DESIGN, MODELING AND IMPLEMENTATION OF ANTENNAS USING ELECTROMAGNETIC BANDGAP MATERIAL AND DEFECTED GROUND PLANES

Surface Meshing Analysis and Genetic Algorithm Optimisation on EBG and Defected Ground Structures for Reducing the Mutual Coupling between Radiating Elements of Antenna Array and MIMO Systems

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Abstract

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Keywords
Electromagnetic Band gap (EBG); Defected Ground Plane, Microstrip patch antenna; Planar Inverted-F Antenna; MIMO; Return Loss; Mutual Coupling, Surface Meshing, Genetic Algorithm.

The main objective of this research is to design, model and implement several antenna geometries using electromagnetic band gap (EBG) material and a defected ground plane. Several antenna applications are addressed with the aim of improving performance, particularly the mutual coupling between the elements.

The EBG structures have the unique capability to prevent or assist the propagation of electromagnetic waves in a specific band of frequencies, and have been incorporated here in antenna structures to improve patterns and reduce mutual coupling in multi-element arrays. A neutralization technique and defected ground plane structures have also been investigated as alternative approaches, and may be more practical in real applications.

A new Uni-planar Compact EBG (UC-EBG) formed from a compact unit cell was presented, giving a stop band in the 2.4 GHz WLAN range. Dual band forms of the neutralization and defected ground plane techniques have also been developed and measured. The recorded results for all antenna configurations show good improvement in terms of the mutual coupling effect.

The MIMO antenna performance with EBG, neutralization and defected ground of several wireless communication applications were analysed and evaluated. The correlation coefficient, total active reflection coefficient (TARC), channel capacity and capacity loss of the array antenna were computed and the results compared to measurements with good agreement.

In addition, a computational method combining Genetic Algorithm (GA) with surface meshing code for the analysis of a 2×2 antenna arrays on EBG was developed. Here the impedance matrix resulting from the meshing analysis is manipulated by the GA process in order to find the optimal antenna and EBG operated at 2.4 GHz with the goal of targeting a specific fitness function. Furthermore, an investigation of GA on 2×2 printed slot on DGS was also done.

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Chapter 1

Introduction

1.1 Background and Motivations

Various isolation improvement techniques for MIMO applications requirements are constantly growing. With the rapid development of a small-size and low-profile antenna in modern wireless communication technologies, the needs in enhancing the system performance have gained a lot of attention. The problem of mutual coupling is exacerbated by the size limitation of antenna arrays in portable MIMO enabled devices. It is therefore, necessary to provide efficient mutual coupling reduction technique for closely-packed antenna element arrays.

In recent years, there has been a growing interest on investigating electromagnetic band gap (EBG) material because of its unique properties. Due to its uniqueness, various kinds of EBG material have been presented and applied to microwave circuit and antennas technology [1-4]. Two main interesting features associated with EBG material are suppression of surface waves and in-phase reflection coefficient for plane waves. The feature of surface wave suppression can be applied to patch antenna designs to improve the antenna's radiation performance and reduce the mutual coupling of the array elements [1, 5-7]. Meanwhile, the feature of in-phase reflection coefficient can be leading to low profile antenna designs [1, 8-10] .

Nowadays, the used of defected ground planes on antenna applications also had gained a lot of attention on many researchers. The defected ground planes are known as its capability in reducing the mutual coupling between the antenna arrays, and could improve the resonant frequency and impedance bandwidth [11]. The defected ground planes can be in the form of defected ground structure (DGS) [12], slotted/slit ground plane and vias [13-16].

Additionally, another useful method in reducing the mutual coupling between the antenna arrays is the neutralization line technique. This technique, introduced an additional coupling by introducing a thin metal strip connecting between the two antennas. This idea was to compensate for the existing complex electromagnetic coupling of the structure [17].

1.2 Development History of EBG

Electromagnetic band gap (EBG) structures and their applications in antennas have become a new research direction in the antenna community. It was first proposed to respond to some antenna challenges in wireless communications [1]. For example:

- To suppress surface waves in the antenna ground plane.
- To design an efficient low profile wire antenna near a ground plane.
- To increase the gain of an antenna.

Authors in [1], defined the electromagnetic band gap structures as an artificial (or sometimes non-periodic) objects that prevent/assist the propagation of electromagnetic waves in a specified band of frequency for all incident angles and all polarization waves. The concept of electromagnetic band gap (EBG) structures originates from the solid-state physics and optic domain, where photonic crystal forbidden band gap for light emissions was first studied by Lord Rayleigh in 1987 [18, 19] and then widely investigated in the 1990s. Thus, the terminology, photonic band gap (PBG) structures, was popularly used in the early days. Since then, an ample of scientific creativity has been witnessed as new forms of electromagnetic structures are invented for radio frequency and microwaves [5]. The feature of the band gap was first realized and experimentally demonstrated by periodic dielectric structures in the early 1990s [20]. Subsequently, arrays of dielectric rod and woodpile structure were reported.

Two important planar EBG structures were invented in the late 1990s, where metallic components were effectively incorporated into the unit cells. One is mushroom – like EBG surface [21] and the other is the uni-planar EBG (UC-EBG) surface [1]. From then on, many EBG structures have been proposed, studied, and compared in various antenna designs such as PIFA [22-26], patch antenna [2, 26-28], dipole antenna [10, 29, 30] and spiral antenna [8, 9, 31].

It had been discovered that the band gap feature of EBG structures has its capability in suppressing the surface wave in microstrip antenna designs. As a consequence, the antenna and efficiency are increased while the back lobes are reduce [5, 32-34]. In addition, EBG structures also been used in microstrip antenna arrays. As an important parameter in array design, the mutual coupling/isolation between array elements affects the entire array. Thus, the EBG structures are used to reduced the mutual coupling, and detailed results can be found in [1, 2, 27, 28, 35-37].

1.3 Development History of Defected Ground Planes

Since the late 1980's, defected ground planes have attracted the interest of many researchers, due to their interesting properties in terms of size miniaturization, suppression of surface waves and arbitrary stop bands. Since then, they have been used in many applications like low pass filters, band pass filters, antennas, waveguides and others. Additionally, this technique could also improve the impedance bandwidth and the resonant frequency of the antennas.

For instance, a defected ground structure (DGS) unit cell is an intentionally designed defect on the ground plane, which creates additional effective inductance and capacitance. This technique can be used to design microstrip lines with desired characteristics such as higher impedance, band rejection and slow-wave characteristics, while significantly reducing the footprint of the microstrip structure. The first DGS structure is the well-known dumbbell shaped DGS, published in 1999 [38]. Since then, this technique has gained lots of attention to many researchers. Many shapes of DGS slot have been studied in planar microstrip antenna designs [39, 40], which provides many good performances - size reduction (resonant frequency lower), impedance bandwidth enhancement (quality factor lower) and gain increasing. Moreover, author in [25, 41-46] had revealed the usefulness of DGS in reducing the mutual coupling between the antenna array. Furthermore, in [47-50] had shown the capability of DGS in eliminates the harmonic and improves the return loss level.

1.4 State of the Art of the Original Contribution

The research work is focused on the design, modelling and implementation of several antenna applications using electromagnetic band gap (EBG) material and defected ground structures (DGS). It also includes the neutralisation transmission concepts between the elements. Various antenna structures such as microstrip patch, PIFAs, printed conducting surface monopoles with EBG and defected ground plane were considered and investigated for better operational performances in terms their spatial radiation (i.e., spatial correlation between the antenna elements) and coupling requirements.

Firstly, the present work is devoted to design and model a planar EBG structure in which a uniplanar compact EBG (UC-EBG) was modelled, developed and implemented for two element array antennas. The EBG was considered for its implementation simplicity as surface mounting structure with the radiating elements. The isolation between PIFAs antenna were achieved and measured results agreed well with the computed one. The computed results stop band frequencies around 2.4 GHz are also compared with distorted uni-planar compact EBG (DUC-EBG).

The research was extended to include 2 × 2 U-shape slot antennas and 4 × 4 PIFAs, operated at single band (2.4 GHz) and dual band bands (2.4 and 5.2 GHz). In these designs the radiating elements were closely spaced to confirm the advantages of inclusion of EBG and defected ground plane. The radiation performance in terms of the total active reflection coefficient (TARC) was studied that reflects the MIMO efficiency in terms of the effect of mutual coupling. This also indicates the trade off between SNR and target capacity of a fixed or a mobile access points. In addition, the channel capacity and capacity loss have also been computed and compared with previous data.

A new design idea for small MIMO antenna systems covering a wide band width was developed and implemented. This results in a new compact, low profile, wide band printed monopole antennas. The proposed antenna offered a good mutual coupling, spatial correlation and channel capacity loss over a wide frequency band from 2.4 to 4.2 GHz. The new design attaints to offer reliable wireless connectivity with a high data throughput in the expanding WiFi/Wimax service applications.

Finally, the design process of antenna elements including the EBG or DGS was presented and studied using genetic algorithm (GA) optimisation method. The workable procedure of CST MW GA and adaptively meshing surface structures method including the MATLAB GA were applied for slot and bowtie antennas respectively. Various EBG and DGS structures were concluded. The optimal solution of the antenna structure derived using GA were examined in details. It should be noted that the proposed programme capability of 2D and 3D adaptive meshing structures with MATLAB GA can be easily handled for analysis.

1.5 Organization of the Thesis

Chapter 1 postulates historical background and literature survey of EBG materials used to improve the antenna's performance. It should be noted that a more detailed review of existing literature is reported at the beginning of each chapters with separate references at the end.

Chapter 2 unfolds the background of the EBG. Three different types of two – dimensional EBG structures are introduced. Several methods in obtaining the characteristic of the EBG are discussed. An overview of the EBG applications in antenna engineering has also been reviewed.

Chapter 3 reviews the importance and operation of defected ground planes and neutralization line technique. An overview of the DGS and neutralization line applications on several wireless communications has also been addressed.

Chapter 4 explains the modelling concept of the proposed EBG structures. The observed simulated and measured characteristics of the proposed EBG are discussed and investigated. The implementation of the new developed EBG on several antenna applications has also been examined.

Chapter 5 examines the MIMO antenna criteria that includes: correlation coefficient, total active reflection coefficient (TARC), capacity channel, capacity loss; on several antennas applications using EBG and defected ground plane.

Chapter 6 introduces the neutralization line technique for a compact, low profile, printed crescent-shaped diversity monopole antenna. The coupling and radiation performances over a wide frequency band were studied against the conventional antenna array without applying this technique.

Chapter 7 presents the use of GA as an optimization process to design the antenna elements including the EGB cell structure and DGS subject to one or more design constraints. The GA and including the adaptive meshing method were presented to find the optimal structures of the proposed antenna, DGS and EBG according to specific cost function.

Last but not least, Chapter 8 summarises the overall conclusions and recommendations for further work on related topics.

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Chapter 2

Electromagnetic Band Gap (EBG) Materials

2.1 Introduction

Electromagnetic band gap materials are presently one of the most rapidly advancing sectors in the electromagnetic area. The EBG have attracted considerable attention due to the growing interest in improving antenna's performance such as increasing the antenna gain and reducing the mutual coupling in array configurations.

Furthermore, EBG materials are a novel class of artificially fabricated structures which has the ability to control and manipulate the propagation of electromagnetic (EM) waves which produce forbidden frequency gaps in which propagation is prohibited [1]. At this forbidden frequency band gap, all the electromagnetic wave will be reflected back and the structure will act like a mirror [2]. The advantage over a metal reflector is that for an EBG, reflection takes place only at forbidden frequency band gap. At other frequencies it will act as transparent medium. This concept is illustrated in Figure 2.1. The EBG structures also have the ability to suppress the surface wave propagation on the ground plane of the antennas and thus minimize the mutual coupling, and also an improvement of the radiation pattern of the antennas on finite ground plane as the currents do not reach the outer edges with high density and thus limits the interfering radiation produced by the spurious waves radiated at the boundaries of the antennas. Surface waves can occur on the interface between two dissimilar materials, such as metal and free space. They are bound to the interface, and decay exponentially into the surrounding material. Figure 2.2 shows the comparison operation phenomenon of the antenna with and without EBG structures.

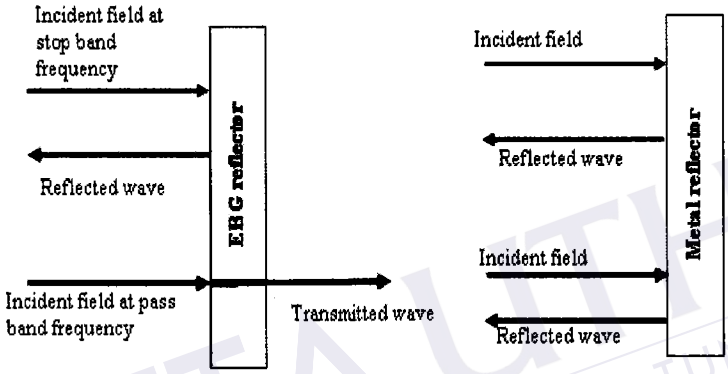


Figure 2.1: Comparison between EBG and metal reflector; the EBG reflector allows waves propagation at passband frequencies and the metal inhibits waves at all frequencies [2].

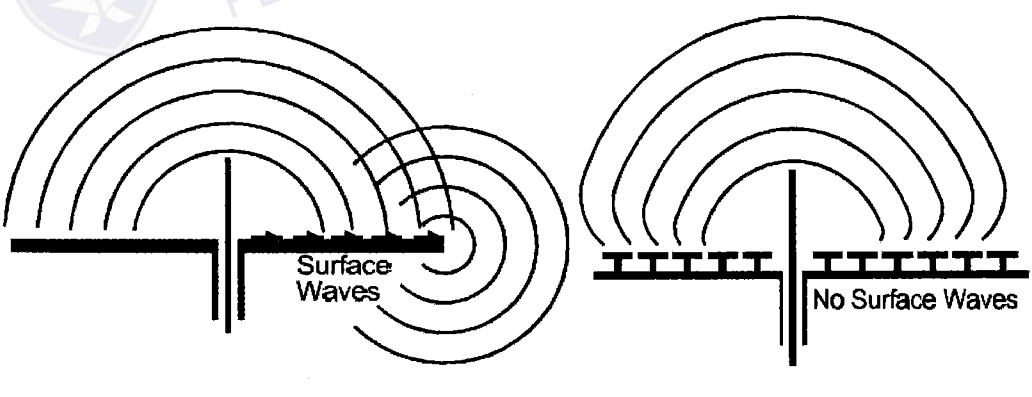


Figure 2.2: Surface wave (a) without EBG, and (b) with EBG [2].

One other interesting characteristic of the EBG structure is that they exhibit high impedance and can be considered as a Perfect Magnetic Conductor (PMC) in a certain frequency band. Conventionally, the antennas are proximity placed on metal sheet or known as Perfect Electric Conductor (PEC.) Unfortunately, if the antenna is placed too close to the conductive surface, the phase of impinging wave is reversed upon reflection, resulting in destructive interference with the wave emitted in the other direction. In other words, the image currents in the conductive sheet cancel the currents in the antenna, resulting in poor radiation efficiency. Therefore, a distance of λ/4 between the ground plane and the antenna must exist, so, that the reflected wave (wave 2) may interfere constructively with the emitted one (wave 1) as shown in Figure 2.3. Differ from EBG structure, which is acting as PMC, the distance can be smaller than λ/4 (Figure 2.4), making it possible to implement to low profile antenna [3]. This is because, the EBG surface reflects all of the power just like a PEC, but it reflects in-phase, rather than out-of-phase, allowing the radiating element to be directly adjacent to the surface. In other words, the direction of the image currents results in constructive, and allowing the antenna to radiate efficiently.

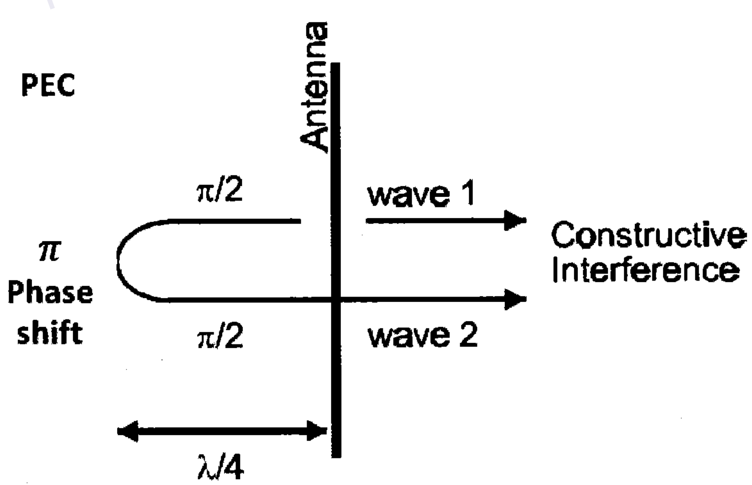


Figure 2.3: A PEC as a ground plane [3].

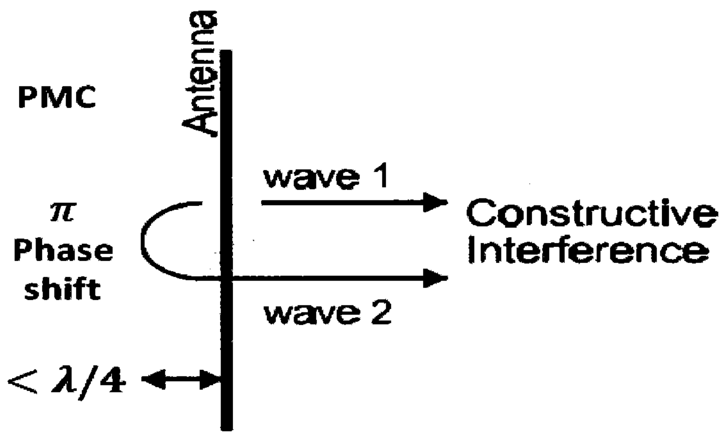
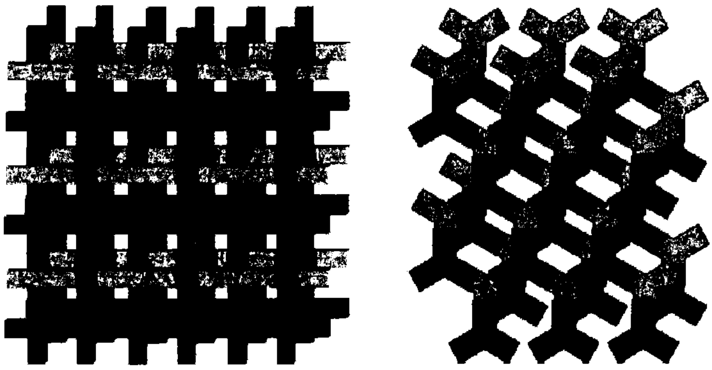


Figure 2.4: A PMC as a ground plane [3].

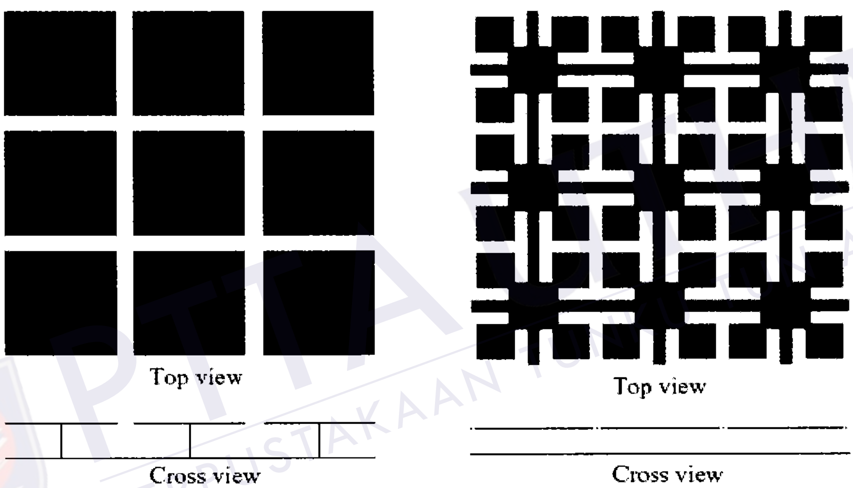
2.2 Electromagnetic Band gap (EBG) Categorization

Electromagnetic band gap (EBG) materials also known as photonic crystal (PC) or Photonic Band Gap (PBG) structures are broadly classified as metamaterials, and are typically realized by periodic arrangement of dielectric materials and metallic conductors. In general, they can be categorized into three groups according to their geometric configuration: (1) three-dimensional volumetric structures, (2) two-dimensional planar surfaces, and (3) one-dimensional transmission line [4]. Figure 2.5 shows two representative 3-D EBG structures: a woodpile structure consisting of square dielectric bars [5] and a multi-layer metallic tripod array [6]. Examples of 2-D EBG structures are plotted in Figure 2.6: a mushroom-like structure [3] and uni-planar design without vertical vias [7]. Figure 2.7 shows the one-dimensional EBG transmission line design [8].



(a) (b)

Figure 2.5: Three-dimensional (3-D) EBG structures: (a) a woodpile dieletric structure and (b) a multi-layer metallic tripod array [4].



(a) (b)

Figure 2.6: Two-dimensional (2-D) EBG surfaces: (a) a mushroom-like surface and (b) a uni-planar surfaces [4].

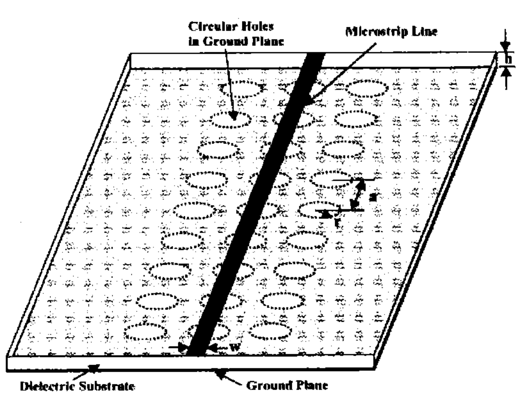


Figure 2.7: One-dimensional (1-D) EBG transmission line [8].

In 1887, electromagnetic wave propagation in periodic media was first studied by Lord Rayleigh and has long been investigated by the microwave community since then. Yablonovitch *et al.* [9] has developed new concepts and ideas on EBG, whereby they show the ranges of frequencies in which light cannot propagate through the structure. The frequency region where the incident waves cannot propagate through the structures is known as 'forbidden frequency gap' or stop band. Figure 2.8 shows when the wavelength is in the stop band region; there is no transmission through the material. However, if the wavelength is in the pass band region, the energy will propagate through the material.

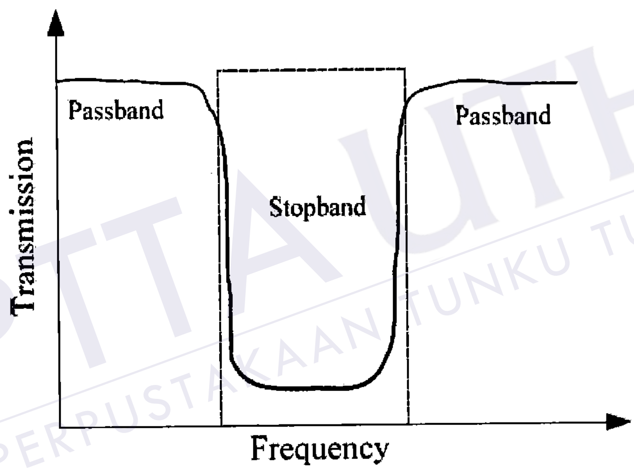


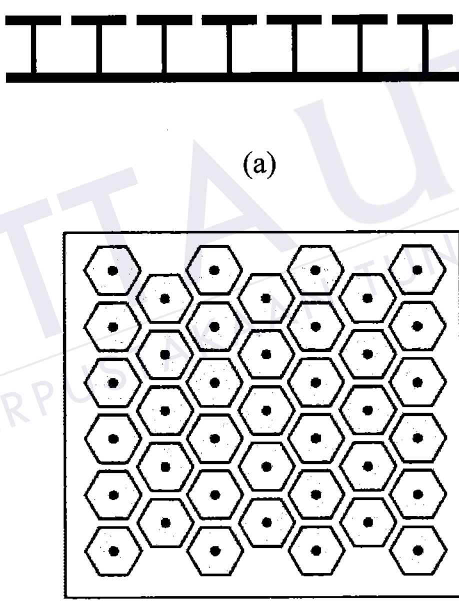
Figure 2.8: Transmission variations of the incident waves through the media as a function of the operated frequency bands [10].

2.3 Two Dimensional EBG Materials

This research work will focus on 2-D EBG materials, that have the advantages of small light weight, low fabrication cost, and are widely considered in antenna engineering applications. The following section will discuss several types of the 2-D EBG materials.

2.3.1 The Metallo-dielectric Structure

The metallo-dielectric structure is considered as a new type of metallic electromagnetic structure and is characterized by having a high surface impedance (HIS) [3]. Figure 2.9 shows the high-impedance surface consists of an array of metal protrusions on a flat metal sheet. They are arranged in a two-dimensional lattice and can be visualized as mushrooms or thumbtacks protruding from the surface. The protrusions are formed as a metal patches on the top surface on the board, connected to the solid lower conducting surface by metal plated vias.



(a)

(b)

Figure 2.9: High impedance surface: (a) Cross section of a high impedance surface (b) Top view of the high impedance surface [11].

The two-dimensional array of resonant elements can be viewed as a kind of electric filter, and many of its properties can be explained using a simple circuit model. The capacitance is due to proximity of the top metal patches, while the inductance originates from current loops within the structure, as shown in Figure 2.10. The electromagnetic properties of this structure can be described by using lumped-circuit elements; capacitor, C and inductor, L, when they are small compared to the operating wavelength, as depicted in Figure 2.11.

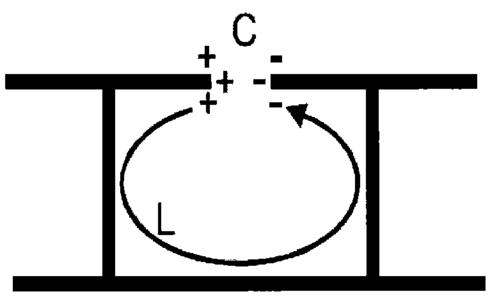


Figure 2.10: Capacitance and inductance in the high-impedance surface [11].

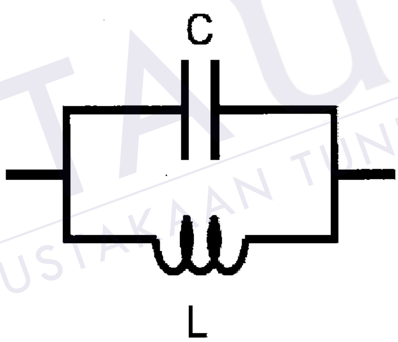


Figure 2.11: Effective circuit used to model the surface impedance [11].

The surface impedance is high close to the resonant frequency ω_o which can be determined from the L and C as follows [3]:

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{2.1}$$

The sheet impedance equals to the impedance of a parallel circuit, consisting of the sheet capacitance and the sheet inductance [3] :

$$Z = \frac{j\omega L}{1-\omega^2 LC} \tag{2.2}$$

The mushroom type unit cell can form a high impedance surface. Considering surface wave propagation, at low frequencies the surface behaves inductively and supports TM waves. At high frequencies, it behaviour changes to capacitive and TE waves are supported, and near the LC resonance frequency, the surface impedance is very high. In this region, waves are not bound to the surface; instead, they radiate readily into the surrounding space [3].

The metallo-dielectric structure is very effective but requires a non-planar fabrication process. Recent research efforts have focused on the development of a planar EBG structure that does not require metal vias and that can be easily be integrated in microwave and millimetre-wave circuits. Hence, other simpler methods are discussed in the following subsection.

2.3.2 Uni-planar Compact EBG (UC-EBG) material

The crystal structure previously described has effective planar geometry, however, the drawback of being large in terms of wavelength. Furthermore, the fabrication process of this design is complicated because of the process of machining the periodic patterns or holes on the substrate, which it could lead to a slight increase in the discrepancies

8.4 References

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