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978-0-521-88991-9 - Electromagnetic Band Gap Structures in Antenna Engineering
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Excerpt
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1 Introduction

1.1 Background

Antenna designs have experienced enormous advances in the past several decades and they are still undergoing monumental developments. Many new technologies have emerged in the modern antenna design arena and one exciting breakthrough is the discovery/development of electromagnetic band gap (EBG) structures. The applications of EBG structures in antenna designs have become a thrilling topic for antenna scientists and engineers. This is the central focus of this book.

The recent explosion in antenna developments has been fueled by the increasing popularity of wireless communication systems and devices. From the traditional radio and TV broadcast systems to the advanced satellite system and wireless local area networks, wireless communications have evolved into an indispensable part of people's daily lives. Antennas play a paramount role in the development of modern wireless communication devices, ranging from cell phones to portable GPS navigators, and from the network cards of laptops to the receivers of satellite TVs. A series of design requirements, such as low profile, compact size, broad bandwidth, and multiple functionalities, keep on challenging antenna researchers and propelling the development of new antennas.

Progress in computational electromagnetics, as another important driving force, has substantially contributed to the rapid development of novel antenna designs. It has greatly expanded the antenna researchers' capabilities in improving and optimizing their designs efficiently. Various numerical techniques, such as the method of moments (MoM), finite element method (FEM), and the finite difference time domain (FDTD) method, have been well developed over the years. As a consequence, numerous commercial software packages have emerged. Nowadays with powerful personal computers and advanced numerical techniques or commercial software, antenna researchers are able to exploit complex engineered electromagnetic materials in antenna designs, resulting in many novel and efficient antenna structures.

For the same reasons, 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. For example,

- How to suppress surface waves in the antenna ground plane?
- How to design an efficient low profile wire antenna near a ground plane?

- How to achieve a uniform field distribution in a rectangular waveguide?
- How to increase the gain of an antenna?

Discovery of EBG structures has revealed promising solutions to the above problems. Due to the complexity of the EBG structures, it is usually difficult to characterize them through analytical methods. Instead, full wave simulators that are based on advanced numerical methods have been popularly used in EBG analysis. Dispersion diagram, surface impedance, and reflection phase features are explored for different EBG structures. The interaction of antennas and EBG structures are extensively investigated. In summary, the EBG research has flourished since the beginning of this new millennium.

1.2 Electromagnetic band gap (EBG) structures

So, what are electromagnetic band gap (EBG) structures? This section addresses this question from two aspects: definition of EBG structures and the relation between EBG and metamaterials.

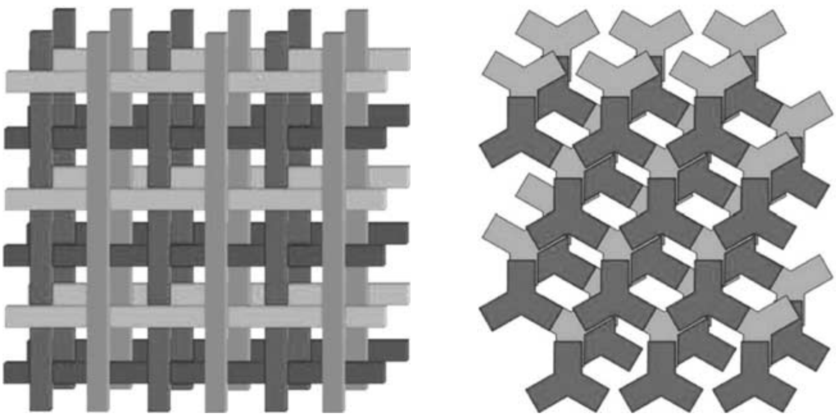
1.2.1 EBG definition

Periodic structures are abundant in nature, which have fascinated artists and scientists alike. When they interact with electromagnetic waves, exciting phenomena appear and amazing features result. In particular, characteristics such as frequency stop bands, pass bands, and band gaps could be identified. Reviewing the literature, one observes that various terminologies have been used depending on the domain of the applications. These applications are seen in filter designs, gratings, frequency selective surfaces (FSS) [1], photonic crystals [2] and photonic band gaps (PBG) [3], etc. We classify them under the broad terminology of "*Electromagnetic Band Gap (EBG)*" structures [4].

Generally speaking, electromagnetic band gap structures are defined as *artificial periodic (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 states*.

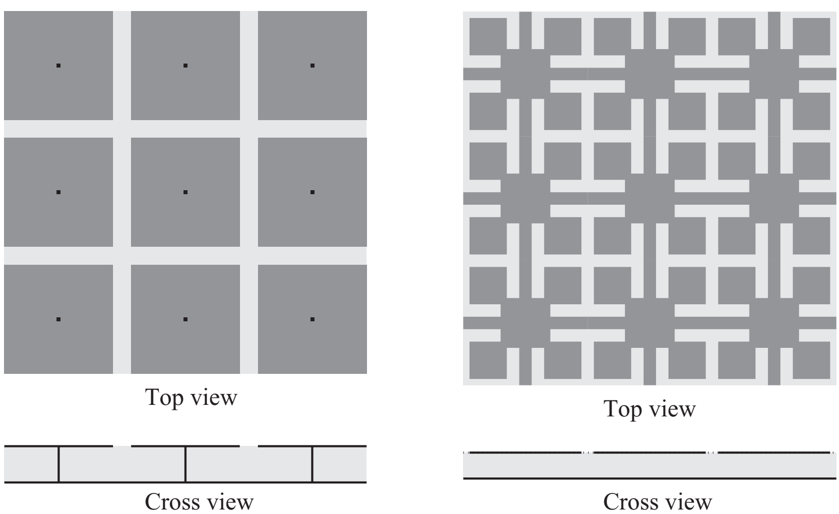
EBG structures are usually realized by periodic arrangement of dielectric materials and metallic conductors. In general, they can be categorized into three groups according to their geometric configuration: (1) three-dimensional volumetric structures, (2) two-dimensional planar surfaces, and (3) one-dimensional transmission lines. Figure 1.1 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 surfaces are plotted in Fig. 1.2: a mushroom-like surface [7] and a uni-planar design without vertical vias [8]. Figure 1.3 shows the one-dimensional EBG transmission line designs [9–10]. This book focuses more on the 2-D EBG surfaces, which have the advantages of low profile, light weight, and low fabrication cost, and are widely considered in antenna engineering.

The planar electromagnetic band gap (EBG) surfaces exhibit distinctive electromagnetic properties with respect to incident electromagnetic waves:



(a) (b)

Fig. 1.1 Three-dimensional EBG structures: (a) a woodpile dielectric structure and (b) a multi-layer metallic tripod array.



(a) (b)

Fig. 1.2 Two-dimensional EBG surfaces: (a) a mushroom-like surface and (b) a uni-planar surface.

(1) When the incident wave is a surface wave ($k_x^2 + k_y^2 \leq k_0^2$, k_z is purely imaginary), the EBG structures show a frequency band gap through which the surface wave cannot propagate for any incident angles and polarization states. A typical dispersion diagram is shown in Fig. 1.4a.

(2) When the incident wave is a plane wave ($k_x^2 + k_y^2 \leq k_0^2$, k_z has a real value), the reflection phase of the EBG structures varies with frequency, as shown in Fig. 1.4b. At a certain frequency the reflection phase is zero degrees, which resembles a perfect magnetic conductor that does not exist in nature.

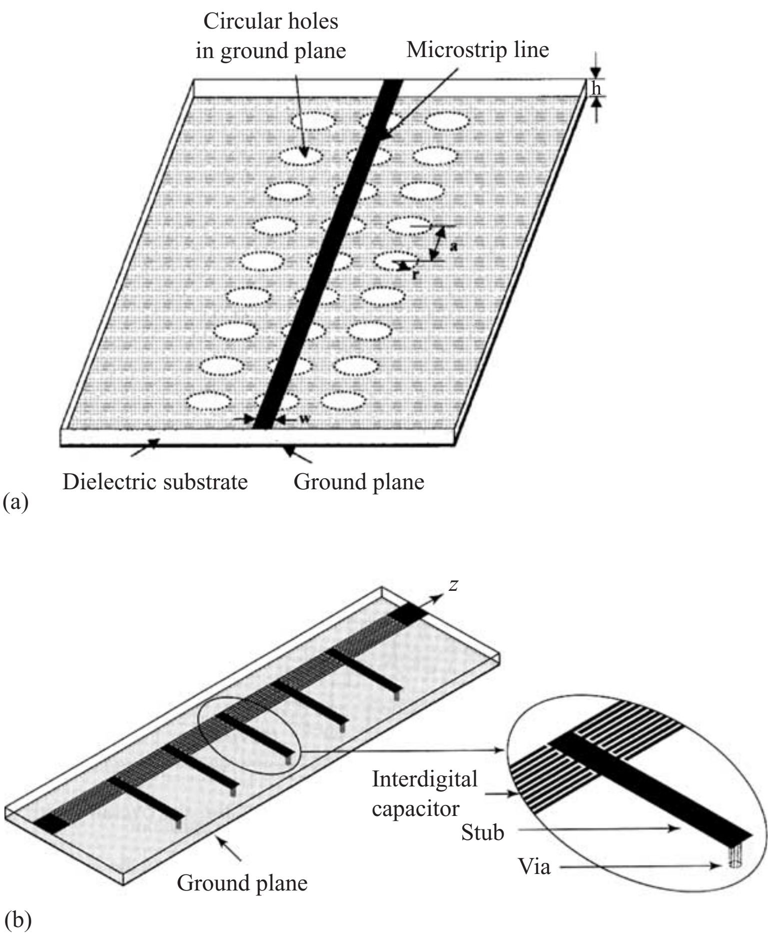


Fig. 1.3 One-dimensional EBG transmission lines: (a) a microstrip line with periodic holes on the ground plane (from [9], © IEEE, 1998) and (b) a composite right- and left-handed transmission line (from [10], © Wiley-IEEE, 2005).

In the above equations, k_x and k_y are the wavenumbers in the horizontal directions, k_z is the wavenumber in the vertical direction, and k_0 is the free space wavenumber.

1.2.2 EBG and metamaterials

Almost at the same time, another terminology, "*metamaterials*," also appeared and has become popular in the electromagnetics community [10–14]. The ancient Greek prefix, *meta* (meaning "beyond"), has been used to describe composite materials with unique features not readily available in nature. Depending on the exhibited electromagnetic properties, various names have been introduced in the literature, including:

- *Double negative (DNG) materials* with both negative permittivity and permeability;
- *Left-handed (LH) materials* inside which the electric field direction, magnetic field direction, and propagation direction satisfy a left-hand relation;

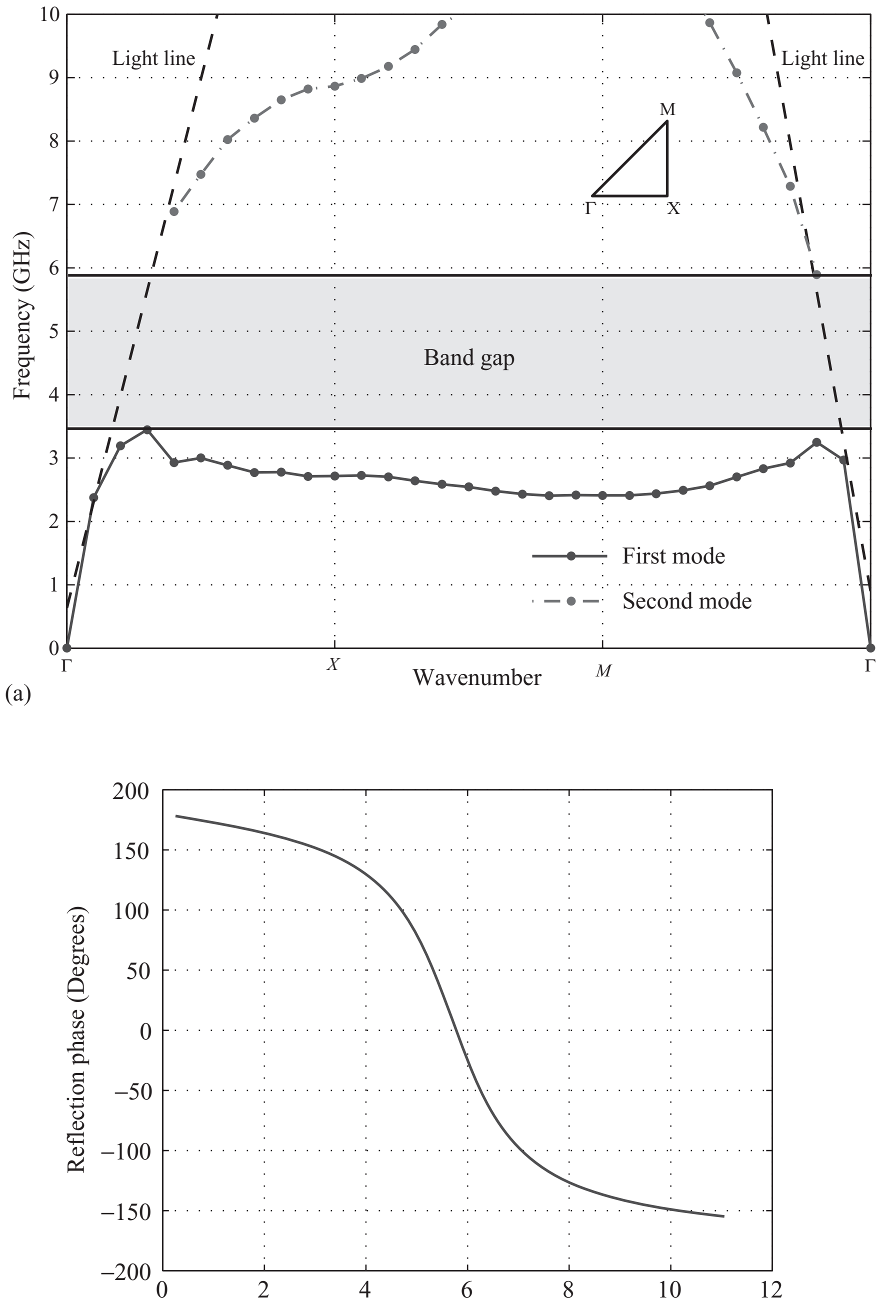


Fig. 1.4 A planar EBG surface exhibits (a) a surface wave band gap and (b) an in-phase reflection coefficient for plane wave incidence.

- *Negative refractive index (NRI) materials* that have a negative refractive index;
- *Magneto materials* with artificially controlled high permeability;
- *Soft and hard surfaces* that stop or support the propagation of waves;
- *High impedance surfaces* with relatively large surface impedances for both TE and TM waves;
- *Artificial magnetic conductors (AMC)* that exhibit the same properties as a perfect magnetic conductor.

It is worthwhile to point out that some of these interesting electromagnetic characteristics are related to each other. For example, the DNG materials always exhibit both the left-handed property and the negative refractive index. A corrugated metal surface can be a soft surface for wave propagation in the longitudinal direction and be a hard surface for wave propagation in the transverse direction. Furthermore, a periodic composite transmission line structure may exhibit the left-handed property in one frequency region and band gap property in another frequency region. Thus, it is an exciting area for researchers to explore these unique properties and their relations for different metamaterials and apply them in various electromagnetics and antenna applications.

Due to their unique band gap features, EBG structures can be regarded as a special type of metamaterials. In fact, in the book *Metamaterials: Physics and Engineering Explorations* edited by Engheta and Ziokowski, half of the chapters focus on EBG materials. Besides the band gap feature, EBG also possesses some other exciting properties, such as high impedance and AMC. For example, a mushroom-like EBG surface exhibits high surface impedances for both TE and TM polarizations. When a plane wave illuminates the EBG surface, an in-phase reflection coefficient is obtained resembling an artificial magnetic conductor. In addition, soft and hard operations of an EBG surface have also been identified in the frequency-wavenumber plane. These interesting features have led to a wide range of applications in antenna engineering, from wire antennas to microstrip antennas, from linearly polarized antennas to circularly polarized antennas, and from the conventional antenna structures to novel surface wave antenna concepts and reconfigurable antenna designs.

In summary, electromagnetic band gap structures are an important category of metamaterials. Their characterizations and antenna applications are the central focus of this book.

1.3 Analysis methods for EBG structures

To analyze unique features of EBG structures, various methods have been implemented. These methods can be put into three categories: (1) lumped element model, (2) periodic transmission line method, and (3) full wave numerical methods. The lumped element model is the simplest one that describes the EBG structure as an *LC* resonant circuit [15], as shown in Fig. 1.5. The values of the inductance *L* and capacitance *C* are determined by the EBG geometry and its resonance behavior is used to explain the band gap feature

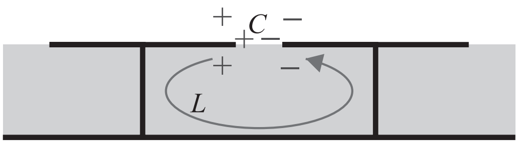


Fig. 1.5 Lumped LC model for EBG analysis.

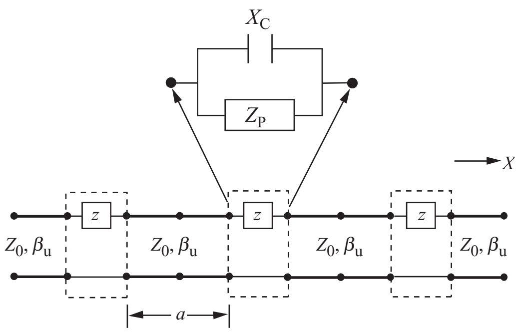


Fig. 1.6 Periodic transmission line method for EBG analysis (from [16], © Wiley InterScience, 2001).

of the EBG structure. This model is simple to understand, but the results are not very accurate because of the simplified approximation of L and C.

The periodic transmission line method is another popularly used technique to analyze EBG structures [16]. Figure 1.6 depicts a transmission line model of EBG structures, where Z_P is the impedance for each periodic element and X_C is the coupling capacitor. The Floquet periodic boundary condition is considered in this approach. After analyzing the cascaded transmission line, the dispersion curve can be readily obtained, which provides more information than the lumped element method. The surface wave modes, leaky wave modes, left- and right-hand regions, and band gaps can be easily identified from the dispersion curve. However, a difficulty in this method is how to accurately obtain the equivalent Z_P and X_C values for the EBG structures. Some empirical formulas have been proposed for simple geometries using multi transmission line (MTL) models, but limited results are found for general geometries.

Owing to the fast development in computational electromagnetics, various numerical methods have been applied in the full wave simulations of EBG structures. Both the frequency domain methods such as the MoM and FEM and the time domain methods like FDTD have been utilized by different research groups to characterize EBG structures. For example, Fig. 1.7 depicts an FDTD model for the mushroom-like EBG analysis [17]. One advantage of the full wave numerical methods is the versatility and accuracy in analyzing different EBG geometries. Another important advantage is the capability to derive various EBG characteristics, such as the surface impedance, reflection phase, dispersion curve, and band gaps. A detailed discussion on the finite difference time domain method will be presented in Chapter 2.

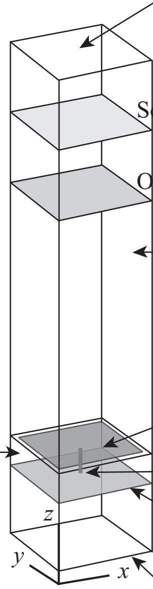


Fig. 1.7 Full wave FDTD model for EBG analysis.

1.4 EBG applications in antenna engineering

The unique electromagnetic properties of EBG structures have led to a wide range of applications in antenna engineering. This section summarizes several typical EBG applications in antenna designs in the hope of stimulating discussions and new avenues of research in this area.

1.4.1 Antenna substrates for surface wave suppressions

Surface waves are by-products in many antenna designs. Directing electromagnetic wave propagation along the ground plane instead of radiation into free space, the surface waves reduce the antenna efficiency and gain. The diffraction of surface waves increases the back lobe radiations, which may deteriorate the signal to noise ratio in wireless communication systems such as GPS receivers. In addition, surface waves raise the mutual coupling levels in array designs, resulting in the blind scanning angles in phased array systems.

The band gap feature of EBG structures has found useful applications in suppressing the surface waves in various antenna designs. For example, an EBG structure is used to surround a microstrip antenna to increase the antenna gain and reduce the back lobe [18–20]. In addition, it is used to replace the quarter-wavelength choke rings in GPS antenna designs [21]. Many array antennas also integrate EBG structures to reduce the

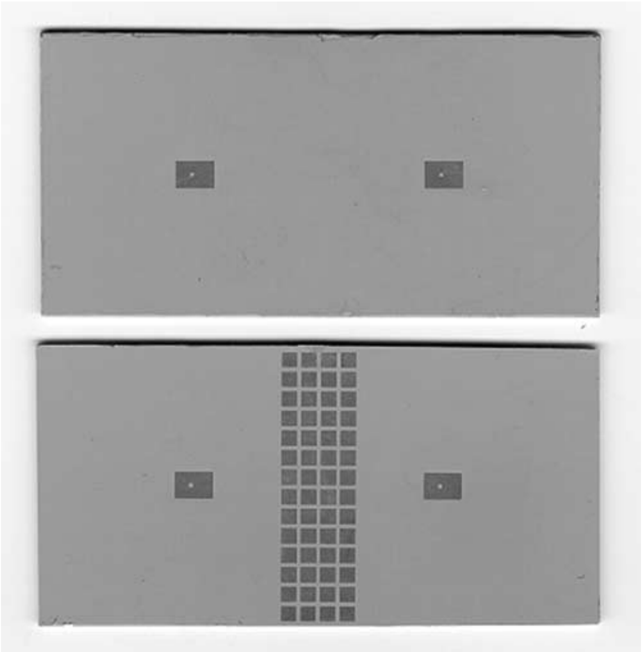


Fig. 1.8 EBG substrate for surface wave suppressions: low mutual coupling microstrip array design (from [22], © IEEE, 2003).

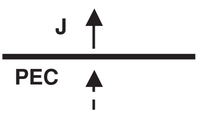
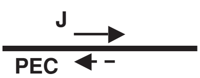
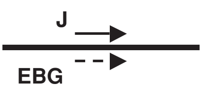
mutual coupling level. For example, Fig. 1.8 shows a comparison of patch antennas with and without EBG structures and an 8 dB reduction in mutual coupling is observed [22].

1.4.2 Antenna substrates for efficient low profile wire antenna designs

Another favorable application of EBG is to design low profile wire antennas with good radiation efficiency, which is desired in modern wireless communication systems. To illustrate the fundamental principle, Table 1.1 compares the EBG with the traditional PEC ground plane in wire antenna designs. When an electric current is vertical to a PEC ground plane, the image current has the same direction and reinforces the radiation from the original current. Thus, this antenna has good radiation efficiency, but suffers from relative large antenna height due to the vertical placement of the current. To realize a low profile configuration, one may position a wire antenna horizontally close to the ground plane. However, the problem is the poor radiation efficiency because the opposite image current cancels the radiation from the original current. In contrast, the EBG surface is capable of providing a constructive image current within a certain frequency band, resulting in good radiation efficiency. In summary, the EBG surface exhibits a great potential for low profile efficient wire antenna applications.

Based on this concept, various wire antennas have been constructed on the EBG ground plane [23–27]. Typical configurations include dipole antenna, monopole antenna, and spiral antenna. EBG surfaces have also been optimized to realize better performance

Table 1.1 Comparisons of conventional PEC and EBG ground planes in wire antenna designs

Options	Efficiency	Low profile
		
		
		

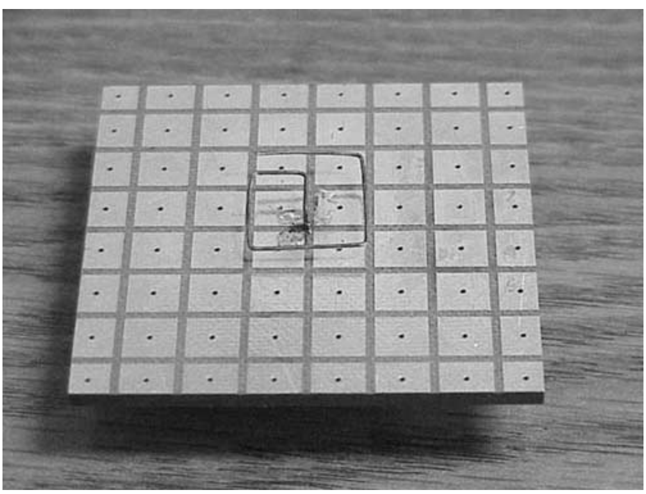


Fig. 1.9 EBG substrate for a low profile curl antenna design (from [24] © Wiley InterScience, 2001).

such as multi-band and wideband designs. For example, Fig. 1.9 shows a curl antenna on an EBG structure that radiates circularly polarized radiation patterns.

1.4.3 Reflection/transmission surfaces for high gain antennas

EBG structures are also applied in designing antennas with a high gain around or above 20 dBi. Traditionally, high gain antennas are realized using either parabolic antennas or large antenna arrays. However, the curved surface of parabolic antennas makes it difficult