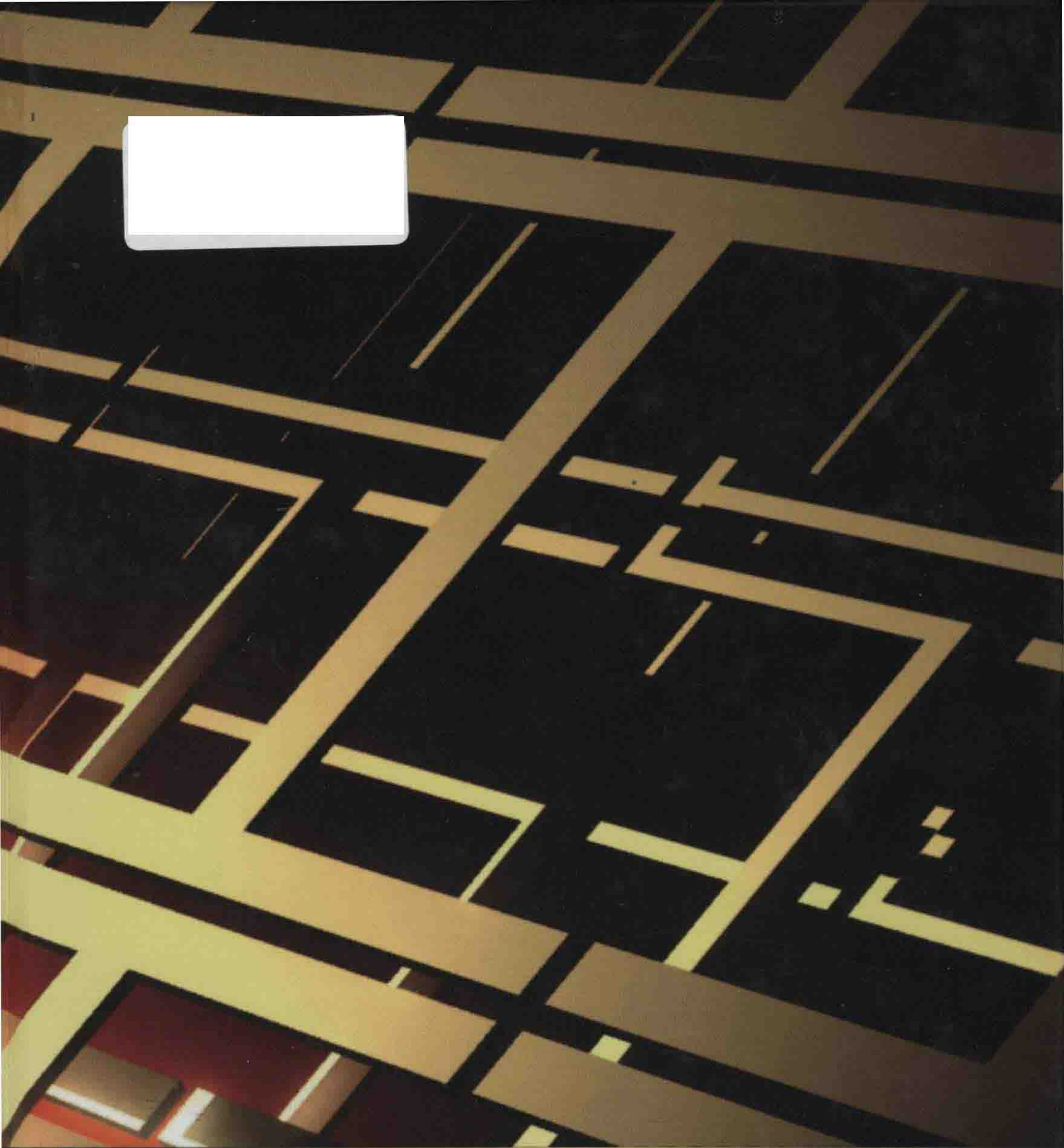

Advances in Metamaterials

Austin Doran

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Edited by **Austin Doran**

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Preface

The world is advancing at a fast pace like never before. Therefore, the need is to keep up with the latest developments. This book was an idea that came to fruition when the specialists in the area realized the need to coordinate together and document essential themes in the subject. That's when I was requested to be the editor. Editing this book has been an honour as it brings together diverse authors researching on different streams of the field. The book collates essential materials contributed by veterans in the area which can be utilized by students and researchers alike.

This book consists of an analysis of the theory, properties and the technological applications of metamaterials for the development of new devices like invisibility cloaks, absorbers and concentrators of EM waves, etc. For developing a new device, it is important to know the electrodynamic features of the metamaterial according to which the device is created. The electromagnetic metamaterials affect EM waves and regulate the surrounding electromagnetic field by changing their permeability characteristics. It is this feature which enables the creation of electromagnetic wave scattering surfaces which utilize metamaterials. This book discusses various aspects related to metamaterials and will be beneficial for both students and experts interested in this field.

Each chapter is a sole-standing publication that reflects each author´s interpretation. Thus, the book displays a multi-facetted picture of our current understanding of application, resources and aspects of the field. I would like to thank the contributors of this book and my family for their endless support.

Editor

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Antenna Designs with Electromagnetic Band Gap Structures

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1. Introduction

The word "meta", in Greek language, means beyond. It implies that the electromagnetic response of metamaterials (MTMs) is unachievable or unavailable in conventional materials. Many efforts have been done to search for an adequate definition for MTMs. In 2002, J.B. Pendry wrote in a conference paper: "meta-materials, materials whose permeability and permittivity derive from their structure". Later, in 2006, C. Caloz and T. Itoh wrote: "Electromagnetic metamaterials are broadly defined as artificial effectively homogeneous electromagnetic structures with unusual properties not readily available in nature" [1]. Perhaps, a serious obstacle on the road to a universal definition for the term MTMs is the fact that researchers working with these objects do not commonly agree on their most essential characteristics. In [2] and [3], some of the problematic aspects of the non-naturality definition were raised, like the difficulty in separating classical composites from the new class of metamaterials. Another argument against the "not found in nature" property is that it unnecessary excludes impressive examples of natural media that could be called metamaterials par excellence, such as structural colors [4].

MTMs cover an extremely large scientific domain which ranges from optics to nanoscience and from material science to antenna engineering. In this chapter, we focus primarily on the subject of MTMs in the electromagnetic field. Personally, We prefer the definition given by D.R. Smith: Electromagnetic metamaterials are artificially structured materials that are designed to interact with and control electromagnetic waves [5]. The term "artificial" refers to the fact that the electromagnetic response of these materials is dominated by scattering from periodically or amorphously placed inclusions (e.g., metallic or dielectric spheres, wires, and loops) [6].

In the family of MTMs, "left-handed" (LH) media drew an enormous amount of interest. This concept was first put forward by a Russian physicist, Victor Veselago, in 1968, for whom the medium is characterized by a simultaneously negative electric permittivity and negative magnetic permeability [7]. Veselago argued that such media are allowed by Maxwell's equations and that electromagnetic plane waves can propagate inside them, but the phase velocity of such a plane wave is in the opposite direction of the Poynting vector. Hence, some researchers use the term "backward wave media" (BWM) to describe these LH materials [8]. When such media are interfaced with conventional dielectrics, Snell's Law is reversed, leading to the negative refraction of an incident plane wave as shown in figure 1.

Nevertheless, Veselago's conjecture was essentially ignored for thirty years due to the absence of naturally occurring materials or compounds that possess simultaneously negative permittivity and permeability.

In 2000, a metamaterial, based on conducting wires [9] and split-ring resonators (SRRs) [10], was demonstrated to have a negative refractive index over a certain range of microwave frequencies [10-13]. Wires, either continuous or with periodic breaks, can provide a positive or a negative effective permittivity. Planar SRRs or wound coils (also known as Swiss Rolls) can provide a positive or a negative effective permeability. Harnessing the phenomenon of negative refraction, these metamaterials offer a good potential for all kinds of applications, such as "perfect" lens [14], imaging [15], resonators [16], and cloaking [17].

Metamaterials possessing these properties are also frequently named "Negative Refractive Index (NRI)" and "Double Negative (DNG) material". In addition to the materials with simultaneously negative permittivity and negative permeability, the single negative metamaterials have also drawn a great interest. Applications are found for these materials either with a negative permittivity "Epsilon Negative (ENG)" [17] or a negative permeability "Mu Negative (MNG)" [18]. Besides, materials with the properties of "Epsilon near Zero (ENZ)" [19] and "Mu Near Zero (MNZ)", known as "nihility" materials have also been studied. A simple synopsis of these metamaterials can be found in figure 2, where the angular frequencies ωpe and ωpm represent, respectively the electric and magnetic plasma frequency [20]. Up to now, we talked about metamaterials who exhibit their great performances by artificially tailoring the permittivity or permeability. Besides, the term "metamaterial" has also been used by some authors to describe other periodic structures such as electromagnetic bandgap (EBG) structures or photonic crystals, when the period is much smaller in physical size than the wavelength of the impinging electromagnetic wave. The electromagnetic response of such structures is dominated by Bragg-type scattering and involves higher order spatial harmonics (Bloch-Floquet modes) [20]. In this chapter, we focus on such a kind of metamaterial, the so-called "electromagnetic band gap" (EBG). Electromagnetic has received great attention among researchers all over the world because of its immense civilian and defense applications. During the Second World War, the use of radar and thereafter the wide use of microwave communication systems facilitated the transformation from radio to microwave frequency. This dramatic change demanded more advanced materials for high frequency performance and opened up new dimensions in the field of electromagnetic materials. Nano-composites and electromagnetic band-gap structures are examples of metamaterials under right hand rules. Electromagnetic band-gap (EBG) structures have attracted increasing interest in the electromagnetic community. Because of their desirable electromagnetic properties [21], they have been widely studied for potential applications in antenna engineering. Hundreds of EBG papers have been published in various journals and conferences in the last 5 years. EBG are periodic arrangements of dielectric or metallic elements in one, two or three dimensional manners. EBG inhibits the passage of electromagnetic wave at certain angles of incidence at some frequencies. These frequencies are called partial band-gap. At a specific frequency band, EBG does not allow the propagation of wave in all directions and this frequency region is called the complete band-gap or global band-gap [22, 23]. Physicists put the original idea of EBG forward and some recent studies revealed the interesting fact that EBG exists in living organisms. The well known examples are the butterfly wing scales and eyes of some insects. In this case, a metallic like reflection effect is obtained by using refractive index differences.

A multilayer thin film with different refractive indices in animals is a good example for this. Recently, these ideas were undergone a preliminary study for its commercialization such as paints for certain applications.

The concept of electromagnetic band-gap (EBG) structures originates from the solid-state physics and optic domain, where photonic crystals with forbidden band-gap for light emissions were proposed in [27–28] and then widely investigated in the [29–33]. Thus, the terminology, photonic band-gap (PBG) structures, was popularly used in the early days. Since then, a profusion of scientific creativity has been witnessed as new forms of electromagnetic structures are invented for radio frequency and microwaves. EBG can be realized in one, two and three dimensional forms. The dimensionality depends on the periodicity directions. Three dimensional EBG are more appropriate for getting a complete band-gap because they can inhibit waves for all incident angles. The band-gap in EBG is analogous to a forbidden energy gap in electronic crystals. Hence EBG are also termed as photonic crystals (PCs). The first attempts towards three-dimensional structures were realized in the form of face centered cubic (fcc) lattice structures [35]. At the initial stages of EBG research, due to the lack of theoretical predictions, a 'cut and try' approach was adopted in experimentally predicting the band-gap. At the beginning, the investigations of EBG were mainly on wave interactions of these structures at optical frequencies and hence PBG emerged with the name of photonic band-gap structures. Now, vast extensions of EBG at microwave [36], millimetre [37] and sub-millimetre wave frequencies [38] are electromagnetic band-gap (EBG) structures. A periodic structure can give rise to multiple band-gaps. However, it should be noted that the band-gap in EBG is not only due to the periodicity of the structure but also due to the individual resonance of one element. A study revealed the mechanisms to form a band-gap in an EBG [21]. The band-gap formation in EBG is due to the interplay between macroscopic and microscopic resonances of a periodic structure. The periodicity governs the macroscopic resonance or the Bragg resonance. It is also called the lattice resonance. Microscopic resonance is due to the element characteristics and it is called the Mie resonance [20]. When the two resonances coincide, the structure possesses a band-gap having maximum width. Depending on the structural characteristics and polarization of the wave, one resonance mechanism (i.e. either the multiple scattering resonance or the single element scattered resonances) can dominate over the other. The characteristic property of stop bands at certain frequencies enables many applications using EBG. At this stop band, all electromagnetic wave will be reflected back and the structure will act like a mirror. At other frequencies, it will act as transparent medium. This concept is illustrated in figure 3.

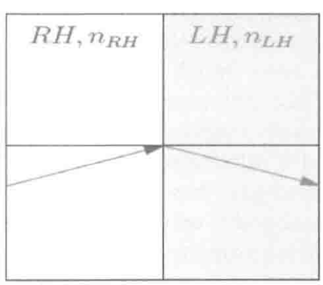

Fig. 1. A negative reflection.

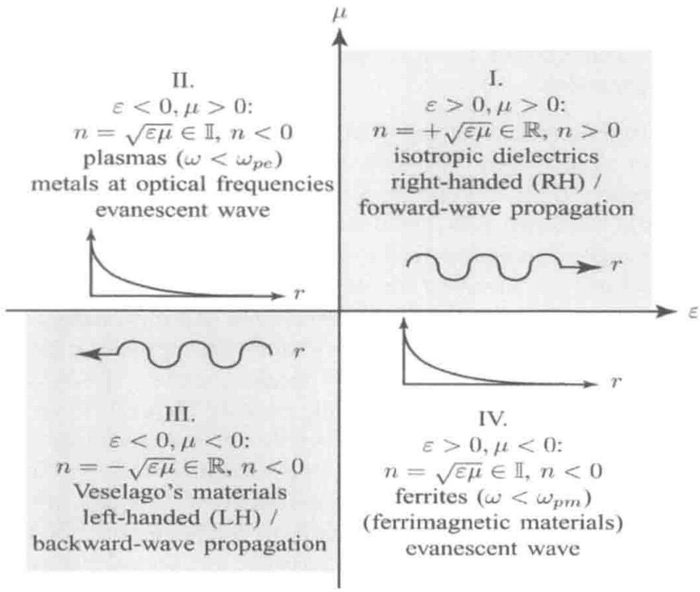

Fig. 2. Permittivity, permeability and refractive index diagram [20].

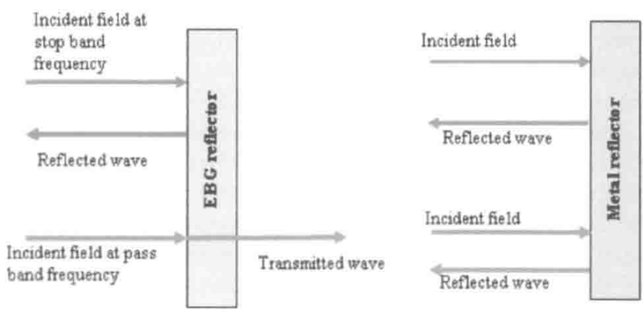

Fig. 3. Diagram illustrating the application of EBG as a mirror and its comparison with a metal reflector [21].

Microstrip antennas mounted on a substrate can radiate only a small amount of its power into free space because of the power leak through the dielectric substrate [32]. In order to increase the efficiency of the antenna, the propagation through the substrate must be prohibited. In this case, the antenna can radiate more towards the main beam direction and hence increase its efficiency. Recently, there has been much interest in the field of Metallo-Dielectric Electromagnetic Band-Gap (MDEBG) structures because of the promising future applications and the important role these artificially engineered periodic materials may play in the field of antennas. The name "Photonic (or Electromagnetic, which is more appropriate for the frequency band of applications) band-gap" has its origin in the fact these structures effectively prevent the propagation of electromagnetic waves within a specific frequency range (the band gap). Two examples of the qualitative geometry of such structures are given in figure 4 [33]. As shown in figure 4, a MDEBG structure is essentially a surface comprising a plurality of elements. Each of the elements is interconnected with each other to form an array of metallic parts embedded in a slab of dielectric. In other words, they are periodical structures of densely packed planar conducting patches separated from a solid metal plane by a dielectric layer. Sometimes metallic pins (or via) are introduced to prevent electromagnetic waves from traveling in the waveguide between the array and the ground. Each unit cell, which is periodically repeated to form the array, essentially behaves as a microwave resonant circuit. The plurality of the resonant elements is parameterized to substantially block surface wave's propagation in the device within a predetermined frequency band gap [35].

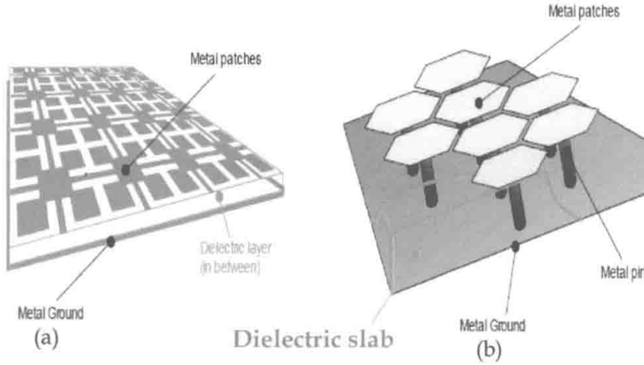

Fig. 4. Simple examples of Metallo-Dielectric EBG structures [32].

The objective of this chapter is to investigate the EM properties of the microstrip antennas based on metallo-dielectric electromagnetic band-gap structures. It is important to emphasize the fact that simple embedded electromagnetic band-gap (EEBG) structures presented in this work are targeting operating frequency band at 0.5 - 20 GHz range. Since simple EEBG structures have impractical geometrical sizes in the 500 MHz to 2 GHz frequency range, more complex EEBG structures need to be employed. In addition, from wireless communication application, miniaturization of electronic systems requires the availability of miniaturized EEBG structures with appropriate patch sizes. The concept introduced in this chapter can be generally applied regardless of the size of the EEBG structures. For wideband radiation, reduction from hundreds of MHz to few GHz either a combination of different methods or use of advanced EEBG structures is the best solution as shown in figure 5 [40]. Figure 5 shows the efficacy range of EEBG structures covered in [40].

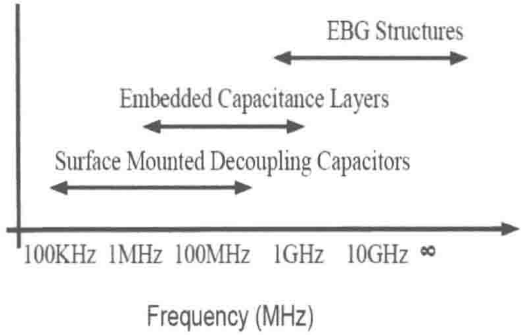

Fig. 5. Efficacy range of different reduction methods.

2. Disadvantages of metal ground planes and the MDEBG solution

MDEBG structures are useful where the presence of classic electric conductors as antenna ground planes adversely affects the performance of the entire electromagnetic device. As it is known, classic conductive surfaces are extensively used as antenna reflectors: they redirect one half of the radiation into the opposite direction potentially improving the antenna gain by 3 dBi.

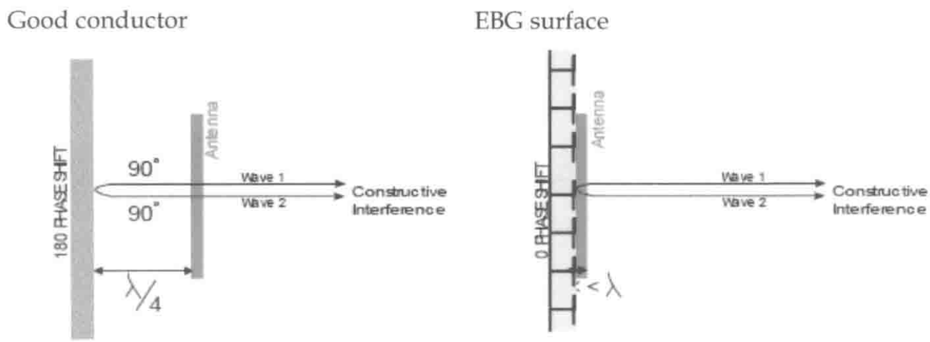

Fig. 6. An antenna separated by ¼ λ from the ground plane (on the left) and the alternative MDEBG layout (on the right).

However, they do have two main disadvantages: first, they reverse the phase of the reflected wave and second, they support propagating surface waves, which can have unwanted effects on the antenna performance. The fact that they reverse the phase 180 degrees is due to the most obvious constraint that the tangent electric field on a classic conductive surface must be zero, so the electromagnetic waves experience a 180 degrees phase shift on reflection. Because of the phase reversal, the image currents cancel the antenna currents, resulting in poor radiation efficiency when the antenna is too close to the conductive surface. This problem is often solved by including a quarter wavelength between the radiating element and the ground plane (see figure 6), but the disadvantage of this solution is the fact that the structure requires a minimum thickness of λ/ 4. It will be shown that, by using the novel MDEBG structures as ground planes, the antenna can be almost be attached to the ground plane, resulting in a useful reduction of volume. It will be proved that, at the frequency where the MDEBG structure does not give any reflection phase shift, a design of MDEBG structures even 8 times thinner than the classic ones (which implement a λ/ 4 spacing between antenna and ground plane) is possible. As stated before, another issue is the propagation of surface waves when normal ground planes are used: these are propagating electromagnetic waves bound to the interface between metal and free space and they will radiate if scattered by bends, discontinuities or surface textures. The unwanted result is a kind of multipath interference, which can be seen as ripples in the radiation pattern (see figure 7) [41].

Again, by using MDEBG structures, it will be shown that surface waves can be suppressed. It follows that, when multiple antennas share the same normal conductive ground plane, like it happens in phased arrays, the above mentioned surface waves may cause undesired mutual coupling between the antennas (see figure 8). Once again, by using MDEBG surfaces structures, it is possible to alter the surfaces properties of the ground plane and avoid this