Chapter 7
Metamaterial-Based Planar Antennas

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Abstract Microstrip patch antenna is used extensively in wireless and mobile applications due to its low profile and lightweight. However, this antenna is prone to low gain, limited bandwidth and increased cross polarization levels. Metamaterial can be integrated onto an antenna to improve its performance. A possible approach to enhance the performance is by suppressing surface waves. This can be achieved by using Electromagnetic Bandgap (EBG) structures. In addition, plane waves that come in contact with EBG structures can be reflected in phase thereby enhancing the radiation properties of the microstrip antenna. Therefore, the main motivation underlying this work is to provide an overview on the evolution, characterization and performance enhancement of microstrip antennas with EBG structures.

Keywords Metamaterial • Microstrip patch antenna • Electromagnetic bandgap (EBG) • Artificial magnetic conductor (AMC) • Evolution • Bandgap structure

1 Introduction

"Metamaterials are macroscopic composites having man-made three dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation" is aptly described by B.A. Munk in his book [1].

This material is artificially engineered to exhibit a behaviour that is not found in nature. There are many categories of metamaterial that have been established over

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the years namely, i.e. Double Negative Material (DNG), Single Negative Material (SNG), Electromagnetic Bandgap Structure (EBG), Artificial Magnetic Conductors (AMC), Frequency Selective Sheets (FSS), High Impedance Surfaces (HIS), Chiral media, Zero Index metamaterial (ZIM) and many more.

It should be noted that some of these material may have overlapping properties. In the early years of the periodic structure research, the EBG structure was described as Photonic Bandgap structures whereby the term was developed by the photonic fraternity that worked on stop band performance of optical periodic structures and solid-state electronic band gaps [2]. In [2], the author has also argued that the usage of photonic bandgap and microwave periodic structures (EBG) can be confusing when in actuality both refers to periodic structures that exhibit bandgaps. In this work the focus will be on EBGs and AMCs.

2 Electromagnetic Bandgap (EBG)

Fabricated periodic elements that may prevent or assist or even localize electromagnetic waves propagation within a specified range of frequency [3, 4] can be defined as an EBG structure. These structures are engineered by arranging dielectric material and metallic conductors periodically.

EBG structures can be classified into three types [3]:

- 3D structures—these structures occupy in all three possible direction of the axis and are fabricated and placed in a volumetric form. Examples of these are the woodpile dielectric structure and the multilayer metallic tripod array.
- 2D structures—these are formed on surfaces. There are two variations to these, i.e. mushroom-like EBG which has a via running through the unit cell and uni-planar EBG surface. These types of structures are widely considered in microstrip antenna designs due to its low profile, low cost and in particular ease of fabrication.
- 1D EBG—this is usually in reference to transmission line structures which use a single row of EBG placed along the transmission line.

EBG structures are able to exhibit a unique behaviour depending on whether the incident wave is a plane wave or surface wave. In the case of surface waves that get in contact with EBG, the bandgap of the EBG denies propagation of the surface waves in all angles and polarization states.

On the other hand, if plane waves get in contact with the EBG structures then the reflection phase would vary with frequency. At a particular frequency, the plane wave would encounter a reflection phase which is zero degrees. In reality this would mean the EBG is now functioning as a perfect magnetic conductor (PMC).

3 Evolution

In 1898, Bose [5] carried out experiments of which the outcomes today can be recognized as exhibiting metamaterial properties. His investigations on polarisers made of wired gratings improved the sensitivity of the receivers. He also reported on book-like structures with multiple pages when placed in front of a beam improved the beam's polarization. These were among the earliest documented work on metamaterial. He also documented experimental observation on the twisted fibres of jute that caused an optical twist on the plane of polarization. J. Bose's observation is the very first attempt in observing the microwave behaviour on twisted material, today know as chiral media.

A Finnish scientist, K.F. Lindman, in 1914, explored and investigated artificial chiral media extensively [6]. He managed to configure various models of wired spirals which were used in the study microwaves. His investigation led him to analyzing wave propagation through a grid of wired scatterers. This scientist also studied Frequency Selective Surfaces (FSS) which allow the separation of a range of frequencies from a broad band signal.

In 1946, Leon Brillouin's research left a prominent niche in the EBG world. His breakthrough work on periodic structures and its ability to suppress k (where k is the wavenumber) vectors of waves that propagate within it enabled fundamental and critical understanding of EBG materials [3, 4]. It was this scientist that enabled the determination of the frequency bandgap of a periodic structure using the dispersion curve. His valuable insight on the EBG characterization later became known as the Brilloiun zone.

Experimental investigations on microwave lenses were carried out in 1948, by Kock [7]. The lenses were built using parallel metallic strips. Kock also established an equation to predict the refractive index of the delay lenses based on its structural dimensions. Thereby his observation allowed engineering of artificial material that allowed the lensing effect of microwaves.

In 1968, Veselego [8] hypothesized the possibility of having simultaneous negative values for permittivity (ε) and permeability (μ). In his paper, he also introduced the concept of right handed and left handed substances. Although his paper argues theoretically the possibility to have $-\varepsilon$ and $-\mu$, he did put in motion that with technological progress that ε and μ less than zero will be realizable despite identifying limitations on experimental observation.

These scientists pioneering work led to many trail-blazing researches in the field of artificially engineered structures that influences the electromagnetic waves propagation.

In 1987, EBG research took off exponentially due to interesting observations made by two scientists. Yablonovitch [9] analyzed and hypothesized the different aspects of inhibited spontaneous emission whereby if a 3D structure with a band gap overlaps on the electronic band-edge, then it is bound to forbid spontaneous emission. During the same time within the same continent of Canada, John [10] hypothesized a 3D photonic super lattice that can enable strong localization of photons in non-dissipative materials. These observations somewhat influence the definition of the EBG whereby these structures are able to localize or inhibit a range of frequency.

The first periodic structure in an arrangement of dielectric spheres in lattice-like diamond shapes that was easily fabricated and possessed a wide photonic band gap was investigated by Chan et al. [11] in 1991. Within the same year Yablonovitch [12], devised his own periodic structure realized with cylindrical holes that were drilled through the substrate material. This structure was then named Yablonovite and it also exhibited a full photonic band gap.

Today, EBG structures are researched intensively and extensively in the application of microstrip antennas. This is due to its promising properties that allow gain and directivity enhancement, relative bandwidth improvement, size miniaturization and mutual coupling reduction.

4 EBG Properties and Their Characterization

EBG structures are a special class of metamaterial. These structures are able to display various functions such as a Bandgap structure (EBG), Artificial Magnetic Conductor (AMC), High Impedance Surface as well as Soft and Hard surfaces.

This work is focused on the first two functions. Therefore characterizing the EBG as a bandgap structure and as an AMC is a fundamental step towards integrating them on to a patch antenna. The following section describes the EBG's bandgap determination using the dispersion diagram and also obtaining the phase reflection plot to determine the region within which EBG acts as an AMC.

4.1 Bandgap Structure

A typical EBG unit cell is shown in Fig. 1. The bandgap feature of this unit cell can be understood using the lumped LC circuit [3] representation as shown in Fig. 2.

The impedance of a parallel resonant LC circuit is:

$$Z = \frac{j\omega L}{1 - \omega^2 LC} \tag{1}$$

Therefore the resonant frequency of the same circuit is derived as:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

where Z is the surface impedance and ω_0 is the resonance frequency at which the EBG structure does not support any surface waves.

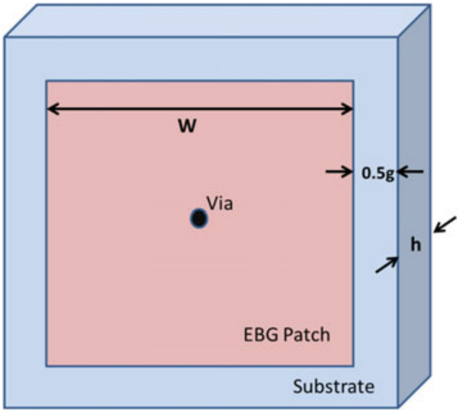


Fig. 1 An EBG unit cell's perspective view and its dimensional parameters

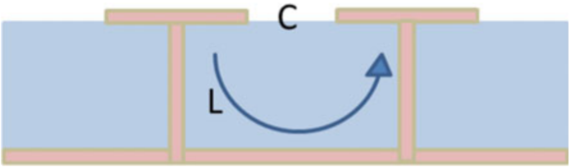


Fig. 2 A cross section view of the unit cells which is used for lumped LC model for EBG analysis

Capacitance, C and inductance L can be determined from the type of material and dimensions that are used:

$$L = \mu h \tag{3}$$

$$C = \frac{W\varepsilon_0(1 + \varepsilon_r)}{\pi} \cos h^{-1}\left(\frac{W + g}{g}\right) \tag{4}$$

where μ is the permeability, ε_r is the dielectric constant, h is the substrate thickness, W is the EBG patch width and g is the width of the gap between the patch.

The approximate computation of the bandgap and impedance is based on static field computations and the fringing fields are not accounted. Defining the Brillouin zone using the dispersion diagram [3] is a more accurate method to determine the surface wave bandgap.

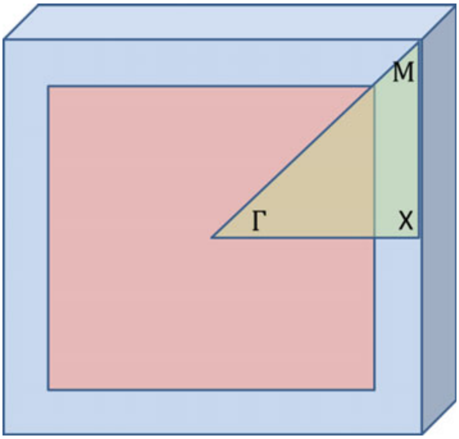
The dispersion diagram is a plot of the frequency versus the wavenumber (k). In order to determine the k for surface waves we need to solve the Eigen-value equation. The solution is not unique to a propagation constant for a particular frequency. Each propagation constant β is known as a specific mode which has its own phase velocity, group velocity and field distribution. Therefore, in a periodic structure the surface wave is also periodic in nature with a phase delay dependent on the wavenumber k and periodicity p.

The dispersion diagram is plotted for a single period for a two dimensional square area where $0 \leq k_{xn} \leq \frac{2\pi}{p_x}$ and $0 \leq k_{yn} \leq \frac{2\pi}{p_y}$.

Table 1 Variation on the wavenumbers; moving from point Γ to X, X to M and M back to Γ

Γ: ⇩ X:	$k_x = 0$ ⇩ $k_x = \frac{2\pi}{(W+g)}$ $(k_x\, varied)$	$k_y = 0$ $(k_y\, remains\, constant)$
X: ⇩ M	$k_x = \frac{2\pi}{(W+g)}$ $(k_x\, remains\, constant)$	$k_y = 0$ ⇩ $k_y = \frac{2\pi}{(W+g)}$ $(k_y\, varied)$
M ⇩ Γ:	$k_x = \frac{2\pi}{(W+g)}$ ⇩ $k_x = 0$ $(k_x\, varied))$	$k_y = \frac{2\pi}{(W+g)}$ ⇩ $k_y = 0$ $(k_y\, varied)$

Fig. 3 The k diagram



The dispersion diagram plot's vertical axis illustrates the frequency and horizontal axis illustrates the transverse wavenumbers (k_x and k_y) over three specific points, i.e. Γ, X and M. Moving from point Γ to X, X to M and M back to Γ, the wavenumbers are varied as shown in Table 1 and the resonant frequencies of the surface modes are identified.

Figure 3 illustrates the EBG unit cell and the Γ, X and M constellation over which the wave numbers are determined. Due to the geometry's symmetry, the triangular Brillouin zone is applicable over the entire unit cell.

4.2 Transmission Line Method to Determine the Bandgap

The transmission line method is an alternative method to determine the EBG structure's bandgap. A periodic lattice and a transmission line sandwiching the substrate can be assumed as a 2 port network. Based on the S-parameters observed upon the 2 ports, an attenuation of S_{21} observed over a range of frequency will be the intended bandgap [13]. This similar approach is also used for filter designs.

The effect of introducing etched square and circular pattern on the EBG bandgap was analyzed in [14]. In [15] a two layer structure is analyzed for its bandgap. This approach allows mushroom-like structures to be characterized. Much research has been undertaken along this transmission line method to identify the bandgap of an EBG structure [16–21].

4.3 Artificial Magnetic Conductor (AMC)

EBG structures in addition to suppressing surface waves, can also act as an artificial magnetic conductor. As the name implies this kind of structure is not available in nature, however, it can be engineered. Normally, an incidental plane wave on a perfect electric conductor (PEC) has a reflection co-efficient of -1, in other words the reflected wave is 180° out of phase. In the case of an EBG structure the reflected phase is 0°, thereby being in phase with the incidental wave [3]. These EBG structures that function as Perfect Magnetic Conductor (PMC) are known as AMC.

The reflection phase of an EBG is a function of frequency. The phase of reflection is made to vary from $-180°$ to $+180°$ as the frequency is made to increase. For the purpose of AMC characterization, the scattered fields from an ideal PEC and an EBG surface are observed. Normalization of the reflected phase from the EBG structure to the reflected phase of the PEC surface is then performed. Subsequently, a π factor is then added to the phase result. This allows to account for the reference of a PEC surface [3, 22]. This characterization enables the determination of the frequency at which the EBG structure functions as an AMC. Usually the frequency band over which the EBG structure is able to exhibit AMC characteristics is defined for a phase reflection of $-90°$ to $+90°$ [23].

The EBG's property as an AMC is capitalized by using it as ground plane to improve the radiation characteristics of a microstrip antenna.

5 EBG Integrated Patch Antennas

Extensive research on patch antennas integrated with EBG structures are being carried out. Due to the dynamic status of this research field, the scope of this descriptive survey in this thesis is limited to microstrip antennas and the improvements that have been achieved in their performance using EBG structures.

In general, the following section will describe on the improvements that can be achieved using EBG structures on microstrip antennas, i.e.

- Improving the radiation characteristics
- Achieving miniaturization
- Eliminating mutual coupling
- Functioning as a filter

5.1 Improving the Radiation Characteristics

EBG structures can be integrated onto an antenna in any one of the following manner to improve the radiation characteristics:

- surrounding the radiating patch
- below the radiating patch as a substrate or as a ground plane
- above the radiating patch as a superstrate

The above are described hereafter.

5.1.1 EBG Positioned Around the Radiating Patch

Surrounding the patch antenna with an EBG structure suppresses the surface waves. Surface waves are prominent in thick substrates which are usually used to improve the bandwidth of a microstrip antenna. Suppressing surface waves in the substrate allows an increased amount of radiated power to couple to space waves thereby enhancing the gain of an antenna [24–26]. In addition, this can also mitigate diffracted surface waves at the edge of the patch that can aggravate back lobe radiation [27]. Power losses which are prominent in thick substrates and high dielectric constant can also be reduced [27].

Therefore suppressing surface waves by enclosing a radiating patch with an EBG structure is one possible approach to further enhance the performance of a patch antenna. A planar fed antenna surrounded by a uniplanar compact EBG (UCEBG) structure was investigated in [24]. It reported on a UC-EBG cell's dispersion diagram analysis and subsequent implementation of the EBG surrounding a 12 GHz patch antenna. The computation and measurement results indicated a more focused radiation pattern and also a gain improvement of almost 3 dB.

A patch antenna placed on an array of air–columns embedded on a 10 mm dielectric substrate functioning as an EBG structure was investigated in [27]. This investigation reported improved gain by 10 dB and improved radiation pattern whereby the back lobe radiation is reduced. However, it should be noted that this researcher carried out his investigation on a 10 mm thick substrate to ensure significant presence of surface waves.

A comparison between a step like substrate structure and mushroom-like EBG consisting substrate was investigated in [28] on a high dielectric constant substrate. The radiation performance of both antenna structures improved significantly. In addition the back lobe radiation was also minimized. Similar observation has also been reported by other researchers [29].

Investigations on these type of antennas with enclosed EBG structures was also investigated for dual-band antennas [30] and antennas in the terahertz frequency [31]. A dual-band antenna comprising of two radiating patches stacked one onto the other and each patch surrounded by fractal EBG has enabled low profile structure for dual-band applications. The gain was improved in addition to wider impedance bandwidth [30]. EBG structures have also showed improved directivity for antennas in the terahertz frequency. However, this investigation was carried using simulation and experimental verification was scaled down. Despite this both simulation and measurement indicated improved directivity for the planar fed patch antenna at terahertz frequency [31].

Drawback of this approach is that the gain improvement observed for this kind of implementation is very low, about 3 dB except in [27]. However, radiation pattern improvements reported were remarkable. Antenna with these EBG structures also have increased dimension compared to conventional patch antennas.

5.1.2 EBG Positioned Below the Radiating Patch

Another possibility of integrating the EBG structure on a patch antenna is below the radiating patch sandwiched between the grounds. In this position the EBG functions as reflector surface and usually known as an AMC. Various efforts have been reported using AMC integrated on a patch antenna and various improvements have been reported in respect of backlobe reduction, gain and impedance bandwidth improvement.

A novel UC-EBG structure functioning as an AMC was investigated in [32] and experimentally verified. The researcher reasons that one way to differentiate the PEC and PMC is by looking at the surface impedance. The surface impedance of a PMC is an open circuit and therefore a periodic pattern would be able to create an open circuit condition.

AMCs sandwiched on the ground plane of a probe fed patch antenna [33], plane fed patch antenna [34] and a plane fed wideband [35–37] antenna have reportedly improved the gain and the impedance bandwidth. In [33], a detailed parametric analysis was carried out on a two layer microstrip patch antenna working within the bandgap and outside the bandgap. Outside the bandgap, 25% improvement on bandwidth and 3 dB gain improvement were obtained. Within the bandgap, impedance bandwidth improved 20% whereas gain improved by 10 dB. The implementation of an AMC on a wideband antenna [35] shows good gain improvement and wider impedance bandwidth.

In [38] a multi periodic EBG structure sandwiched between the ground planes was analyzed. Comparisons were made against a periodic EBG structure. There was a slight improvement in the gain of the multi periodic EBG structure by 0.6dBi. A slight improvement in the impedance bandwidth was also noted.

Investigations in [39] reported on suppressing the parallel-plate modes that exist in an aperture coupled antenna. By introducing an AMC structure, back lobe suppression was achieved. Two types of reflector surfaces formed by an AMC and a PEC were compared against the antenna without the reflectors. It was reported that the sidelobe suppression was significant for both the PEC and AMC structures compared to the antenna without reflectors. The PEC and AMC surfaces, however, showed similar back lobe suppression.

Dual-band characteristic using a single radiating element was also reported using 2 layers of EBG substrates [40]. However, it was reported additional unwanted resonant frequencies appeared due to parasitic coupling between radiating patch and the EBG structure during measurements.

Wearable antennas have also benefitted from EBG placed below the radiating patch [41]. It is reported that the EBG structure has reduced the radiation into the human body by over 15 dB and the effect of frequency detuning caused by the human body. This was made possible due to the back lobe suppression made possible by the EBG placement.

5.1.3 EBG Positioned Above the Radiating Patch

EBG structures can also be placed above the radiating patch. By doing so, the radiation characteristic of a patch antenna can be improved. Various investigations have been carried out to illustrate this improvement on patch antennas and also on wideband antennas. The superstrate structures are also known as Frequency Selective Sheet (FSS).

Square loop [42] and circular ring [43] FSS sheets have been used to enhance the directivity of a patch antenna. In addition wideband and broad band antennas too have seen improvement in gain by using EBG structures as superstrate [44, 45]. This is crucial as gain is usually compromised in wideband and dual-band structures in comparison to single resonant antenna.

Studies have also been carried out using genetic algorithm to enable optimized design of the FSS [46] which showed improved gain and directivity. In addition, in [47], the researcher has used several radiating elements as in an array antenna to excite the EBG structure. This approach improved the radiation bandwidth and the gain by almost 2 dB.

Most of these works were carried out with a maximum of two layers of EBG structure. This is to ensure that the dimensional increase in the patch antenna's profile is proportional with its radiation characteristic improvement.

5.2 Enabling Miniaturization

Achieving miniaturization for wireless antennas are crucial due to ever evolving demands for more compact and low profile communicating devices. EBGs can be integrated onto a patch antenna to achieve miniaturization

In [48] a patch antenna designed to resonate at 10 GHz was integrated with an EBG structure on the ground plane. This antenna configuration exhibited a resonant frequency of 2.4 GHz thereby enabling a size reduction of 75%. In addition the radiation pattern was acceptable with a gain value of 2.4 dB.

The investigation in [49] compared the performance of the conventional mushroom-like EBG with a spiral EBG. The spiral structure showed a drop in the bandgap frequency from 6 to 7 GHz to almost 2–3 GHz for the same dimension of a unit cell. Therefore miniaturization is achieved.

The performance of a miniaturized antenna designed with meandered slots for Bluetooth application was further improved with the usage of an EBG structure [50]. The EBG structure placed on the ground plane increased the transceiver's distance significantly by 22 m.

In addition, miniaturization was achieved in [51] by placing an AMC as a reflector for a slotted patch antenna which serves as a telemetry system using the 2.45 GHz band to enable signal transmission and reception in indoors and the 6–7.5 GHz band for radar sensing part. The radar sensing was made possible due to the AMC reflector working as a perfect magnetic conductor (PMC) plane from 6 to 7.5 GHz.

5.3 Mitigating Mutual Coupling

Array antennas are prone to mutual coupling and this issue is usually solved using complex feed networks. EBG structures have been recognized to mitigate the mutual coupling between array antennas which is a simpler alternative to complex feed networks. By reducing the mutual coupling, the directivity and gain of a microstrip antenna can be improved.

In [52], it was demonstrated that the mushroom-like EBG embedded between two radiating patches could substantially reduce mutual coupling by up to 8 dB.

Similar mutual coupling reducing works were also carried out by other researchers. The research of [53] was implemented on two slot antennas on a single substrate which improved the radiation pattern and the gain.

On the other hand, the investigation in [54] was done on a 2 layer structure whereby the EBG structure was placed on top of a dual radiating element. The EBG on the top layer forms a row of cells which appears between the radiating elements. This study showed a 10 dB reduction in mutual coupling.

5.4 Performing as a Filter

The EBG's property of exhibiting a bandgap over a range of frequencies is exploited to function as a bandstop filter in microstrip antenna applications. The research carried out in [55] implemented a single row of EBG cells on the ground plane placed directly below in parallel to the planar feed. These EBG cells act as a filter to inhibit a desired band of frequencies between 3–4 GHz, while the impedance bandwidth of the antenna without the EBG filter is from 2 to 6 GHz.

Similar integration of the EBG as a filter was also implemented on an array antenna [56]. These structures were located under the feed line and in addition a combination of EBG structures are analyzed:

- Mushroom-like EBG structure
- Minkowski and mushroom-like EBG structure
- Sierpinski and mushroom-like EBG structure

The radiation pattern improved for all the combinational structures compared to the mushroom-like structure only.

6 Summary

An overview on the evolution of the metamaterial generally and EBG more specifically is covered in this paper. In addition, various possible EBG structure characterization methods, possible integration onto a patch antenna and its ability to improve the radiation characteristics were also reviewed. This overview lays the foundation for researchers to further explore the myriads of applications that can benefit from the integration of metamaterial on to antennas.

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