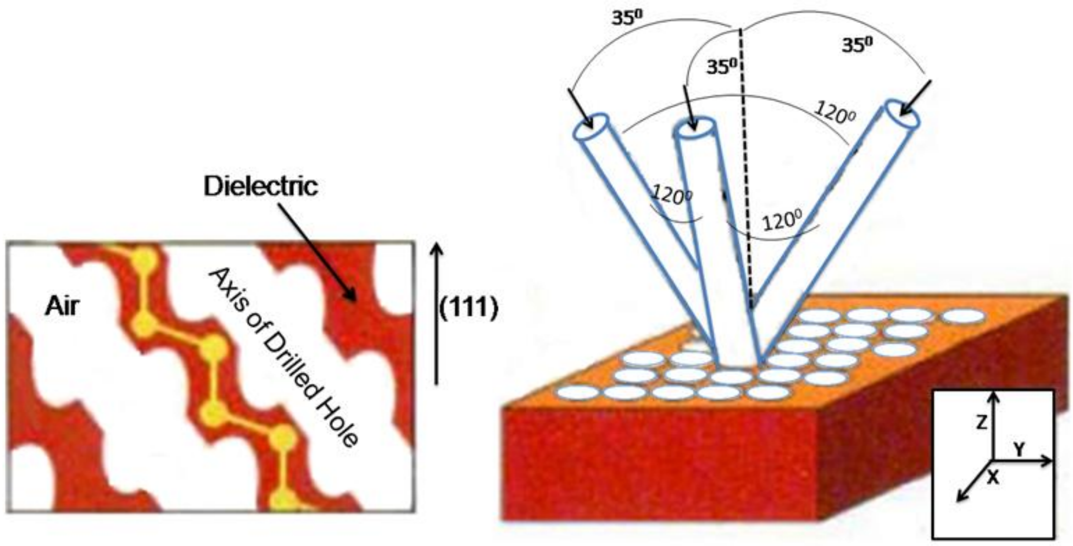

Figure 3.1 First Photonic Crystal by Yablonovitch [16].

Since 1987, other scientists have cited the potential of materials that completely reflect certain electromagnetic frequencies; these new findings have been valuable resources throughout the scientific community. John Maddox wrote in Nature that with these materials, "all kinds of almost-magical things would be possible" [10].

It is interesting to see that analogous band gaps exist when EM wave propagate in a periodic dielectric structure. If such a bandgap or frequency gap exists, EM waves with frequencies inside the gap cannot propagate in any direction inside the material. To understand this concept we consider the analogy of crystals in electronic materials [12].

Researchers explained the concept of metallic waveguides and dielectric mirrors, to understand the concept of photonic crystals. These cavities and waveguides are widely used to control the propagation of microwaves. Metallic cavities do not allow microwaves to propagate under a certain threshold frequency and metallic waveguides allow propagation of microwaves along its axis only [12]. Photonic crystals having different dielectric mediums not only imitate the properties of waveguides and cavities, but also bring out a strategy to have complete control over EM waves outside the microwave regime like light waves [12]. Further, these crystals are scalable and applicable to wider range of frequencies. We may construct a photonic crystal with a given geometry in the millimetre range for microwaves and with micron dimensions for infrared control. If a crystal reflects light of any polarization incident at any angle for some frequency range, then that crystal is said to be complete photonic or electromagnetic band gap [11].

Due to their remarkable potential to control the entire electromagnetic spectrum with simple synthesis, EBG structures bring a revolution in the material science technology. It has been described that the greater dielectric contrast between the mediums can open wider gaps [12].

3.2 **Types of EBG Structure:**

EBG structures are periodic in nature, which may be realized by drilling, cuffing, and etching on the metal or dielectric substrates. They may be formed in the ground plane or over the substrate. On the basis of dimensions EBG structures are categorised as one dimensional (1-D), two dimensional (2-D), and three dimensional (3-D) periodic structures that satisfies Bragg's conditions, i.e., inter-cell separation (period) is close to half guided wavelength ($\lambda_g/2$). They are capable of forbidding electromagnetic propagation in either all or selected directions [13] [15].

3.2.1 **3-D EBG Crystals**

In the beginning a 3D EBG was designed only. A successful attempt to obtain a 3D periodic dielectric structure was made in Iowa State University (ISU) [4]. It was called the woodpile structure as shown in the figure 3.2. Three dimensional EBG crystals have periodicity along all the three dimensions and the remarkable feature is that these systems can have complete band gaps, therefore that propagation states are not allowed in any direction [14].

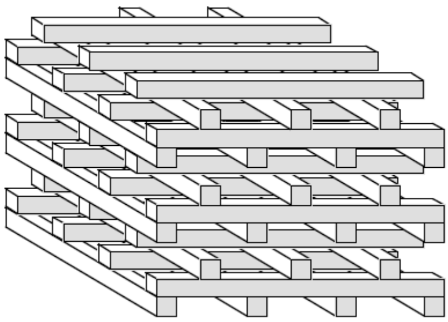

Figure 3.2 Three dimensional EBG Structures [15]

Although, a perfect 3-D EBG structure is required to block all waves in all directions, but then these structures are difficult to fabricate and integrate. From literature, we learned that 2-D EBG could be even more valuable. 2-D EBG structures are easy to fabricate and are capable of maintaining a similar control on the wave propagation in the structure as the 3-D structure.

3.2.2 2-D EBG Crystals

These crystals have periodicity in two dimensions and are homogeneous along the third direction, or we can say that, all variations happen in the two dimensions, whereas everything is constant along the third dimension, thereby propagation is allowed along one axis of the crystal [15]. These 2-D EBG structures have substantial advantages in terms of compactness, stability, and fabrication, which make them more attractive for microwave devices [14].

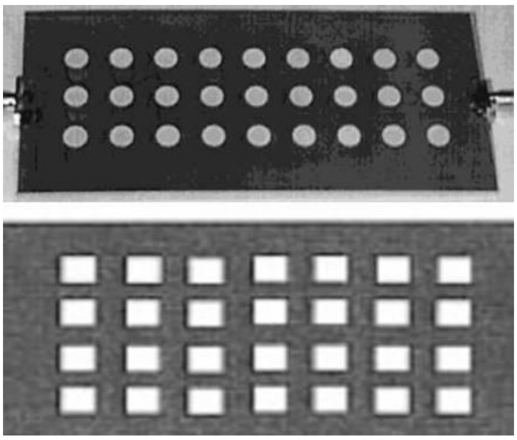

Figure 3.3 Two dimensional EBG structures [17] [18].

One of the greatest advances in the development of these 2-D EBG structures in microwave range has been their implementation in microstrip technology.

3.2.3 1-D EBG Crystals

One dimensional EBG structures can also be implemented in microstrip technology. 1-D EBG structures have periodicity of two different media along one direction only. These basic crystals exhibit three important phenomena: photonic band gaps, localized modes, and surface states. However, as the index contrast is only along one direction, the band gaps and bound states are limited to that direction. Nevertheless, these simple structures show most of the features of 2-D and 3-D EBG crystals [12].

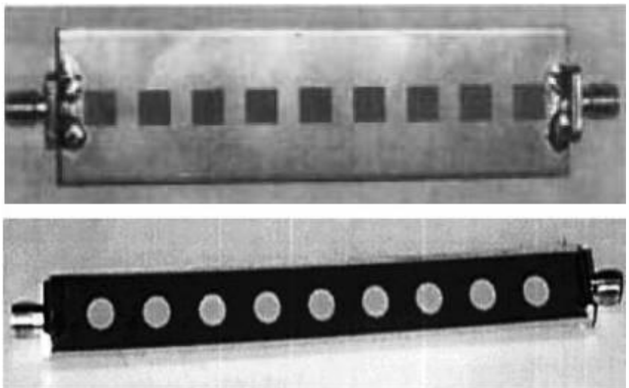

Figure 3.2.1 One dimensional EBG structure [16]

3.3 Applications of EBG Structures

EBG technologies have a wide range of applications in RF and microwave engineering, including filters, waveguides, cavities, antennas etc. In order to get the most of this technology, a fully integrated receiver or emitter system should be developed in which all the components are designed using EBG technology. First step in order to achieve this goal is a design of the individual component.

3.3.1 Applications of EBG Structures in Antenna Engineering

A massive amount of basic EBG applications exists especially within the microwave and low millimetre-wave region, for example in electronically scanned phased arrays, high precision GPS, Bluetooth, mobile telephony, antennas etc.

Phased array antennas are the key components to provide higher performance by manipulating and steering wireless signal beams towards the desired directions. Phased arrays involving phase shifters are conventionally used in several applications.

EBG structures are the very promising candidates to exterminate the problems created by surface waves while at the same time improving the performance. Gonzala and Kelley proposed that, replacing the dielectric substrate by the EBGs increases the gain of the antenna and reduces the surface waves [20], [21].

William. E. Mckinzie designed a Metallo-Dielectric EBG antenna witch behaves as Artificial Magnetic Conductors; these EBG designed for the solutions in printed circuit technology [22].

As the world goes wireless, data, and voice transmission are becoming even more popular. Attention is now focused on to make devices fast, compact, and high performing.

For this, Romula and his co-workers proposed a high impedance electromagnetic surface, for cell phone handset geometry, to reduce the radiations [24].

Several antenna configurations using electromagnetic bandgap crystals have already been studied such as: dipole antennas [25-26], slot antennas, [27], patch antennas [20, 28-29], bow-tie antennas [30], spiral and curl antennas [31-32], superstrate antennas or resonant cavity antennas [33-34], parabolic reflector antennas [35] and combinations of the above [36]. It has been demonstrated that by using the EBG substrates for patch antennas, the surface wave effects are significantly reduced [37] and are able to provide relatively broadband frequency performance.

There are two main advantages in using the metallo Dielectric EBG antennas, first they suppress surface currents, and second they introduce in-phase image currents.

Enoch et. al. designed a high impedance surface using metamaterial for the directive emissions in the antennas [38]. Similarlly, Robert Coceioli et. al. developed a uniplanar compact PBG substrate, to reduce surface wave losses for an aperture coupled fed patch antenna on a thick high dielectric constant substrate [39].

Some simple two-dimensional arrays of conducting elements have been used to improve the performance of patch antennas [40].

Microwave filtering has also been turned out to be an important area where Electromagnetic bandgap materials play an important role [41]. The broad stop-band can be exploited to suppress spurious pass-bands present in conventional microstrip filters. The sharp cut-off can also be used to improve the roll-off on a low-pass filter. Furthermore, combinations of conventional designs and Electromagnetic bandgap materials could lead to very compact structures.

3.3.2 <u>Resonators and Filters using EBG Structures</u>

Resonators based on EBG technology have been recently proposed as an alternative to current technologies [42-45]. Resonator structures can be fabricated on different laminates by using inexpensive standard printed circuit board (PCB) processing techniques and can be used in commercial products.

Tim Eular and John Papapolymeror proposed a micromachined resonator at 45 GHz based on defect induced EBG laminate with high quality factor and low losses [42]. Some other researchers also designed high quality factor filters [42, 43], with high isolation [44] and low insertion losses [44, 45] with wide band width.

The concept of EBGs has been utilized to develop the devices of high isolation with high quality factor that can integrate monolithically with other components. According to the demands, Chappel and his co-workers designed 2, 3, and 6 pole filters using mettalo-dielectric EBG lattice. Chappel also designed a wide bandgap structure using the high-k ceramics, which was embedded into a polymer to create an EBG substrate. J.C Vardaxoglu et. al. also proposed a tunable wide bandgap using mettalo-dielectric EBGs [46]. Hell and his team proposed a reconfigurable EBG cavity resonator with low insertion losses [47].

The use of EBG circuits for filter applications [48-52] in microwave technology has been proposed in different ways. Vesna Radistic designed the EBG by etching a 2-D structure of holes in the ground plane of the microstrip circuit [48].

To produce compact designs using the "Uniplanar Compact EBG Structures" where, the slow wave effect is produced by a distributed LC two-dimensional structure, which allows a considerable size reduction in the circuit. A spurious-free band pass filter and high-performance low pass filter using a coupled microstrip, was proposed by Fei-Ran Yang and his group [49].

Loptegi and his researchers also designed different band pass filters using defect ground structures [50]. Ducain Nesic proposed a PBG microstrip slow wave structure. This proposed structure exhibits slow wave and low pass characteristics. It was fabricated by using modified microstrip line, without etching the ground plane [51-52].

3.3.3 EBG Defect and Wave Guides

The area of conventional waveguides is a field where hybrid solutions could play an important role. Fei-Ran Yang designed a wave guide using PBG structure. The structure is a 2-D square lattice with each cell consisting of metal pad and four connecting lines [53]. Recently the coupled cavity waveguides (CCW) have attracted considerable attention. This perception can enable bends in the waveguide with very low bend reflection losses [54].

Joannopoulos and researchers proposed a channel drop filter structures composed of two waveguides [55]. Mekias et. al. demonstrated an efficient transmission of light around the photonic bandgap waveguides. They revealed that there was complete transmission at certain frequencies [56]. Furthermore, they require infinitely deep structures that can be readily analysed. A more practical approach was based on a dielectric waveguide that uses the inverse geometry, i.e. air holes in a dielectric host. Using these structures guiding is maintained within the periodic plane by total internal reflection, which is not the case for air filled guides.

Defects induced waveguides, commonly referred as coupled cavity waveguides (CCW), are used for making efficient waveguides, bends, and splitters. Spectral properties of the waveguides depend upon the nature of defects and their spacing. Both broad band and a narrow band waveguides can be produced by using these chains of defects.

Andrew. L. Raynolds examined a waveguide using the hexagonal lattice of air holes drilled in the dielectric substrate [57]

Another interesting application of defects induced waveguides is the terahertz local oscillator generation. It is well known that a defect mode within an electromagnetic bandgap is localized. The PBG acts as a high-Q and loss-less cavity, and that it is possible to make an efficient and compact oscillator. Using a non-linear material as the defect it has been shown that it is possible to generate THz radiations [58].

3.3.4 EBG Tuned Microwave Devices

Tunable devices using EBG structures are very promising components for todays devices. The properties of EBG components rely on the contrast between the dielectric constant of the materials involved. Variation of the dielectric constant will lead to sensitive tuning of the properties of the EBG component. Some alternatives exist to accomplish tuning of Electromagnetic bandgap materials:

(1) Micromechanically or electrically modifying the device geometry and/or dielectric loading [59] [60].

(2) By creating some defects and

(3) By using ferroelectric and ferromagnetic substrates [62].

In micro electro mechanical systems (MEMS) fabrication technologies, the position of the switches and membrane was modified electrically and local properties of the EBG components was modulated.

In the forth alternative, they use different dielectric substrates are used on which the EBG structures were designed. By changing the permittivity and the permeability of the substrate, by using external electric or magnetic field, they achieve tuning in the EBG components is achieved .

A tunable filter using fractral electromagnetic bandgap structure was designed, simulated and fabricated, and its tuning was achieved using micromachined capacitive bridge [59].Another ultra wide bandstop filter was designed and tuned using MEMS switches based on EBG co-planar waveguides [60].

Tunable electromagnetic bandgap structures based on ferroelectric or ferromagnetic thin films were also reported in literature [61]. To achieve tunable EBG performance ferroelectric capacitors are also considered [59] [62]. In addition, to achieve tunable electromagnetic bandgap EBG performance, ferroelectric varactors are considered in LC circuits, for periodically loading coplanar waveguides (CPWs). Asymmetric or symmetric tuning of the bandgap width was achieved by changing the capacitance of the varactors in LC circuits [61]. Yongje Sung presented a novel approach to obtain the electromagnetic bandgap structure with a wide tunable stopband filter using defected ground structure (DGS) [63]. Miguel and researcher also proposed a multiple frequency tuned photonic bandgap microstrip structure [64].

3.3.5 <u>Miniaturization</u>

Miniaturisation of microwave devices and antennas has become increasingly important in recent years. Modern wireless communication systems require small microwave elements that are relevant to high-level integration into compact lightweight systems.

Miniaturisation can be achieved by several techniques. Roger and his co-workers designed a magnetic conductor and to reduce its size and cost. In order to do that they integrated some capacitance of the FSS without resorting to a second layer of overlapping patches [65]. By increasing the capacitor and inductor in Sivenpiper High Impedance Surface, size of the EBG cell was reduced [66]. Feresidis et. al. introduced the concept of closely coupled metallo dielectric electromagnetic band-gap structure, and designed 2-D double layer dipole arrays. These arrays are closely packed [67].

It is well known that at certain frequencies outside the band gap, periodic structures support waves, commonly termed as slow waves, with reduced phase velocity and guided wavelength with respect to the wave propagating in a comparable homogeneous medium. This property can be exploited for the miniaturisation of microwave elements, such as the triple array elements [68]. An approach to this is to examine elements with periodic loading. Multiple-order periodic loading of basic elements possesses a good degree of flexibility in the design [68, 69]. Fractal-type structures are subsequently produced using second order loading. This can also be used for multiband AMC designs [70]. Another way of increasing the length of the loading stubs without increase the unit cell and at the same time to increasing the capacitive coupling between successive elements is the inter digital topology. The loadings of successive dipoles are shifted so that they can extend to the full length allowed by the array geometry.

3.3.6 **Planar EBG Structures**

EBG technology represents a major breakthrough with respect to the current planar approaches, mainly due to their ability to guide and efficiently control electromagnetic waves. As the frequency increases, a planar structure that integrates the antenna, mixers, local oscillator, and all peripheral circuitry onto one single substrate becomes an attractive option.

Planar EBG's are of particular interest at microwave frequencies due to ease of fabrication. These EBG's are usually periodic in one and two dimensions. Planar EBG structures consist of uniformly distributed periodic metallic patterns on one side of a dielectric slab. They exhibit some interesting features such as distinctive passband and stopband, slow wave effects, low attenuation in the passband and suppression of surface waves when serving as the ground of planar microstrip circuit. Several Planar EBG configurations have been reported in the literature like uni-planar designs without vertical vias, one and two dimensional EBG transmission line design etc. in which they used EBG basis points with different geometries, and shapes like circular shape, square, hexagonal, fork shape, plus sign and many more. In some planar devices, they create defects by creating a discontinuity in periodic pattern. For example in a planar circular defect induced EBG structure with triangular lattice, they remove some circles or change their size for creating some discontinuity. Some of these types of EBG structures are shown in the figure. 3.5.

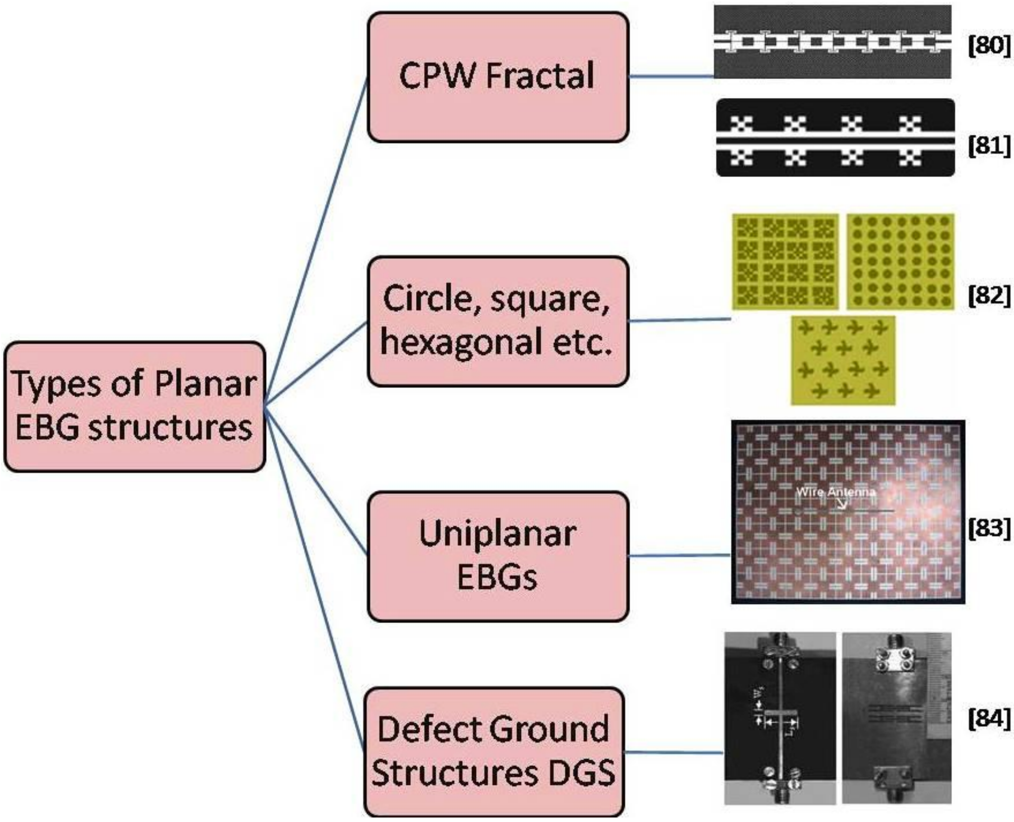

Figure 3.5. Classification of Planar EBG Structures

I conventional circle EBG, the development evolves to circle, circle-plus and annular rings EBGS. The CPW line is perturbed with the square EBG followed by Minkowski's iterations [71] on the conventional square EBG. Defect ground structure (DGS) [72] [73] is a new class of very wideband low pass filter that has been successfully utilized in antennas and filters. DGS is studied in various forms, uniplanar compact PBG (UC PBG) [74] is a periodic form of DGS in which a cascade of LC equivalent resonators is realized in the ground plane. A stepped-impedance bandstop filter is also realized in planar form. A hybrid DGS-EBG is designed to realize a very fine passband and wide stop band performance [75].

V. Radisic et al [76] proposed 2D uniform hole-patterned EBG structure on the ground plane of a microstrip transmission line to realize wide stopband. Recently, cascading of three different EBG structures [71] were also proposed to achieve wider stopband. A new type of compact microstrip line is photonic bandgap (PBG) structures employing in T-type microstrip line for filter applications. A miniature band rejection filter with four cell was simulated, fabricated, its band rejection characteristics is lower than -10 dB from 23 GHz-32 GHz. Proposed filter was very compact and much easier to fabricate [77]. Periodically loaded ultra wideband (UWB) bandpass filter based on the EBG concept was proposed. Compact wideband filters with steep transition bands can be designed easily using this methodology [78]. Two different uniform photonic bandgap structures used as stopband filters for microsrip lines at 5.4 GHz were proposed and compared in terms of the pattern shapes, and effects on the s parameters. This work suggested the use of 1D pattern to reduce the transversal size of the filter. [79]. 1-D uniplanar periodical structures and defect high-Q resonators for co-planar waveguide, co-planar stripline, and slotlines were also proposed. These uniplanar structures consists of 1-D periodic etched slots along a transmission line or alternating characteristics impedance series having wideband bandstop filter characteristics.

There are several other applications of these Planar EBG structures shown in the figure below.

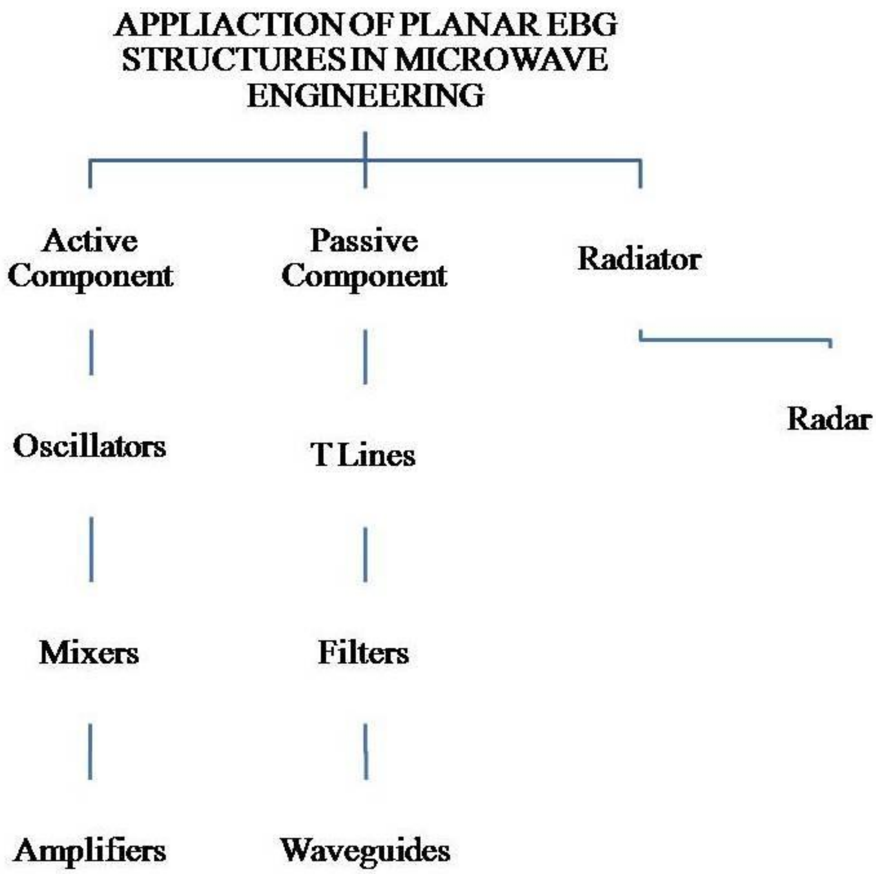

Figure 3.6 Applications of Planar EBG Structures

These planar EBGs are periodic in one and two dimensions but we learned from the literature that the two dimensional EBGs could be even more valuable. Present work also focuses on 2 dimensional planar EBG structures.

3.3 <u>Phenomenon Of EBG Structures:</u>

This section is deals with the details of bandgap theory using the Bloch wave formulism. Using the wave propagation equation it is concluded that any periodic structure leads to a band of frequency where propagation is not allowed, referred to as bandgap phenomenon.

The phenomenon of bandgap structures appeared in the late 1960's in the optical domain. At first, the explanation to this phenomenon was given by kogelnik and shank in their explanation to the dispersion characteristics of the distributed feedback lasers [85]. At that time, they did not value the phenomenon of the bandgap produced by the periodic variations in the refractive index, but they just focused on explaining the phenomenon. They proved that the periodic variation in the refractive index of a structure produced forward and backward propagating waves that interact with each other through coupled wave equations. By solving these coupled wave equations, they found through the dispersion relation that there existed a certain frequency band along which there was no wave propagation due to the presence of evanescent waves.

Two approaches are generally used to obtain the solution of the propagation of electromagnetic waves in a periodic layered medium. One is the Coupled-Mode theory and other is the Bloch wave expansion method [87].

3.4.1 <u>Bloch Wave Expansion</u>

Here the phenomenon of bandgap structure and existence of a forbidden band are discussed using the Bloch- Wave formulation.

The properties of the periodic medium are described by its dielectric and permeability tensors, which are periodic, function of x and y for the two dimensional periodic systems, reflecting the translational symmetry of the medium:

$$\varepsilon(x) = \varepsilon(x+a), \mu(x) = \mu(x+a)$$

$$\varepsilon(y) = \varepsilon(y+b), \mu(y) = \mu(y+b)$$

where *a* and *b* are arbitrary lattice vectors. These equations merely state that the medium looks exactly the same to an observer at *x* as at *x*+*a*. In a three dimensional periodic medium, there exist permittivity lattice vector a_1, a_2, a_3 which define the periodicity of the lattice , such that the medium remains invariant under translation through any vector *a* which is the sum of integral multiples of these vectors.

The propagation of the electromagnetic waves in a periodic medium is described by the Maxwell's equations. By combining the source free Faradays and Ampere's Laws at fixed frequency *ω* [88],

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3.1)$$

$$\nabla \times \vec{B} = \mu_0 \varepsilon_r \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (3.2)$$

As $\vec{E}$ and $\vec{H}$ are proportional to $e^{-i\omega t}$ at frequency *ω*, and $\partial/\partial t$ can be replaced by (iω).Now by putting this value in equation (3.1) and (3.2) we obtained the following equations

$$\nabla \times \vec{E} = i\omega\vec{B} \quad (3.3)$$

$$\nabla \times \vec{B} = i\omega\varepsilon_r\varepsilon_0\mu_0\vec{E} \quad (3.4)$$

Now by eliminating the $\vec{B}$ in eqn. (3.3) & (3.4) we will get the following relation

$$\nabla \times \left(\nabla \times \vec{E}\right) = \omega^2 \varepsilon_r \varepsilon_0 \vec{E} \quad (3.5)$$

On the other hand, it can be written as follows.

$$\frac{1}{\varepsilon_r} \nabla \times \left(\nabla \times \vec{E_r}\right) = \frac{\omega^2}{C^2} \vec{E} \quad (3.6)$$

Where $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$

Where let ε is the dielectric function of the metallic period $\varepsilon(r)$ and c is the speed of light in vacuum. This is an Eigen value equation, with eigen (ω/c^2) and an eigen operator $\vec{\nabla} \times \frac{1}{\varepsilon} \vec{E}$ is a Hermitian operator (acts the same to the left and right) under the inner product $\int \vec{E} * \overrightarrow{E'}$ between the two fields $\vec{E}$ and $\overrightarrow{E'}$ [89].

This equation can be solved by various methods. Here the plane wave expansion method is used for solving eqn. (3.6).

Plane wave expansion method refers to a computational technique in electromagnetic to solve the Maxwell's equation by formulating an eigen value problem out of the equation.

Plane wave are solutions to the homogeneous Helmholtz equation, and from a basis to represent field in the periodic media. The electric or magnetic fields are expanded for each field component in terms of the Fourier series components along the reciprocal lattice vector. Similarly, the dielectric permittivity (which is periodic along reciprocal lattice vector for photonic crystals) is also expanded through Fourier series components [88]. We express the eigen function as a superposition of plane waves:

$$E_{kn}(r) = \sum_G E_{kn}(G) exp(i(k+G).r) \tag{3.7}$$

Where *n* and *G* are the band index and the reciprocal lattice vector, respectively, and in summation *G* runs over all the reciprocal lattice vectors, including *G=0*. In the superposition of the plane wave's different phenomenon like Bloch wave, formula and Bragg's plane condition are used [90].

By inserting eqn. (3.7) into eqn. (3.6), the following eigen value equation for the expansion coefficient $\{E_{kn}(G)\}$ is obtained

$$-\sum_{G'} \kappa\,(G-G')(k+G')\,\{(\mathrm{k}+\mathrm{G}')\times \mathrm{E_{kn}}\,(\mathrm{G}')\} = \frac{\omega^2}{c^2} E_{kn}(G) \tag{3.8}$$

Where $\kappa(G-G')$ is the furrier transform of the inverse dielectric tensor, $\varepsilon^{-1}(r)$.

For a 2D crystal uniform in the z direction with a period ε in the *x-y* plane and *k* vector parallel to the 2D plane [13], eqn. (3.6) for TM modes is transformed to:

$$\sum_{G'} \kappa\,(G-G')|k+G'|^2 E_z(G') = \frac{\omega^2}{c^2} E_z(G) \tag{3.9}$$

For plotting a dispersion relation of the 2 dimensional square lattice, Fourier analysis of the eqn. (3.9) has been done. The Fourier coefficient *κ(G)* is:

$$\kappa(G) = 2f\left(\frac{1}{\varepsilon_a} - \frac{1}{\varepsilon_b}\right)\frac{J_1 G r_a}{G r_a} \qquad G \neq 0$$

$$= \frac{f}{\varepsilon_a} + \frac{1-f}{\varepsilon_b} \qquad \mathrm{G} = 0 \tag{3.10}$$

Where r_a is the radius of the basis points, $f = \frac{\pi r_a^2}{a^2}$ is the filling fraction, a is the lattice constant, and $J_1(Gr_a)$ is the Bessel function of first kind. The G vector is a 2D reciprocal vector in the *x*-*y* plane [91]. By putting, the values of dielectric constants and the filling fraction one can plot the dispersion diagrams. For example, we plot the dispersion relation for the square metallic lattice with circular basis point in which the ε_a is considered as the dielectric constant of metallic basis points and the ε_b is the dielectric constant of the air. The radius of the circular metallic basis point is 1.76 mm, and lattice constant for square lattice 8 mm [5].

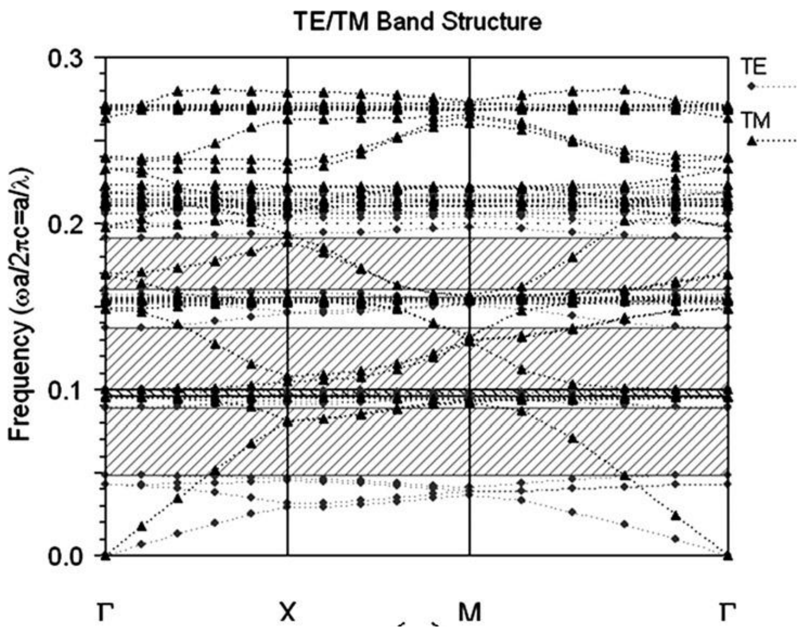

Figure 3.7 Dispersion diagram for square metallic EBG structures [5].

Dispersion diagrams shows the relation between the frequency ω and the wave vector *k* and it is equivalent to the Brillouin diagram used to illustrate the energy band structure in periodic crystals. The horizontal axis of the dispersion diagrams indicate the wave number β in the Brillouin zone. In the 2-D case, β will be $\sqrt{(k_x^2 + k_y^2)}$, where k_x and k_y are the wave numbers in the x & y directions, respectively. The X, Y, and M in the Brillouin zone represent the high symmetry points in the spectral domain[92].

3.4.2 Brillouin Zones

Brillouin zones are an important characteristic of crystal structures. The construction and illustration of Brillouin zones for a three dimensional lattice are somewhat difficult to follow. The construction of Brilliouin zones for a two dimensional lattice is much easier to follow.

“A Bragg Plane” for two points in a lattice is the plane which is perpendicular to the line between the two points and passes through the bisector of that line. The first Brillouin zone for a point in a lattice is the set of points that close to the point than the Bragg Plane of point. In other words, one can reach any of the point without crossing the Bragg Plane of any other point in the first Brilliouin zone of a lattice point [93].

The second Brillouin zone is defined as the points which may be reached from the first Brillouin zone by crossing only one Bragg plane. This can be generalised to define the n^{th} Brilliun zone as the set of points, not in the previous zones that can be reached from one $(n-1)^{th}$ zone by crossing one and only one Bragg plane. In constructing the Brillioun zones for a point it is expedient to first determine the nearest neighbours, the next nearest neighbours and so on [93].

Figure 3.8 shows the Bragg planes between the central lattice point and other lattice points. For example, the yellow circle in the middle of Figure 3.8 represents the centre of one EBG cell. The centres of the four nearest adjacent cells, vertically and horizontally, are marked as red circles. In between the yellow circle and each red circle is a red line, which is the Bragg plane.

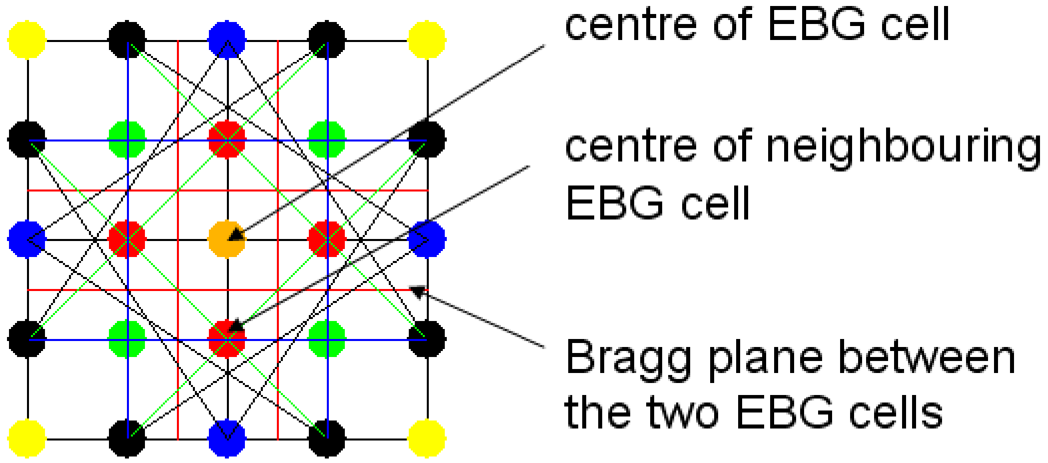

Figure 3.8 Construction of the Bragg planes in relation to the central lattice point [82].

The first Brillouin zone extends from the chosen point of the lattice to the Bragg planes. The area that is beyond the first Bragg plane, but walled in by Bragg planes as well, is the second Brillouin zone. Whenever a Bragg plane is crossed, a new Brillouin zone begins. This zone ends at the borders of the Bragg planes. Figure 3.8 shows an example of the first four Brillouin zones in a 2D square lattice. The colours correspond to the colours in Figure 3.8, for example, the red Bragg planes between the central circle and the red circles of Figure 3.9 mark the borders of the red Brillouin zone shown in Figure 3.9.

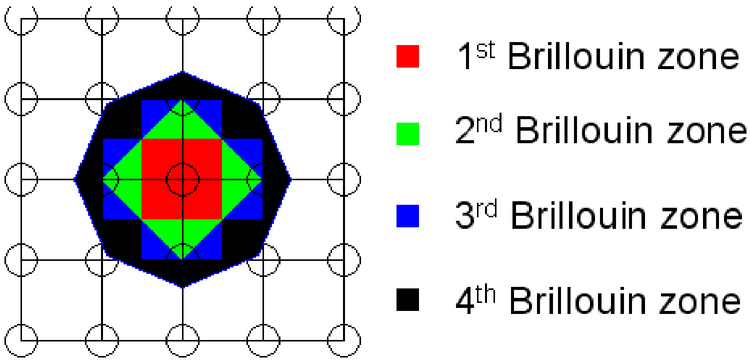

Figure 3.9 The first four Brillouin zones in a square lattice [82].

For a square lattice, the first Brillouin zone is a square and for a hexagonal lattice, the first Brillouin zone is a hexagon. Usually there is also symmetry in the Brillouin zone, so that the calculation of the dispersion diagram is along the lines connecting the critical points. Critical points are points of high symmetry [93]. The nomenclature for the cube is used for the square lattice as well. Γ denotes the centre of the Brillouin zone, X stands for a centre of a face and M is the centre of an edge. This region of symmetry within a Brillouin zone is called the irreducible Brillouin zone. For a square lattice, the irreducible Brillouin zone is triangle shaped.

3.5 Conclusion

In this chapter a detailed discussion about the history of EBG structures, type of EBG structure, different applications of EBG structures and EBG structure as a filter, resonator etc is given. This chapter gives the better understanding of the phenomenon of EBG structures and wave propagation in periodic media. The detailed analysis of plane wave propagation in periodic media has been explained using the Bloch wave function and Bragg's condition, by which one can understand the origin of bandgaps and brillouin zones are understood.

References

1. Li Yang, M. Fan, F. Chen, J. She, Z. Feng, " A Novel Compact Electromagnetic–Bandgap (EBG) Structure and Its Applications for Microwave Circuits", IEEE Transaction on Microwave Theory and Techniques, Vol. 53, No.1, 2005.

2. J. Liang, H.Y.D. Yang, "Microstrip Patch Antennas on Tunable Electromagnetic Band-Gap Substrates," IEEE Transaction on Microwave Theory and Techniques, Vol. 57, No.6, 2009.

3. P. Baccarelli, P. Burghignoli, F. Rezza, A. Galli, P. Lampariello, S. Paarulotto and G. Valerio, " Dispersive Analysis of Wide-Bandstop Compact EBG Microstrip Lines for Filter Applications", ISMOT 2007.

4. R.S. Kshetrimayum, L. Zhu, " EBG Design using FSS Elements in Rectangular Waveguide", ACES Journal, Vol. 21, NO. 2, 2006.

5. R. Verma, K. S. Daya, " Effect of Forbidden Bands of Electromagnetic Bandgap Engineered Ground Plane on the Response of Half Wave Length Linear Microwave Resonator", Journal of Applied Physics, 109, 084505, 2011.

6. F. Yang, Y. R. Samii, "Electromagnetic Band Gap Structures in Antenna Engineering", Cambridge University Press 2009.

7. E. Yablonovitch, "Photonic band-gap structures" Optical Society of America, Vol. 10, No. 2, 1993.

8. E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics" Phys. Rev. Lett., 58, 2059, 1987.

9. S. John, "Strong Localization of Photons in Certain Disordered Dielectric Super Lattices," Phys. Rev. Lett. 58, 2486, 1987.

10. J. Maddox, "Photonic Band-Gaps Bite the Dust," Nature 348, 481, 1990.

11. E. Yablonvitch, " Photonic Band-gap Crystal," Review Article J.Phys.: Condense. Matter, Vol. 5, pp. 2443-2460, 1993.

12. J. D. Joannopoulos, R. D. Meade and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*, New Jersey: Princeton University Press, 1995.

13. J. Shumpert, T. Ellis, G. Rebeiz and L. Katehi, "Microwave and Millimeter-Wave Propagation in Photonic Band-Gap Structures," *AP-S/URSI,* p. 678, 1997.

14. D.W. Prather, S. Shi, A.Sharkawy, J. Murakowski, G.J. Schneider," Photonic Crystals: Theory, Applications, and Fabrication", John Wiley & Sons, New Jersey, 2009.

15. C.M. Soukoulis, "The History and Review of the Modelling and Fabrication of Photonic Crystals", Nanotechnology 13, 420-423, 2002.

16. M.A.G. Laso, M.J. Erro, D. Benito, M.J. Grade, T. Lapetegi, F. Faleone, and M. Sorolla, "Analysis and Design of 1D Photonic BandGap Microstrip Structure using a Fiber Grating Model", Microwave and Optical technology Letters, Vol. 22, No. 4, 1999.

17. F. Falcone, T. Lopetegi, M. Sorolla, "1D and 2D Photonic BandGap Microstrip Structures," Microwave and Optical technology Letters, Vol. 22, No. 6, 1999.

18. G. Cokir, L. Sevgi, "Design of A Novel Microstrip Electromagnetic BandGap (EBG) Structures," Microwave and Optical technology Letters, Vol. 46, No. 4, 2005.

19. M. Johri, Y.A. Ahmed, T. Bezboruah, " Photonic Bandgap Materials: Technology, Applications and Challenges", Current Science, Vol. 92, No. 10, 2007.

20. R. Gonzalo, P. de Maagt, and M. Sorolla, "Enhanced Patch Antenna Performance by Suppressing Surface Waves using Photonic Band-Gap Structures., IEEE Transactions on Microwave Theory and Techniques, vol. 47, No. 11, pp.2131-2138, 1999.

21. P.K. Kelly, L. Diaz, M. Piket-May, and L. Rumsey, "Scan Blindness Mitigation using Photonic Bandgap Structure in Phased Arrays", Proc. SPIE, vol. 3464, pp. 239-248, 1998.

22. R. Hurtado, W. Klimczak, W.E. McKinzie, and A. Humen , “Artificial Magnetic Conductor Technology Reduces Weight and Size for Precision GPS Antennas,” Navigational National Technical Meeting, San Diego, CA, 2002.

23. R. Remski, “Modeling Photonic Bandgap (PBG) Structures using Ansoft HFSS7 and Optimetrics,” Ansoft International Roadshow (Lecture Series), slides 36-40, copyright Ansoft Corporation, 2000.

24. R.F. Jimenez Broas, D.F. Sievenpiper, and E. Yablonovitch, “A High-Impedance Ground Plane Applied to Cellphone Handset Geometry,” IEEE Transactions on Microwave Theory and Techniques, vol.49, no. 7, pp. 1262-1265, 2002.

25. P. Salonen, M. Keskilammi, and L. Sydanheimo, .A low-cost 2.45 GHz photonic band-gap patch antenna for wearable systems., Proc. 11th Int. Conference on Antennas and Propagation ICAP 2001, pp.719-724, 17-20, Manchester, UK, 2001.

26. M. M. Sigalas, R. Biswas, Q. Li, D. Crounch, W. Lleung, R. Jacobs-Woodbury, B. Lough, S. Nielsen, S.McCalmont, G. Tuttle, and K.M. Ho, “Dipole Antennas on Photonic Band-Gap Crystals Experiment and Simulation,” Microwave and Optical Technology Letters, vol. 15, no. 3, pp. 153-158, 1997.

27. I. Ederra, J.J. Sanz, B. Martinez, R. Gonzalo, and P. de Maagt, “Slot Antenna Configuration using PBG Technology,” Proc. Jina, Nice, France, vol.2. pp.169-172, 2002,.

28. R. Gonzalo, I. Ederra, C. Mann, and P. de Maagt, “Radiation Properties of Terahertz Dipole Antenna Mounted on Photonic Crystal,” Electronics Letters, vol. 37, iss.10, pp. 613 .614, 2001.

29. A.S. Andrenko, Y. Ikeda, and O. Ishida, “Application of PBG Microstrip Circuits for Enhancing the Performance of High-Density Substrate Patch Antennas,” Microwave and Optical technology letters, vol.32, no.5, p.340-344, 2002.

30. E. R. Brown, C.D. Parker, and E. Yablonovith, “Radiation Properties of a Planar Antenna on a Photonic-Crystal Substrate,” Journal of Optic Soc. Am. B., vol. 10, no. 2, pp. 404-407, 1993.

31. T.H. Liu, W.X. Zhang, and M. Zhang, “A spiral Antenna Backed on Photonic Bandgap Material”, proc. ISAP, Fukuoka, Japan,2000.

32. J.M. Baracco, and P. de Maagt, “Radiating Element on a Photonic Bandgap Structure for Phased Array Applications., Proc. Jina, Nice, France, vol.2. pp.169-172, 2002.

33. M. Thevenot, C. Cheype, A. Reineix, B. Jecko, “Directive Photonic-Bandgap Antennas,” IEEE Transactions on Microwave Theory and Techniques, vol. 47, no 11, pp. 2115-2122, 1999.

34. B. Temelkuran, E. Ozbay, J-P.Kavanaugh, G. Tuttle, and K-M. Ho, “Resonant Cavity Enhanced Detectors Embedded in Photonic Crystals,” Applied Physics Letters., vol. 72, no 19, pp.2376-2378, 1998.

35. M. Thevenot, A. Reineix, B. Jecko, “A Dielectric Photonic Parabolic Reflector,” Microwave and Optical Technology Letters, vol. 21, no 6, pp. 411-414, 1999.

36. M. Qiu and S. He, “High-Directivity Patch Antenna with Both Photonic Bandgap Substrate and Photonic Cover,” Microwave and Optical Technology Letters, vol. 30, No 1, pp. 41-44, 2001.

37. R. Gonzalo, G. Nagore, I. Ederra, B. Martinez, H. Pellemans, P. Haring Bolivar, and P. de Maagt, “Coupling between Patch Antennas on Photonic Crystals., Proc. 24th ESTEC, Noordwijk, the Netherlands, pp.17-22, 2001.

38. S. Enoch, G. Tayeb, P. Sabouroux, N. Guérin, and P. Vincent, "A Metamaterial for Directive Emission", Phys. Rev. Lett. 89, p.213902, 2002.

39. R. Coccioli, F. Yang, K. Ma, and T. Itoh, “Aperture-Coupled Patch Antenna on UC-PBG Substrate,” IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 11, pp. 2123-2130, 1999.

40. Y. R. Lee, A. Chauraya, D. S. Lockyer, and J. C. Vardaxoglou, “Dipole and Tripole Metallodielectric Photonic Bandgap (MPBG) Structures for Microwave Filter and Antenna Applications,” IEE Proc. Optoelectron., vol. 127, no. 6, pp. 395-400, 2000.

41. T. Lopetegi, M.A.G. Laso, R. Gonzalo, M.J. Erro, F. Falcone, D. Benito, M.J. Garde, P. de Maagt, and M. Sorolla, “Electromagnetic Crystals in Microstrip Technology,” Optical and Quantum Electronics, vol. 34, no.1/3, pp.279-295, 2002.

42. T. Euler, J. Papapolymerou, “Silicon Micromachined EBG Resonator and Two-Pole Filter with Improved Performance Characteristics,” Microwave and Wireless Components Letters, IEEE, Volume: 13 Issue: 9,pp: 373 ,2003.

43. H-ju Hsu, M.J. Hill, R.W. Ziolkowski, J. Papapolymerou, “A Duroid-Based Planar EBG Cavity Resonator Filter with Improved Quality Factor” Antennas and Wireless Propagation Letters, Vol. 1 Issue: 2 , pp: 67 -70, 2002.

44. W. J. Chappell, M. P. Little, and L. P. B. Katehi, “High Isolation, Planar Filters Using EBG Substrates,” IEEE Microwave And Wireless Components Letters , Vol. 11, No. 6, pp. 246-248,2001.

45. W. J. Chappell, X. Gong, "Wide Bandgap Composite EBG Substrates", Special Issue on Metamaterials, IEEE Transactions on Antennas and Propagation, Vol. 51, N0. 10, 2003.

46. J. C. Vardaxoglou, A. Chauraya, A. P. Feresidis, and. P. de Maagt, "Tunable Metallodielectric Electromagnetic Band Gap (MEBG) Structures with defects", IEEE International Conference on Electromagnetics in Advanced Applications (ICEAA), Torino, Italy, pp. 667-670, 2003.

47. M.J. Hill, R.W. Ziolkowski, amd J. Papapolymerou, “A High-Reconfigurable Planar EBG Cavity Resonator,” IEEE Microwave and Wireless Components Letters, vol. 11, No. 6, pp. 255-257, 2001.

48. V. Radisic, Y. Qian, R. Coccioli, and T. Itoh, “Novel 2-D Photonic Bandgap Structure for Microstrip Lines,” IEEE Microwave and Guided Wave Letters, vol. 8, pp.69-71, 1998.

49. F.R. Yang, K.P. Ma, Y. Qian, and T. Itoh, “A Uniplanar Compact Photonic Bandgap (UC-PBG) Structure and its Applications for Microwave Circuits., IEEE Transactions on Microwave Theory and Techniques, vol. 47, pp.1509-1514, 1999.

50. T. Lopetegi, M.A.G. Laso, J. Hernandez, M. Bacaicoa, D. Benito, M. J. Garde, M. Sorolla, and M. Guglielmi, “New Microstrip Wiggly - Line Filters with Spurious Passband Suppression,” IEEE Transactions on Microwave Theory and Techniques, vol. 49, no. 9, pp. 1593-1598, 2001.

51. D. Nesic, “A New Type of Slow-Wave 1-D PBG Microstrip Structure without Etching in the Ground Plane for Filter and Other Applications,” Microw. Opt. Techn. Let., Vol. 33, No. 6, pp. 440-443, 2002.

52. D. Nesic, “A New Type of Slow-Wave 1D PBG Microstrip Band-Pass Filter,” Microw. Opt. Techn. Let., Vol.37, No.3, pp.201-203,2003.

53. F-R Yang, K-P Ma, Y. Qian and T. Itoh, “A Novel TEM Waveguide using Uniplanar Compact Photonic-Bandgap (UC-PBG Structure),” IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 11, pp. 2092-2098, 1999.

54. U. Peschel, A. Reynolds, B. Arredondo, F. Lederer, P. Roberts, T. Krauss, and P. de Maagt, “Transmission and Reflection Analysis of Functional Coupled Cavity Components,” IEEE Journal of Quantum Electronics, special issue: Photonic Crystal Structures and Applications, vol.38, nr.7, pp. 830-837, 2002.

55. S. Fan, P. R. Villeneuve, J. D. Joannopoulos and H. A. Hauss, “Channel Drop Filters in Photonic Crystals,” Optics Express, vol. 3, no. 1, pp. 4-11, 1998.

56. A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve and J. D. Joannopoulos, “High Transmission Through Sharp Bends in Photonic Crystal Waveguides,” Phys. Rev. Lett., vol. 77, no 18, pp. 3787-3790, 1996.

57. A. Reynolds, U. Peschel, F. Lederer, P. Roberts, T. Kraus and P. de Maagt, ‘Coupled Defects in Photonic Crystals,” IEEE Transactions on Microwave Theory and Techniques, vol. 49, nr. 10, pp. 1860-1867, 2001.

58. M. Tani, P. Gu, K. Sakai, H. Kitahara, M. Suenaga, and M. W. Takeda, “THz Wave Generation by Difference Frequency Mixing in Photonic Crystal Cavity,” proc. 8th International conference on terahertz electronics, pp. 301-304, Darmstadt, Germany,2000.

59. M.F. Karim, A. Q. Li, A.Yu, A. Alphone, “ Tunable Filter using Fractal Electromagnetic BandGap (EBG) Structures”, Sensors and Actuators A 133, 355-362, 2007.

60. Z.L. Deng, N.B. Zhang and J.M. Huang, “A Tunable Ultra Wideband Band-Stop Filter Based on EBG Structure using MEMS Technology’, Proceeding of IEEE 2009.

61. D. Kuylenstierna, A. Varobiev, G. Subromanyam and S. Geovorgian, “ Tunable Electromagnetic BandGap Structures Based on Ferroelectric Films”, IEEE 2003.

62. L.Y.V. Chen, R. Forse, D. Chase, R.A. York, “ Analog Tunable Matching Network using Integrated Thin-Film BST Capacitors”, MTT-S Digest IEEE 2004.

63. Y. Sung., “Tunable BandStop Filter Based Defected Ground Structure using a Metal Plate”, Microwave and Optical Tecnology Letters, Vol. 51, No. 1, 2009.

64. M.A.G. Laso, T. Lapetegi, M. J. Erro, D. Benito, M. J. Garde and M. Sorolla, “Multiple-Frequency-Tuned Photonic Bandgap Microstrip Structures”, IEEE Microwave and Guided Wave Letters, Vol. 10, No. 6, 2000.

65. S. Rogers, W. McKinzie, G. Mendolia , “AMCs Comprised of Interdigital Capacitor FSS Layers Enable Lower Cost Applications,” IEEE AP-S Int. Symp., Columbus, OH, 2003.

66. S. Tse, B. Sanz Izquierdo, J.C. Batchelor and R.J. Langley, “Reduced sized Cells for Electromagnetic Bandgap Structures,” Elec. Let., Vol. 39 No. 24, 2003.

67. A.P. Feresidis, G. Apostolopoulos, N. Serfas, and J. C. Vardaxoglou, "Closely Coupled Metallodielectric Electromagnetic Band Gap (CCMEBG) Structures Formed By Double Layer Dipole and Tripole Arrays", IEEE Transanctions Antennas and propagation, 2004.

68. A. P. Feresidis, G. Apostolopoulos and. J. C. Vardaxoglou, "Miniaturised Metallodielectric EBG structures", IEEE International Conference on

Electromagnetics in Advanced Applications (ICEAA), Torino, Italy, pp. 671-674, 2003.

69. G. Goussetis, A. P. Feresidis and J. C. Vardaxoglou, "Performance of Metallodielectric EBG Structures with Periodic Loaded Elements", Proc. IEE Seminar on Metamaterials, for Microwave and (Sub)Millimetre Wave Applications, London, UK, pp. 7/1-7/5, 2003.

70. A.P. Feresidis, A. Chauraya, G. Goussetis, J. C. Vardaxoglou and P. de Maagt, "Multiband Artificial Magnetic Conductor Surfaces", Proc. IEE Seminar on Metamaterials, for Microwave and (Sub)Millimetre Wave Applications, London, UK, pp. 2/1-2/4, 2003.

71. B.B Mandelbrot, The Fractral Geometry of Nature, W.H. Freeman.,1999.

72. C.S. Kim, J.S.Park, D.Ahn and J.B.Lim, "A Novel 1D Periodic Defected Ground Structure for Planar Circuits", IEEE Microwave Guidd Wave Lett. 10, 131-133, 2000.

73. D. Ahn, J.S. Park, J. Kim, Y. Qian and T. Itoh, " A Design of the Low-Pass Filter using the Novel Microstrip Defected Ground", IEEE Trans Microwave Theory Tech 49, 86-93, 2001.

74. F-R. Yang, K-P Ma, Y. Qian And T. Itoh, "A Uniplanar Compact Photonic Bandgap (UC-PBG) Structure and its Applications for Microwave Circuits", IEEE Trans Microwave Theory Tech 478, 1509-1514, 1999.

75. M.N. Mollah, N.C Karmarker, and J.S. Fu, "Novel Tapered Hybrid Defected Ground Structure," Int.J. of RF and Microwave CAE 14, 544-550, 2005.

76. V. Radisic, Y.Qian, R.Coccioli, and T. Itoh, "A Novel 2D Photonic Band Gap Structure for Microstrip Lines", IEEE Microwave Guided wav let. 8, 69-71, 1998.

77. M-H. Kim, N-S. Kim, Y-B Park, S-H. Kim, J-W Jung, S-Y Kang, Y Yun, K-H. Park, J-S Kim, K-J Kim, S-H Choi, and K-H Ahn, "A Miniaturized Band Rejection Filter with New Compact PBG (Photonic Band Gap) Cell Employing T-type Microstrip Line", EMC09/ Kyoto IEICE, 2009.

78. H.C. Jayatitaka, D.M. Klymyshyn, “Wideband Microstrip Bandpass Filter Based on EBG Concept”, IEICE Trans, Electron, Vol. E90-C, No. 12, 2007.

79. M.M. Karbassian, H. G. Shiraz, “ EFFECT of Shape of Patterns on the Performance of Microstrip Photonic Band-Gap filters”, Microwave and Optical Technology Letters, Vol. 48, No. 6, 2006.

80. F. Martin, F. Falcore, J. Benache, T. Loptegi, M.A.G.Laso, M.Sorolla, “Dual Electromagnetic Band Gap CPW Structures for Filter Applications,” IEEE Microwave and Wireless Compnent Letters, Vol. 13, No. 9, 2003.

81. N.C. Karmakar, Md. N. Mollah, S.K. padhi, R.L.L. Ling, S.M. Roy, “Planar Electromagnetic Bandgap Structures,” International Journal of RF & Microwave Computer Aided Engineering, 415-430, 2006.

82. K. Herbertz, “Electromagnetic Bandgap Filter” PHD Thesis, Department of Electrical and Electronic Engineering Optical and Semiconductor Devices Group, Imperial Collage London, 2010.

83. J.R. Sohn, K.Y. Kim and H.S. Tae, “Comparative Study on Various Artificial Magnetic Conductors for Low profile Antenna,” Progress in Electromagnetic Research PIER 61, 27-37, 2006.

84. M.K. Mandal and S. Sanyal, “ A Novel Defected Ground Structure for Planar Circuits,” IEEE Microwave and Wireless Components Letters, Vol. 16, No. 2

85. H. Kogelnik and C.V. Shank, “Coupled Wave Theory of Distributed Feedback Lasers,” J. Appl.Phys., Vol. 43, No.5, pp. 2327-2335, 1972.

86. E. Yablonovitch, “Inhibited Spontaneous Emission in Solid State physics and Electronics,” Phys. Rev. Lett., Vol.58, No. 20, 1987.

87. A. Yariv, P. Yeh, “Optical Waves in Crystals,” Wiley & Sons, 1984.

88. Z. Zhang, S. Satpathy, “ Electroanetic Wave Propagation in Periodic Structures: Bloch Wave Solution of Maxwell’s Equations,” Physical Review Letters, Volume 65, No. 21, 1990.

89. R.D. Meade, K.D.Brommer, A.M. Rappe and J.D. Joannopoulas, “Existence of a Photonic Band Gap in Two Dimensions,” Appl. Phys. Lett. 61, 4, 1992.

90. B. Lombardet, L.A. Dundas, R. Ferrini and R. Houdre, "Bloch Wave Propagation in two Dimensional Photonic Crystals: Influence of Polarization," Optical and Quantum Electronics, 37, 293-307, 2005.

91. Y.S. Jalili, S. Shamehri, " 2D Photonic Bandgap Crystals: Characteristics and Optical Properties," Iranian Physical journal," 2-3,30-33,2008.

92. Y. Toyota, A.E. Engin, T.H. Kim, M. Swaminathan, "Stopband Analysis Using Dispersion Diagram for Two Dimensional Electromagnetic Bandgap structures in Printed Circuit Boards," IEEE Microwave and Wireless Components Letters, Vol.16, No. 12, 2006.

93. C. Kittel, " Introduction to Solid State Physics," 8th edition Wiley 2005.