The study of high performance, compact electromagnetic band-gap microstrip filters

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The Study of High Performance, Compact Electromagnetic Band-Gap Microstrip Filters

Huang Shao Ying

School of Electrical & Electronic Engineering

A thesis submitted to the Nanyang Technological University

in fulfillment of the requirements for the degree of

Master of Engineering

2006

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Statement of Originality

I hereby certify that the content of this thesis is the result of work done by me and has not been submitted for a higher degree to any other University or Institution.

21-March-2006

Date

Huang Shao Ying

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To my family

Summary

In this study, electromagnetic band-gap (EBG) periodic structures are studied. A novel dual-plane EBG (DP-EBG) microstrip configuration and an EBG structure with a U-shape microstrip line (MLIN) geometry are proposed and successfully employed in the development of high performance compact microstrip filters.

Electromagnetic band-gap (EBG) structure has been a term widely accepted nowadays to name the artificial periodic structure that prohibits the propagation of electromagnetic waves in certain frequency bands at microwave or millimeter wave frequencies. These periodic structures have been applied in the designs and optimizations of microwave circuits such as planar passive filters, antennas, and phase shifters. Planar EBG structures (2-D or 1-D) have attracted a lot of attention in microwave circuit designs due to their prominent stopband characteristic, their ease of fabrication, and their compatibility with monolithic circuits.

With the knowledge on the development of EBG technology, a novel DP-EBG microstrip configuration is proposed where two traditional EBG periodic structures; the perturbed ground plane (GND) and the modulated microstrip line are combined so as to enhance the filtering functionality within a compact physical size. On the other hand, tapering techniques are intensively studied. They are applied to EBG structures in order to eliminate passband ripples caused by the periodicity of the structure. A U-shaped and a meander MLIN geometry are also proposed to be employed in the design of planar EBG filters to achieve good lowpass

Table 1: Configurations of EBG Structures

EBG Structure	Configuration	Number of EBG Cells	Geometry& Location EBG Cells	Tapering	MLIN Geometry
Traditional EBG	Single Planar	6	Etched circle, GND	No	Straight
DPC-EBG	Dual Planar	6	Etched circle, GND	Yes	Straight
			Inserted Patch, MLIN	No	
Small-size EBG	Dual Planar	3	Etched circle, GND	Yes	Straight
			Inserted Patch, MLIN	No	
U-shaped EBG	Dual Planar	4	Etched circle, GND	Yes	U-shaped
			Inserted Patch, MLIN	Yes	
Meander EBG	Dual Planar	4	Etched circle, GND	Yes	Meander
			Inserted Patch, MLIN	Yes	

Table 2: Performances of EBG Structures

EBG Structure	20-dB Rejection Bandwidth (GHz)	Ripple Level (dB)	Selectivity ($\frac{dB}{GHz}$)	Circuit Area (mm ²)
Traditional EBG	4.15	2.80	25.15	70×21
DPC-EBG	6.59	1.56	27.98	70×21
Small-size EBG	8.50	0.80	14.73	48×21
U-shaped EBG	8.18	0.54	22.50	33×30
Meander EBG	8.60	0.38	25.19	41×45

filtering functionality in a small circuit area.

Good EBG filter structures have been designed and implemented by applying the proposed configurations and techniques. The configurations and performances of the proposed novel EBG filter structures are tabulated in Table 1 and 2, respectively. As can clearly be seen in Table 2, the novel structures have obtained significant improvement of performance in terms of bandwidth of the stopband, transmission in the passband, and selectivity with a small physical size as compared to the traditional EBG microstrip structure. The proposed structures are easy to fabricate and compatible with MMIC technology. The proposed DP-EBG configuration, the study on tapering techniques, and the application of U-shaped and meander MLIN geometry for EBG filter designs are useful in the future exploration of high performance planar passive filters employing EBG structures.

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List of Acronyms

BPF	Bandpass Filter
CB-CPW	Conductor-Backed Coplanar Waveguide
CPW	Coplanar Waveguide
DGS	Defected Ground Structure
EBG	Electromagnetic Band-Gap
EC	Electromagnetic Crystal
EPS-BPF	Electromagnetic Periodic Structure Bandpass Filter
FBG	Fiber Bragg Grating
FDTD	Finite-Difference Time-Domain
LPF	Lowpass Filter
MMIC	Monolithic Microwave Integrated Circuits
MoM	Method of Moments
MPBG	Metallic Photonic Band-Gap
PBG	Photonic Band-Gap
PC	Photonic Crystal
TE	Transverse Electric
TEM	Transverse Electromagnetic
TM	Transverse Magnetic
UC-PBG	Uniplanar Compact Photonic Band-Gap

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Chapter 1

Introduction

Wireless communications is a fast developing research field due to the wide physical range of communication and the convenience of access it provides. In the past decade, in the world of wireless communications, high-speed data service for voice and multimedia applications is in high demand. Microwave devices are required to work at higher frequencies with a broad working frequency band. However, when the operating frequency is shifted to a higher range, traditional microwave circuits exhibit limitations due to the increase in loss. Planar microwave circuits (printed microwave circuits) such as patch antennas, microstrip lines, and coplanar waveguides (CPW) are widely used in devices working at high frequencies due to their good properties such as low profile, light weight, compactness, and ease for array arrangement. These properties make them suitable for portable applications in wireless communications and for phased-array devices in military applications .

1.1 Motivation

Nowadays, commercial communication applications such as cell phones, and military applications such as phased-array antennas demand high performance compact filters with good rejection over a broadband with low loss. In addition, filters

are required to be manufactured at low cost and in industrial-qualified technology. Although traditional planar filters such as stepped-impedance filter, microstrip couple-line bandpass filter are widely used, they suffered in terms of the large circuit area required and the spurious in the frequency response.

Electromagnetic band-gap (EBG) structure has been a term widely accepted nowadays to name the artificial periodic structures that prohibit the propagation of electromagnetic waves at microwave and millimeter wave frequencies. The three-dimensional (3-D) artificial periodic band-gap structure was introduced at optical frequencies [1] [2] [3] and known as photonic band-gap (PBG) structure. Due to the scalability of the periodic structure, relevant research work has progressed into the field of microwave, millimeter wave, and infrared [4].

The unique feature of EBG structures is the existence of the band-gap where electromagnetic waves are not allowed to propagate. It has been widely applied as the substrate of planar microwave circuits to provide filtering functionality. For example, some are used in patch antennas to suppress the surface waves [5] and some are employed in power amplifiers to reduce the harmonics [6]. As compared to conventional planar filters, EBG filter structures show advantages of wide stopband with high attenuation, compact in size, and incorporatable to circuits.

The planar EBG structure [7] in which planar periodic elements are etched in the ground plane exhibits a better control on the wave propagation while simplifying the fabrication process. The only drawback of planar structures is that they are not able to prohibit the wave propagation in the entire 3-D space. Nevertheless, planar EBG structures have made great contributions to high performance compact microstrip filter designs due to the highly attenuated stopband and the compatibility with MMIC technology. By employing planar EBG structures, the bandstop filter [8] and lowpass filter [9] were proposed obtaining a stopband with large bandwidth and high attenuation.

In a traditional 1-D EBG microstrip structure [8] where EBG cells are in a single plane, a good stopband performance is usually obtained by increasing the number or the size of cells, thus resulting in an increase in passband ripple level as well as an increase in circuit area. In this type of planar EBG structure, there are two main compromises; one is between the stopband performance and the physical size; the other is between the stopband and the passband performance; which limits the applications of the structure. In this study, solutions are proposed to obtain better compromises in planar EBG structure designs. High performance compact planar EBG filter structures are designed for applications in microwave circuit designs.

1.2 Objectives

In view of the recent development of EBG technology and EBG technology applied to planar filter designs, the aim of this project is to seek for solutions to overcome limitations in planar EBG structure designs that are due to the compromises mentioned above, thus to design new EBG microstrip filtering structures with improvements in terms of insertion loss in the passband, the width and depth of the stopband, the circuit area, and the fabrication simplicity. The major objectives are listed as follows:

- To increase the bandwidth and attenuation of the stopband without an increase in physical size of the planar EBG microstrip structure
- To eliminate ripples in the passband of a planar EBG structure thus improving the insertion loss of the structure
- To design a compact and high performance planar EBG structure so that it is easy to fabricate and compatible with monolithic microwave integrated circuits (MMIC)

In order to obtain a good understanding of planar EBG structures to fulfill the above objectives, two measures are taken. Firstly, the examination of the effects that dielectric materials have on the wave propagation characteristic of an EBG structure and secondly, the effects of tapering techniques adopting tapering functions and the low sidelobe array theory [10] [11] [12] on an EBG structure.

For the design of structures, the method-of-moment (MoM) is used for the simulation of the planar structures and the simulations are to be performed using the MOM-base simulation softwares, *Agilent* Advanced Design System (*ADS*) and *Zeland* IE3DTM. Designs are to be implemented to provide independent verification for the simulation.

1.3 Major Contribution of the Thesis

To achieve the proposed objectives of the project novel dual-plane EBG configuration has been proposed and studied intensively. It has successfully been employed to filter designs to optimize the performance of microstrip line EBG filtering structures. Several important contributions have been made:

1) A novel approach to control the wave propagation in EBG microstrip filtering structures has been proposed base on the study on the effect of dielectric materials on the performance of EBG structure [13].

2) A summary on the effect of tapering techniques base on tapering functions and low sidelobe array theory on the performance of EBG microstrip structures has been made [14].

3) A dual-plane EBG configuration has been successfully designed and applied in the design of a 6-cell and 5-cell dual-plane compact EBG (DPC-EBG) microstrip structure [15] [16] [17]. The dual-plane arrangement increases the variation of electromagnetic fields in EBG structures. Therefore, with a small amount

of EBG cells, the dual-plane EBG structure is able to significantly enhance the rejection band in terms of bandwidth and attenuation.

4) A 3-cell small-size EBG (S-EBG) structure [18] has been designed and implemented. It is based on the design of DPC-EBG structure. With the modification on the microstrip line, the S-EBG structure demonstrates a relatively wide and deep stopband and a smooth passband with only three EBG cells.

5) A 3-cell [19] and a 4-cell [20] U-shaped dual planar EBG microstrip lowpass filter structure has been developed. With the U-shape topology of the microstrip line and the dual planar configuration, the two novel EBG structure demonstrates superior lowpass filtering functionality within a very small physical size. As compared to the S-EBG structure, the proposed structure achieves an improvement of the performance yet maintaining a small circuit area due to the unique geometry of the microstrip line. It provides additional flexibility for the layout design of circuits.

6) A 4-cell meander dual planar EBG microstrip structure [21] with a meander topology have been proposed providing excellent lowpass filtering functionality. This meander DP-EBG structure exhibits better passband and stopband performance than a U-shape DP-EBG structure at the expense of a small increase in the circuit area. It was designed as an alternative of U-shape DP-EBG structure that are used as a high performance compact lowpass filter in microwave circuits.

1.4 Organization of the Thesis

The first chapter has provided an introduction to the thesis. It has given an overall view of the project, introduced the objectives of this study, and listed the main contributions of this project.

Chapter 2 gives a review on the electromagnetic band-gap structure which

includes the theory, the classification, and the applications of EBG structures.

Chapter 3 demonstrates the effects of dielectric materials on the wave propagation of EBG structures.

Chapter 4 summarizes the tapering techniques that are used to lower the passband ripple level of EBG structures.

Chapter 5 introduces the dual-plane EBG configuration and demonstrates its advantages in the 6-cell and 5-cell dual-plane compact EBG bandstop filter design and the 3-cell small-size EBG bandstop filter design.

Chapter 6 presents dual planar EBG structures with special topologies - U-shape topology and meander topology. The design and implementation of a 3-cell and a 4-cell U-shaped dual planar EBG microstrip lowpass filter structure is introduced. A meander dual planar EBG microstrip structure was proposed as an option when employing high performance compact planar EBG lowpass filters in circuit designs.

Chapter 7 concludes the thesis. Important findings and the fulfilment of the thesis objects are described in details. Recommendations for future work are also included in Chapter 7.

Chapter 2

Literature Review

Electromagnetic band-gap (EBG) structures are artificial periodic structures that prohibit the propagation of electromagnetic waves in the direction of periodicity in certain frequency bands at microwave or millimeter-wave frequencies [22]. Due to the unique stopband that planar EBG structures exhibit, they have attracted a lot of attention in planar filter design.

A classical planar bandstop filter is implemented using shunt connected stubs separated by quarter-wavelength sections of a transmission line (Fig. 2.1) [23]. Not only is this a filter that occupies a large circuit area, it is also a design with a stopband bandwidth of 20% or less. For filters with a bandwidth much less than 20%, it presents difficulties when dealing with the design because the required characteristic impedance of the open stubs are usually too high to be implemented. For the filter with a wide bandwidth, the fabrication of the traditional design is also difficult because they require very tightly coupled lines. There are papers that are able to realize a filter with a very narrow stopband [24]. The EBG structure exhibits a wide and deep stopband in the frequency response. As a bandstop filter, an EBG structure shows advantages of large bandwidth and high attenuation in the stopband, relatively small circuit area, and compatibility with planar waveguides

Figure 2.1: Schematic of strip-line for bandstop filters with narrow stop bands

such as microstrip line and CPW.

Many decades ago, in the field of microwave, waveguides and transmission lines loaded at periodic interval with identical obstacles are defined as periodic structures [25]. They are found to have passband-stopband characteristics as well as the support of waves with phase velocities much less than the velocity of light. They are employed in the development of microwave devices such as filters. 1-D periodic gratings in dielectric waveguides working at microwave frequencies are proposed to provide reflections in a single direction [26] [27]. The study on the control of wave propagation at microwave frequencies began after the discovery of photonic band-gap in optical materials [1] [2] [3].

EBG structures are initially introduced as three-dimensional periodic structure that has photonic band-gap [1] [2]. They are named photonic band-gap (PBG) structure or photonic crystals (PCs). The earlier proposals were focused on the optical applications of these crystals [1] [2] [3]. Most of these proposals were based on the fact that the photo density of states vanished in the band gap.

In 1990, the first photonic band-gap structure [28] was realized at microwave frequencies because this periodic dielectric structures can be fabricated by conventional machined tools. The interest in photonic crystals was expanded to applications in the microwave and millimeter-wave bands. This interest was initiated at Workshop on Photonic Band-gap Structures in 1992 in which several applications such as planar antennas, delay lines, and nonreciprocal devices were proposed

[4]. Since then, the theory and applications of the periodic structures working at microwave and millimeter-wave frequencies are developing fast due to their wide applications in the field of microwave communications [5] [29]. The term PBG was used loosely to describe these structure, although the lattice does not have a true band-gap, but attenuation over the frequency band.

The proper terminology of the periodic structure in the microwave and millimeter-wave domain, either periodic structures, photonic band-gap structures, photonic crystals, electromagnetic band-gap structures, or electromagnetic crystals, is still of great controversy, and is under discussion [30] [31] [32].

In order to distinguish the periodic structures that work in the microwave and millimeter-wave bands from those working at optical frequencies, the term electromagnetic band-gap (EBG) is used to name the artificial periodic structure that controls the propagation of electromagnetic waves in the microwave and the millimeter-wave frequency ranges.

Nowadays, in the field of optics, photonic band-gap structures or photonic crystals is an important topic. A lot of applications such as dielectric mirrors [33], resonant cavities [33] [34], waveguides [35], filters, switches [36] [37], photonic crystal fibers [38], multiplexers [39], and sensors [40] have been proposed. Investigations into the theory and modeling of photonic crystals are carrying out and other new applications are being explored [41] [42]. However, the dimension of periodic element in photonic crystals is in nano-meter range, which presents technological challenges in fabrication.

In the field of microwave and millimeter-wave, the fabrication of electromagnetic band-gap structures is relatively easy due to the large dimension of EBG cells. Therefore, the investigations on the EBG structures and their applications have been carried out at a faster pace as compared to that in the field of optics. The fabrication process is further simplified with the introduction of planar EBG

Figure 2.2: Categorization of EBG structures

structures which only requires etching on printed circuit board (PCB). Another reason for the fast development of EBG structures is their wide applications in microwave circuits which are the key technology of the fast developing wireless and broadband technology.

In the microwave band, EBG structures show characteristics of wide stop-band and slow-wave effect. Due to the unique stopband with large bandwidth and high attenuation, EBG structures are good reflectors, absorbers, and filters. They are mainly applied to suppress surface waves intrinsically in the design of patch antenna and to tune harmonics in nonlinear devices such as power amplifiers. Moreover, the periodic structures are employed to enhance the compactness

of circuits such as antennas and bandpass filters due to their slow-wave effect.

There are a large number of EBG structures with various structures to suit different applications and there are hundreds of publications presenting studies on the design, the theory, and the application of these EBG structures. Nevertheless, they simply fall into the following two categories, as shown in Fig. 2.2, base on the dimension of the periodic element:

- Electromagnetic crystal (EC)
- Planar EBG structure

In this review, electromagnetic crystal is used to describe the structures that have three-dimensional EBG units whereas planar EBG structure is for the structures with two-dimensional periodic units. There is another type of periodic structure named high-impedance electromagnetic surface [43] which consists of a lattice of metal plates and conducting vias in the dielectric substrate to connect the plate to a solid metal sheet. It is considered as a combination of the EC and the planar EBG structure. Fig. 2.2 shows the categorization of EBG structures. ECs and planar EBG structures are reviewed in the following sections. The review of high-impedance electromagnetic surface is included in Appendix D.

2.1 Electromagnetic Crystal (EC)

Electromagnetic crystals (ECs) consist of implants periodically arranged in a host medium. The material of the implant and the host media are different and the contrast between their dielectric constants is required for the existence of the band-gap. Fig. 2.4 shows the schematics of ECs. As shown in Fig. 2.4, the black and grey color of elements in the structure represent materials with different dielectric constants.

Figure 2.3: A fabricated 3-D dielectric EC [26]

Figure 2.4: Schematic of electromagnetic crystals

Dielectric materials and metal are two types of materials commonly used to construct ECs. According to the material of the implant and the host media, ECs are further divided into three main categories: dielectric ECs, metallodielectric ECs, and metallic ECs. Dielectric ECs only consist of dielectric materials. They are dielectric materials with holes drilled in the structures or comprise dielectric elements arranged periodically in another dielectric material with a different dielectric constant. Metallodielectric ECs are comprised of metallic periodic elements embedded in a dielectric host media (except air). If the host media is air, the structure belongs to the third category which is metallic EC. Other than periodic

structures with metallic parts embedded in the air, metallic ECs include metals with periodic air holes.

Other than the two types of materials mentioned above, ceramics are embedded periodically into a polymer host to create an EBG structure that possess good stopband properties [44].

2.1.1 Dielectric EC

Dielectric ECs have longer history than any other type of EBG structures [26] [27]. It has been known for many decades in microwave theory that periodic loadings along the guided wave direction may introduce frequency band-gaps where the propagation of electromagnetic wave is prohibited. The gratings were introduced in dielectric waveguides constructing a 1-D EC, which provides a band-gap in a single propagation direction. Applications for leaky-wave antennas and band-reject filters were proposed [45] [46] for the 1-D EC.

The idea of making a 3-D or 2-D EC was introduced when EBG technology emerged more than ten years ago. The first batch of EBG structures were adopted from photonic crystals by directly scaling up the dimension of the periodic structure. The first EBG material was realized in 1990 by Yablonovitch and Gmitter [28]. Base on the earlier research [1]-[2] done at optical frequencies, the experiment was conducted at microwave frequencies due to the availability of fabrication and testing facilities. This fabricated 3-D photonic band-gap structure [28] (shown in Fig. 2.3) consists of spherical air atoms in a dielectric material.

This first EC is able to obtain band-gap in any direction of propagation and it is a 3-D EC. Fig. 2.4 shows the generic representation of a one-, two-, and three-dimensional EC; the black and grey color represent the materials with different permittivities. As illustrated in the figure, a 1-D EC exhibits a band-gap in a single direction whereas a 2-D EC is able to obtain band-gaps in directions on

Figure 2.5: Different lattice structures

Figure 2.6: Experimental setup in [5] for measuring radiation patterns of a planar bow-tie antenna

the plane that is perpendicular to the direction of the periodic robs.

3-D Dielectric EC

3-D dielectric ECs consist of spherical dielectric atoms supported by dielectric material of another type with different permittivity. Spheres form unit cells of various lattice structures. Fig. 2.5 shows three different lattice structures. Each EC is able to generate a characteristic band-gap due to interactions between multiple scattering from the lattice and from scatterings by individual atoms.

Figure 2.7: Cross-sectional view of a generic planar antenna on the substrate

Figure 2.8: Schematic of the 3-D Alumina EC [27]

Due to the complete absence of propagation in the band-gap, 3-D ECs show great potentials to be employed as the substrate of planar antennas to suppress or reduce the surface waves which are excited in the substrate by the radiating element and severe in a thick substrate with high dielectric constant is used. A number of applications of ECs for antennas were demonstrated. In [5], a bow-tie antenna on a face-centered-cubit 3-D EC radiates predominantly into the air rather than into the substrate. Fig. 2.6 shows the experimental setup for measuring radiation patterns of the bow-tie antenna (the two triangular patches on the substrate) on a 3-D EC material or a uniform substrate. Most of surface waves in the substrate are suppressed by the EC, which is shown in Fig. 2.7(b). Fig. 2.7(a) shows the propagation of waves of an antenna on a uniform dielectric substrate as a comparison. In this case, the EC substrate material was fabricated by drilling

holes in an epoxy-based dielectric (Stycast) with $\epsilon = 13$ in the microwave band. Its dimensions are $15\text{cm} \times 15\text{cm}$ wide and 8cm thick. The condition for the optimization of the performance is that the driving frequency should locate at the band-gap of the EC.

Fig. 2.8 shows the schematic of another EC in the application for a slot antenna [29]. As can be seen in the figure, the EC is made up of stacking layers of cylindrical alumina rods ($\epsilon = 9.61$). It was used as the substrate to suppress surface waves. With the effect of the band-gap provided by the EC substrate, the antenna shows an increase in radiation power of 2-3 dB. For the 3-D Alumina EC itself, there is a study on its simulation and characterization being presented in [47].

3-D ECs perform well when they are employed to suppress surface waves in thick substrates. They are able to attenuate electromagnetic field propagation through the dielectric substrate even there is no ground plane. However, only thick substrates are suitable for 3-D ECs to maintain the good suppression of surface waves. In the case when the substrate is thin, 2-D ECs with air columns drilled via the dielectric material are suitable to use for the performance improvement of the antenna.

2-D Dielectric EC

Instead of controlling the wave propagation in any direction in the crystal, a 2-D EC exhibits band-gaps in the direction which is perpendicular to the periodic columns. Fig. 2.9 shows two typical configurations of 2-D dielectric ECs. Fig. 2.9(a) shows the schematic of a dielectric-rod array structure with square lattice of cylindrical rods. In the structure in Fig. 2.9(a), the dielectric material is not connected and is concentrated at one point in the unit cell. The other air-hole array structure with square lattice of square holes drilled through the substrate is

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Figure 2.9: Schematic of 2-D dielectric ECs

Figure 2.10: Schematic of a micromachined tapered slot antenna [52]

shown in Fig. 2.9(b). As can be seen in this figure, the dielectric material in this structure is connected. In [48], the propagation characteristics of these two types of ECs were studied. It was reported that the dielectric-rod array structure had a large band-gap for TM modes but none for TE modes whereas the air-hole array structure had a large gap for TE modes but none for TM modes.

The filtering functionality of the dielectric-rod array structure was studied with different tapering techniques and the effect of the size of the array (the number of periods) and the filling factor (the thickness of the EC in the waveguide) were also examined [49]. The ripples in the passband were eliminated by the adopted tapering techniques at the expense of decrease in the bandwidth and attenuation

Figure 2.11: Schematics of 2-D EC microstrip circuits with air-hole array

of the rejection band. The attenuation increased when the number of periods increased. With an increase in filling factor, the bandwidth and the attenuation of the stopband increase and the center frequency is shifted to a lower frequency. The electromagnetic radiation characteristic of this dielectric-rod array structure was investigated in [50]. The EC with fractal dielectric-rod was proposed in [51], which demonstrates new characteristics in the frequency response such as multi-band behavior and enlargement of stopbands. The fractal 2-D dielectric EC was characterized by applying a full-wave method developed for diffraction gratings. The same method was applied to investigate the characteristics of 2-D ECs with periodic defects of the variation of geometrical and physical parameters [52].

Air-hole array structures with multi-column of holes are used as the substrate of antenna designs such as microstrip patch antenna [53] and tapered slot antenna (TSA) [54]. The use of such structures in antenna designs is to improve their performance in terms of gain and directivity. They are able to suppress the surface waves due to the band-gap in the frequency response. Fig. 2.10 shows the schematic of the optimized TSA with a micromachined substrate. By introducing a defect (or defects) in the 2-D EC with cylindrical air-hole, high performance planar two-pole waveguide filter can be constructed using silicon as the substrate [55] [56].

Figure 2.12: Photograph of power amplifier [6] with the 3-D EBG microstrip structure incorporated at the output

The air-hole array structure was also used as the substrate of the microstrip line resulting in a prominent band-gap in the direction along the conducting line. The effects of different lattice structures and different shape of the drilled hole were studied in [57]- [58]. Fig. 2.11 shows the schematics of the 2-D EC microstrip circuits with air-hole array studied in [57]. According to the results reported, in a microstrip line circuit, two or one column of holes are sufficient to obtain the band-gap because of the high confinement of electromagnetic fields around the transmission line. The geometry of lattice has major effects on the performance of EC microstrip structure while the effect of the hole-shape is minor. A EC microstrip structure with a honeycomb lattice of circular drilled holes was incorporated at the output of a class AB GaAs field-effect transistor (FET) power amplifier (Fig. 2.12) to tune out the second harmonic resulting in an increase in the power-added efficiency (PAE) [6]. EC microstrip structures of different periods were cascaded to construct a lowpass filter with a very wide high frequency rejection bandwidth [59].

1-D Dielectric EC

When dielectric layers or gratings in the dielectric material are arranged in a single direction, the structure is a 1-D dielectric EC exhibiting a band-gap in the direction

Figure 2.13: The schematic of a periodic dielectric circular waveguide studied in [58]

Figure 2.14: Transverse section of the parabolic 1-D dielectric EC reflector composed of seven dielectric dishes [61]

of periodicity.

1-D dielectric ECs were well known and widely applied in the form of highly reflecting coatings for mirrors before the emerge of EBG technology several decades ago. Nowadays, although the idea of periodic structure has extended to 2-D and 3-D, 1-D dielectric ECs are still important in the research on EBG technology.

Because of the simple structure with respect to 2-D or 3-D ECs, the theoretical study on the wave propagation in ECs is started from the study on the propagation behavior of 1-D ECs. Fig. 2.13 shows the schematic of a EBG circular waveguide alternatively filled with different dielectric materials. The propagation of the guided wave in this 1-D EBG waveguide was theoretically examined in [60].

In some applications, 1-D ECs are sufficient to control the wave propagation. They were used to construct a high-Q image guide resonator in [61]. They are employed in the design of resonator antennas, which are able to obtain high gain with a very thin structure [62]. Besides, they were used to design the directive

antenna. Fig. 2.14 shows the transverse section of a 1-D dielectric EC parabolic reflector with seven dielectric dishes separated with a slab of air [63]. A defect mode can be obtained by introducing a defect into the dielectric period which was used to achieved electromagnetic radiation in a directive antenna [64]. The antenna was further developed to radiate directive patterns for multiple frequencies which was applied to a GSM/DCS antenna [65].

In this section, we have introduced all electromagnetic crystals whose periodic elements are three-dimensional and mainly reviewed dielectric ECs. A review on metallodielectric ECs and metallic ECs is included in appendix B. Due to the three-dimensional inclusion, ECs are able to realize the control of wave propagation in a 3-D, 2-D, and 1-D manner. All dielectric ECs show a prominent band-gap in the direction of periodicity in the frequency response. They were proposed for applications in various areas such as antennas (including patch antennas and wire antennas), waveguides, and power amplifiers.

The introduction, investigation, and application of ECs are important for the development of microwave technology. ECs are used to overcome performance limitations of traditional microwave circuits and thus, significantly improving their compatibility. This makes ECs applicable to many MMIC circuits and find new applications.

2.2 Planar EBG Structures

As compared to PBG structures working at optical frequencies, ECs have advantage of much easier fabrication because the appropriate lattice constant is about four orders of magnitude larger than it is in PBG structures. However, the fabrication of dielectric ECs and metallodielectric ECs requires special techniques to drill holes in a material or to place inclusions into a host media.

An EC is difficult to fabricate. Planar EBG structures are introduced where planar periodic elements are arranged in a plane. The fabrication of planar EBG structures is simplified tremendously. Yet, the structures are able to provide similar control of wave propagation to that of an EC. The only trade-off of these planar structures is that they are not able to provide an omnidirectional control on the wave propagation due to the planar configuration. Planar EBG structures are attractive to applications for microwave circuits due to their good compatibility with planar circuits and waveguides and also their ease of implementation. They have therefore attracted a lot of attention in the research of EBG technology.

2.2.1 2-D Planar EBG Structure

2-D planar EBG structures comprise 2-dimensional EBG inclusions periodically arranged on a plane. Therefore, they are able to provide band-gap in directions on the plane with EBG pattern. Some structures are composed of metallic elements embedded in a dielectric host plane or metallic patches on a dielectric slab whereas some are metal plane with apertures. In our review, they are divided into the following categories:

- Planar periodic metallic element array
- 2-D planar EBG structure with etched patch
- uniplanar compact PBG (UC-PBG) structure
- anisotropic 2-D planar EBG structure

Planar Periodic Metallic Element Array

2-D planar EBG structures in this category are composed by metallic elements periodically arranged on a dielectric slab or embedded in the slab. Disregarding the locations of the periodic elements, both types of structures are metallodielectric.

Figure 2.15: Schematic of the three-layer planar metallic EBG structure [64]

Figure 2.16: Photograph of a patch antenna in metallic tripole arrays [66]

Meshed planar EBG structure In some proposals on planar structures, metallic elements are connected (with a network topology) forming meshes (Fig.2.15(a)). In [66], filter structures working at far infrared wavelengths were proposed by embedding metallic meshes in a flexible polyimide dielectric. Fig. 2.15 shows the cross sectional view of the proposed structure and the grid pattern of each metal layer. Depending on the periodic pattern of the metal grids, the filter structures exhibit either simple highpass or more complex transmission characteristics.

Metallic meshes were used as the ground plane of a stripline to overcome drawbacks when a uniform ground plane was used. Base on the study reported in [67], the stripline with planar EBG meshes demonstrates slow wave effect and high impedance characteristic. Meanwhile, the meshed ground plane is able to suppress

Figure 2.17: Schematic of a dielectric substrate with planar periodic square patch array [67]

Figure 2.18: Metaldielectric planar EBG filter press fit in a rectangular waveguide [70]

coupling between two coupled striplines.

Fig. 2.16 shows another planar EBG structure with periodic arrays of conducting tripoles printed on a dielectric slab which is integrated with a patch antenna [68]. This planar metallic EC as well as those with periodically printed dipoles has similar geometry as the meshed EBG structures introduced above. They show slow wave effect and prohibit the propagation of waves in certain frequency band. They were used to construct bandstop filters and to achieve microstrip resonators with high Q factor and patch antennas with high performance.

Metallic patch array Some planar periodic metallic element arrays are composed of isolated metallic patches on the dielectric slab or embedded in the slab.

Figure 2.19: Schematic of a 2-D planar EBG structure [7]. The rectangular lattice of circles are etched in the ground plane of a microstrip line

Fig. 2.17 shows the schematic of a planar periodic patch array on a grounded dielectric substrate studied in [69]. This substrate is able to construct a modeless substrate. The FDTD algorithm was used to model this type of periodic structure in [70]. It can be used for high-gain leaky-wave antenna. Similar structure can be constructed using coated thin film which exhibits a complete band-gap [71]. With several such EBG dielectric slabs stacked monolithically (Fig. 2.18), a high performance bandpass filter can be obtained which was proposed and used in a waveguide in [72].

2-D Planar EBG Structure with etched patch

In 2-D planar EBG structures of this type, periodic elements are patches etched in the ground plane of planar microwave circuits. These structures show band-gaps in the directions of periodicity in a plane. 2-D planar EBG structures are able to obtain similar or better stopband performance than a 2-D dielectric EC with holes drilled through the substrate has while greatly simplifying the fabrication process. Therefore, they are intensively studied and have been widely employed in a number of microwave circuits.

Antennas are one of the main areas where 2-D planar EBG structures are

Figure 2.20: Photograph of a fabricated 2-D planar EBG microstrip circuit with the compensated right-angle microstrip bend [7]

employed and studied. Due to the band-gap provided by this type of EBG structures, they are used in the design of various planar antennas to reduce their surface mode levels [73] [74] or to suppress the harmonics [75] thus to improve the gain of the antenna and to reduce the side lobes.

2-D planar EBG structures are also integrated with microstrip lines exhibiting bandstop filtering functionality. The first 2-D planar EBG microstrip structure was introduced in [7]. Fig. 2.19 shows the schematic of the proposed structure. As can be seen in the figure, square lattice of circles are etched in the ground plane. The structure is able to inhibit the propagation of the fundamental quasi-TEM mode in the substrate and it exhibits band-gap in the propagation of waves. The planar structure has easy fabrication process because it removes the needs to drill holes through the substrate. Moreover, it is found that it achieves larger stopband than a 2-D air hole array dielectric EC [57]. The EBG microstrip filter structure has progressed with a easy fabrication process.

In a study done in [7], it was found that the optimal ratio of the radius of the circle r to the structure period a , r/a is found out to be 0.25 where the best compromise between the ripple level in the passband and the width and depth of the stopband is able to be obtained. A 2-D planar EBG microstrip circuit with

Figure 2.21: The schematic of a 4-element patch antenna array incorporated with 2-D planar EBG structures [78]

the compensated right-angle microstrip bend (Fig. 2.20) was found to have similar bandstop performance to that of a straight EBG microstrip structure.

The coupled mode theory was formulated to analyze this 2-D planar EBG microstrip structure [76]. The structure with different lattices and different geometry of etched patches (square and triangle) was studied in [77]. The study concluded that the effect of lattice is significant while that of the geometry of the etched patch is minor. For a structure with a fixed lattice, the area of the etched patch affects the bandwidth of the rejection band instead of the geometry. In the same paper, the effect of the relative location of the patches and the microstrip line in the transversal direction on the wave propagation was also reported. When the central line of the patches overlaps the longitudinal center line of the microstrip line in the transversal direction, the wave propagation is perturbed to the biggest extent, which is due to the high confinement of EM fields around the conducting line.

The 2-D EBG microstrip structure with circular etched patches was used to suppress coupling of two close microstrip lines or two intersecting microstrip lines working at different frequencies [78]. It was used as reflectors at two ends of a microstrip line to construct a Bragg resonator [79].

Other than the band-gap, the 2-D planar EBG microstrip structure (Fig.

Figure 2.22: Ground plane of the microstrip lowpass filter employing 2-D planar EBG structure [9]

2.19) exhibits the slow wave effect and is used as a phase shifter for phased array antenna. In [80], it was found that the electrical delay increases linearly as the number of period increase at certain frequency, which means the structure is suitable to use satisfying the requirements of a phase shifter [81]. Fig. 2.21 shows the schematic of a four-element patch antenna array incorporated with the 2-D planar EBG structure at the input of each antenna element proposed in [80].

2-D planar EBG structures are applied for filters. In [9], a tapered 2-D planar EBG structure is used to construct a microstrip lowpass filter with good performance. Fig. 2.22 shows the ground plane of the microstrip lowpass filter employing 2-D planar EBG structure. Fig. 2.23(a) shows the schematic of the tapered 2-D planar EBG structure used in the bandpass filter design in [82]. In this design, as can be seen in Fig. 2.23(b), the EBG structure was inserted between the top layer of two hairpin resonators with symmetric feed-line tapping (Fig. 2.23(c)) and a ground plane bottom layer.

The introduction of the planar EBG structure brought considerable impact in the world of microwave. They are compatible with monolithic technology. Due to the easy and low cost fabrication, they can easily be employed in mass produced microwave circuits or array circuits with a large amount of elements. The proposal on the planar EBG structure paves the way towards a wider range of applications and it drives the development of EBG technology.

Figure 2.23: Schematic of the novel bandpass filter structure in [80] using tapered EBG cells and hairpin resonators

UC-PBG Structure

2-D planar EBG structures exhibit a band-gap in the directions of periodicity on the plane where patches are periodically etched. They perform well in terms of suppression of harmonics as well as reduction of surface waves. However, they are inferior in terms of compactness when they are compared to the uniplanar compact PBG (UC-PBG) structure that is another type of 2-D planar EBG structure.

The UC-PBG structure was introduced in [83]. Besides the compact size, the structure shows characteristics of slow wave effect, wide stopband, and uniplanar configuration. The slow wave effect of the structure was demonstrated by the author in an earlier publication [84].

Fig. 2.24(a) shows the schematic of this structure patterned in the ground plane of a microstrip line and Fig. 2.24(b) shows the single element of this EBG structure. As shown in the second figure, the UC-PBG element consists of a square metal pad with four connecting branches. These narrow branches, together with

Figure 2.24: Schematic of the uniplanar compact photonic band-gap (UC-PBG) structure [81]

Figure 2.25: FDTD simulation results of S-parameters of the microstrip on the UC-PBG ground plane in [81]

insets at connections, introduce additional inductance seen by the microstrip, and the gaps between neighboring pads enlarge capacitance. Since the propagation constant is determined by the series reactive elements combined with the shunt capacitances, it is much larger in the UC-PBG structure than that of a microstrip line on a uniform ground plane. Thus, this UC-PBG microstrip structure demonstrates broad stopband and has slow wave effect, as shown in Fig. 2.25 and Fig. 2.26, respectively. The wide rejection band, severe slow wave effect, and compact size make the UC-PBG structure advantageous over 2-D planar EBG structures with etched patch reviewed previously.

Figure 2.26: Slow-wave factor of a microstrip line on the UC-PBG ground plane [81] in comparison with a conventional microstrip line

Figure 2.27: Top view of the fabricated patch antenna surrounded by three UC-PBG periods in [83]. A 50-mil gap is left between the patch and the UC-PBG metal pattern

In [85], the UC-PBG structure is used to suppress the undesirable surface waves of an aperture-coupled patch antenna in order to improved its performance. Fig. 2.27 shows the top view of its fabricated prototype. As can be seen in the figure, the patch antenna is surrounded by UC-PBG cells which is able to provide a stopband in the frequency band of the antenna to reduce surface wave loss. With the UC-PBG structure, the antenna shows over 3 dB higher gain in the broadside direction than the same antenna etched on a grounded dielectric slab with the same thickness and dielectric constant. Cross-polarization level remains 13 dB down the co-polar component level for both E - and H -planes.

Figure 2.28: Microstrip BPF on UC-PBG ground [84]

Figure 2.29: Schematic of the conductor-backed coplanar waveguide (CB-CPW) [81]

The UC-PBG structure is etched at the ground plane of a traditional parallel-coupled line microstrip bandpass filter (BPF) [86] to suppress the spurious passbands (Fig. 2.28). The UC-PBG structure provides intrinsic spurious rejection and therefore extra filters are not required. The physical size of the UC-PBG BPF is small due to the slow wave effect of the UC-PBG structure. The periodic structure was also etched in the ground plane of a traditional stepped-impedance lowpass filter to improve its performance.

Besides the integration with the microstrip line, they are incorporated to coplanar waveguides (CPW) to improve their performance. The UC-PBG structure is employed to suppress the parallel-plate mode formed between top and ground planes in the design of a conductor-backed coplanar waveguide (CB-CPW)

Figure 2.30: Schematic of a UC-PBG waveguide in [86]

[83] (Fig. 2.29(a)) resulting a CB-CPW without energy leakage. Fig. 2.29(b) shows the schematic of the proposed nonleaky CB-CPW with the UC-PBG structure in the ground plane.

When the UC-PBG pattern is fabricated on a conductor-back dielectric substrate, a magnetic conducting surface can be realized at the stopband frequency [87]. Two of such UC-PBG magnetic conducting surfaces were used as the sidewalls to provide magnetic boundary in a novel TEM-waveguide design [88]. Fig. 2.30 shows the schematic of this waveguide which generates a relatively uniform field distribution in a frequency band. Phase velocities is close to the speed of light and the velocity curve is flat at operating frequencies, indicating the establishment of a TEM mode. The waveguide was modeled using neurocomputational technique and the electric field in it was analyzed [89]. The proposed novel waveguide is used in the design of a quasi-optical power amplifier in [90]. Besides, the proposed TEM waveguide shows potential application for the electromagnetic compatibility testing.

With regard to a magnetic conducting surface, other than the UC-PBG patterned plane, other frequency selective surfaces (FSS) are possible to use [91] [92] [93].

Besides the applications mentioned above, UC-PBG structures were employed in the design of mode suppressor for other waveguide such as non-radiative

Figure 2.31: Multilayer EBG structure with a harmonic configuration [99] [100]

dielectric (NRD) waveguide in the design of hybrid planar/NRD circuits [94]. They are also used in the design of a nonlinear transmission line (NLTL) frequency multiplier in [95] to improve the conversion efficiency.

Other than applications, there are some modified UC-PBG structures based on the original design [83] being proposed to lower the center frequency of the stopband [96] or to achieve multiband structures [97]. Studies on the dispersion characteristics of the UC-PBG structure are reported [98] [99] and some proposed circuit model is presented in [100].

As we have reviewed, the UC-PBG structure on a single plane is widely applied to a lot of microwave devices due to the unique features they provide. Some EBG structures were proposed with several 2-D UC-PBG patterned layers stacked in the direction perpendicular to the plane of substrate. They are called multilayer EBG structure which is an expansion of the previous monolayer structure. The multilayer EBG structure shows broader stopband than the structure with a single 2-D EBG layer. According to the ratio of periods on different layers, there are two

variants of this structure. One is with a harmonic configuration and the other is with an inharmonic configuration.

A multilayer EBG structure has a harmonic configuration when the ratio of the period on each layer is harmonic. This type of structures is introduced for a microstrip line in [101] [102]. Fig. 2.31(a) shows its cross sectional view and Fig. 2.31(b) and (c) show the unit cell on each layer. As can be seen in Fig. 2.31(a), it consists of two UC-PBG layers on the intermediate and the bottom layer, respectively. The period of the structure on the bottom layer, p_b , is a which is twice of the period of the structure at the intermediate layer. Therefore, the periods of the two planar EBG structures are in a harmonic ratio, and the superpositioned structure has a global period of a which is identical to the larger one of the two periods. This multilayer EBG structure exhibits a much wider stopband than a monolayer one, but its cutoff frequency is identical to that of the monolayer structure due to the harmonic configuration.

A two-layer EBG structure with periods in an inharmonic ratio is presented in [102] [103]. As shown in Fig. 2.32(a), it has a UC-PBG bottom layer with a period of a , but the period of its UC-PBG intermediate layer is designed to be $2a/3$. The periods are in an inharmonic ratio which results in a larger global period of $2a$. Therefore, other than a broad stopband, the structure is able to obtain a lower cutoff frequency due to the larger period and the structure becomes more compact. In this inharmonic structure, an inductor pattern (Fig. 2.32(c)) or a capacitor pattern (Fig. 2.32(d)) is used on the intermediate layer. They are able to induce the reactive loading effect to lower the cutoff frequency for optimal performance of the two-layer EBG structure.

Figure 2.32: Multilayer EBG structure with a inharmonic configuration [100] [101]

Anisotropic 2-D Planar EBG structure (Anisotropic PBG)

For 2-D planar EBG structures have been reviewed above, including metallic meshes, 2-D planar EBG structure with etched patch, and UC-PBG structure, they all have discrete periodic elements arranged on a plane. Therefore, they exhibit band-gap in directions on the plane. In the category of 2-D planar EBG structure, there is another type of structure called anisotropic PBG structure which shows band-gap in a single direction in spite of the 2-D configuration of elements [104]. It is first proposed by Caloz *et al* in [105]. Fig. 2.33 shows the ground plane of the proposed anisotropic PBG structure in this paper. As this figure shows, the ground plane consists of an array of etched slots of alternating widths. Its pattern is a 2-D square lattice periodic structure with a unit cell geometry exhibiting a 180° symmetry. The structure is anisotropic because when a microstrip line is

Figure 2.33: Ground plane of an anisotropic 2-D planar EBG structure [102]

in the z -direction, the induced current can flow through the structure freely and the signal is transmitted, while the signal is attenuated when the line is rotated 90° clockwise or anticlockwise (in the y -direction) because the stepped-impedance slots break the continuity of metal paths. Therefore, z is the propagation direction (PD) and y is the attenuation direction (AD).

The period of the anisotropic PBG structure, a , is much smaller than wavelength in this structure, in contrast to a conventional 2-D EBG structure ($a = \lambda_g/2$). The gap in AD is not due to Bragg-like diffraction, but to the first resonance of the array transverse stepped-impedance slots of the PBG ($L_z \approx \lambda/2$). The transmission characteristics of the anisotropic PBG are essentially insensitive to the position of the line in both the PD and AD, as a direct consequence of the "impedance effectiveness".

This structure is also included in [106] and [102]. The anisotropic characteristics of 2-D planar EBG structures are applied to the design of microstrip diplexer antennas to enhance the isolation between transmitting (T_x) and receiving (R_x) ports [104] [107] [108] and to the design of diplexer filters [109].

Figure 2.34: Photograph of a 2-D planar EBG microstrip structure and a 1-D planar EBG microstrip structure in [8]

2.2.2 1-D planar EBG Structure

Instead of exhibiting band-gap in several directions, 1-D planar EBG structure control the wave propagation in a single direction which satisfy the Bragg reflection condition. 1-D planar EBG structures are suitable for waveguide such as microstrip line and coplanar waveguide (CPW). They exhibit excellent reflection functionality in a wide frequency band and they are used to construct reflectors and filters. 1-D planar EBG microstrip structures and the tapering techniques used in EBG technology are to review in this section. The review on 1-D planar EBG CPW structures is included in Appendix C.

1-D planar EBG Microstrip Structure

- With EBG elements in the ground plane

Cermet Topology Fig. 2.34 shows the photograph of a 2-D planar EBG structure with square lattice of circles etched in the ground plane [7] and a 1-D planar EBG microstrip reflector with one single column of discrete circles periodically etched exactly below the microstrip line in the ground plane (cermet topology) [8]. Due to the high confinement of fields around the microstrip line, the wave propagation behaviors of these two reflectors are similar to each other. The proposed 1-D planar EBG microstrip structure is able to control the wave propagation

Figure 2.35: Schematic of a compact 1-D planar EBG microstrip structure with a meander microstrip line [111]

effectively while its physical size in the transversal dimension is greatly reduced, as can be seen in the figure.

For the 1-D planar EBG structure with cermet topology, different techniques and models such as the fiber grating model [110], the coupled mode theory [111], and the SOC de-embedding technique [112] are applied to analyze their transmission characteristics.

Traditionally, the bandwidth and attenuation of the stopband can be increased by increase the number of EBG period. However, it is achieved at the expense of a significant increase in the physical size of the structure in longitudinal dimension. Without an increase in the physical size, several novel 1-D planar EBG reflector base on the structure in Fig. 2.34 were proposed with enhanced stopband performance.

In [113], a compact EBG microstrip reflector was proposed using a meander microstrip conductor line. Fig. 2.35 shows the photograph of the proposed structure. As can be seen in the figure, a large number of EBG periods are included in a small physical size. In this structure, high attenuation and selectivity are obtained in the stopband due to the large number of EBG unites and the circuit area remains small because of the meandering topology. In [114], the high ripples caused by the periodicity of the EBG structure and the turnings on the microstrip line were al-

Figure 2.36: Schematic of a chirped 1-D planar EBG microstrip structure with circles etched in the ground plane [113]

leviated by applying tapering techniques. Tapering techniques are commonly used to optimize the performance of EBG structures in terms of transmission in the passband. They will be reviewed as a separate section in the later section.

Instead of increasing the number of period, a 1-D chirped planar EBG microstrip structure was proposed in [115] to obtain an increase in the bandwidth of the stopband. In this structure, the chirping technique that was first used in optical fiber Bragg grating and in microwave corrugated waveguides was adopted. Fig. 2.36 shows the schematic of this proposed structure. The period of the structure a_i is given by the following equation as a function of its position in the device:

$$a_i = a_0 \cdot (1 + i\delta) \quad (2.1)$$

where a_0 is the period corresponding to the central hole of the structure, δ is the adimensional chirp parameter that controls the period variation, and $i = 0, \pm 1, \pm 2, \dots$

The chirped 1-D planar EBG microstrip structure exhibits an increased width of the rejection band although resulting a growing ripple in the passband. Tapering techniques were applied to flatten the frequency response in the proposed chirped structure.

Another novel technique was introduced in [116] to obtain a 1-D planar EBG microstrip reflector with wide stopband by proposing a 1-D multiperiod EBG

Figure 2.37: Schematics of 1-D planar EBG structure with multiperiod [114]

Figure 2.38: Layout of microstrip bandpass filter with cascaded 1-D planar EBG structures [118]

structure with two periods in one structure. Circles are etched in the ground plane in the same way as that of the 1-D planar EBG microstrip structure in Fig. 2.34. However, the distance between adjacent circles are varied. There are several possible arrangements of the circles in the multiperiod EBG structure and the performance of two of them (Fig. 2.37) were examined. With two different periods combined in one structure, the associated stopbands are joined together to form a very wide stopband. As the result of the comparison of the two multiperiod structure, the bandwidth of the stopband is affected by the arrangement of the circles. It was found that the proposed multiperiod structure is able to obtain wide stopband when the number of consecutive periods for each period is large.

All the three new 1-D planar EBG structures above are good reflectors

Figure 2.39: Schematic of a diplexer with two meandered, tapered 1-D planar EBG microstrip structures [119]

showing a wide stopband. Other than reflectors or filters, 1-D planar EBG structures can be employed to reduce harmonics in microwave circuits such as dielectric resonator filter (DRF) [117], active antennas [118], and coupled ring bandpass filters [119]. Fig. 2.38 shows the schematic of a microstrip bandpass filter with two cascaded 1-D planar EBG structures [120]. Both EBG structures consist of rectangular patches etched in the ground plane, but they have different period of the structure. In this structure, the second and third harmonics were attenuated significantly. A tapered and meandered 1-D planar EBG structure is employed in the design of diplexer to switch transmit/recieve paths in a multi-band transceiver antenna in [121]. Fig. 2.39 shows the schematic of the proposed diplexer.

The control of the stopband in a 1-D planar EBG microstrip structure was realized by optical means [122] [123], which implies the potential applications requiring a switchable stopband in the frequency response.

Defected Ground Structure (DGS) Defected ground structure (DGS) is a microstrip structure with one or several defect elements etched in the ground plane and provides band-gap characteristics. The defect elements can be arranged periodically to obtain a band-gap satisfying the Bragg reflection condition.

Figure 2.40: Defected Ground Structure (DGS) [122] [123]

Figure 2.41: Schematic of lowpass filters employing DGSs [123]

The DGS was proposed in [124] by Kim *et al* in 2000. Fig. 2.40(a) shows the schematic of a DGS unit section which is etched in the ground plane of the microstrip line. The narrow and wide etched areas of the defect in the metallic ground plane give rise to increasing the effective capacitance and inductance of a transmission line, respectively. Only a single element is able to provide cutoff frequency and attenuation pole in some frequency.

The DGS unit is modelled using the equivalent circuit shown in Fig. 2.40(b). A method was demonstrated in [125] to extract the equivalent circuit parameters base on the simulation results using field analysis method. The circuit model was

Figure 2.42: Optimized circuit model [124]

Figure 2.43: Schematic of a DGS with five units [125]

validated when the DGS was used in the design of three-pole low-pass filters. In the lumped low-pass filter, the DGS was used to implement the parallel LC resonator whereas open stubs were used to realize the parallel capacitance. Fig. 2.41(a) and (b) show the schematic of the low-pass filters using the DGS unit sections and open stubs.

This equivalent circuit model was modified in [126]. The new model is more adequate because it has parallel capacitance to model the fringing fields due to the defects in the metallic ground plane (Fig. 2.42).

The effect of a metallic enclosure on the performance of a DGS with five units (Fig. 2.43) was studied [127]. It was found that the effect of finite ground plane on the propagation behavior of an unshielded DGS can be neglected when the half width of the ground plane is more than five times of the width of the unit. It was also observed that the effect of the enclosure on a shielded DGS can be neglected when the distance between the side wall of the enclosure and the center

Figure 2.44: Schematic of a DGS lowpass filter with two DGS units and a compensated line width [126]

of the conducting line is more than five times of the width of the etched unit, the heights of the upper and lower wall of the enclosure are more than three and six times of the thickness of the substrate, respectively.

In [128], a broad microstrip line (Fig. 2.44) is used to replace the open stubs in the low-pass filter structure proposed in [125]. This new low-pass filter shows advantages of simple structure, small size (the required area is only half that of the conventional LPF in [125]), less discontinuities, and high power handling capability. By arranging the same DGS units and a modulated microstrip line into a compact double-plane configuration, a bandstop filter with ultra-wide stopband was designed and implemented in [129]. Fig. 2.45 shows its 3-D schematic and top view.

Base on the original DGS, DGS with new geometries were proposed, such as the butterfly-radial slot (BRS) structure [130], the S-shape DGS (the unit cell from the proposed electromagnetic periodic structure bandpass filter (EPS-BPF) in [131]), the spiral DGS [132], and the fractal DGS [133]. They obtain improvement in stopband performance in terms of bandwidth or selectivity. Equivalent circuit models were derived for some of these proposed DGSs.

Other than DGS, a single EBG cell which is constructed in a two-layer

Figure 2.45: Bandstop filter with DGS units and a modulated microstrip line [127]

dielectric substrate as shown in Fig. 2.46 is able to generate a cutoff frequency and an attenuation pole [134]. The location of the attenuation pole can be shifted by adjusting the patch dimensions and positions of the shorting pins. Its equivalent circuit model was proposed and it was used to construct a 3-pole wideband notch filter.

Network Topology Other than unconnected patches etched in the ground plane, there are 1-D planar EBG structures with etched patterns that follow a continuous profile (network topology). A 1-D planar EBG microstrip structure with a continuous etched pattern is able to significantly reduce the level of the rejected bands at harmonics of the design frequency. The EBG structures with a sinusoidal and a triangular etched pattern demonstrate the nonperiodic frequency response in [135].

The 1-D EBG microstrip structure with a continuous etching profile in the ground plane is able to realize multiple deep and wide stopbands. In [136], the two- and three-frequency-tuned microstrip EBG structure was achieved when the etched pattern was formed by addition of various sinusoidal functions tuned at the design frequencies. A simple and fast fiber Bragg grating (FBG)-based model for the analysis and design of 1-D planar EBG microstrip structures with a sinusoidal

Figure 2.46: Schematic of a two-layer microstrip EBG structure [132]

patten etched in the ground plane was proposed in [137] by using the equivalence found between the parameters of FBGs and the microstrip EBG structures.

1-D planar EBG microstrip structures with patches etched in the ground plane shows good reflection characteristics. However, they are sensitive to the working environment due to the etched sections. They are severely interfered when metallic planes are placed close to it and therefore, their performance are deducted in such a situation.

- **With EBG elements in the microstrip line**

Microstrip line with etched holes in it Some 1-D planar EBG microstrip structures were introduced with EBG units etched in the microstrip line and remains a uniform ground plane, which lowers the sensitivity of the structure.

The structure shown in Fig. 2.47 was proposed in [138]. Rectangles were periodically etched in the microstrip line and a band-gap was exhibited in the

Figure 2.47: 1-D planar EBG microstrip structure with rectangular holes etched in the microstrip line [136]

Figure 2.48: 1-D planar EBG microstrip structure units with defects etched in the microstrip line [137]

direction of propagation. More complicated EBG cells in the microstrip line (Fig. 2.48) were proposed in [139]. The proposed cells shows remarkable slow-wave and bandstop effects. The cell in Fig. 2.48(b) was modeled using the equivalent circuit shown in Fig. 2.49. The cells were cascaded to construct a bandstop filter with excellent performance. The compact microstrip resonant cell (CMRC) was incorporated in oscillator [140] and mixer [141] to suppress the harmonic and to terminate unwanted frequency mixing products.

Although the 1-D planar EBG microstrip structures mentioned above are able to protect the structure from being interfered by other metallic surfaces, they are suffered by poor power handling capability which is caused by the thin metallic lines in the microstrip line after etching. The introduction of 1-D planar EBG microstrip structure with varied width of the microstrip line is able to alleviate this problem.

Figure 2.49: L - C equivalent circuit for cell 2 [137]

Figure 2.50: Schematic of "Wiggly-line" filter after applying the strip width perturbation [140]

Microstrip line with width variation The microstrip line with the width continuously perturbed following a sinusoidal law is able to provide a band-gap in the direction of wave propagation. It was applied to the design of a parallel-coupled-line microstrip bandpass filter and suppressed the spurious passband effectively [142]. Fig. 2.50 shows the schematic of this new microstrip BPF. In this BPF, the harmonic passband of the filter is rejected by the modulated wave impedance while the desired passband response is maintained virtually unaltered. With the EBG pattern in the microstrip line, this filter is able to suppress spurious passband without being suffered by interference from surroundings. Furthermore, the classical design methodology for coupled-line microstrip filters can directly be used in this design.

There are some other 1-D planar EBG structures constructed by inserting patch with unique geometry [143] [144] [145]. The microstrip structure with single EBG cell in [143] and [145] shows wide stopband and slow-wave characteristics. The center frequency and the bandwidth of the stopband can be controlled by the

Figure 2.51: Schematic of the doubly electromagnetic periodic structure (DEPS) in a microstrip line [144]

dimensions of the EBG cell.

- **With double 1-D planar EBG structures**

Fig. 2.51 shows the schematic of a 1-D planar EBG structure with square patches etched in both the microstrip line and the ground plane [146]. This doubly electromagnetic periodic structure (DEPS) exhibits a stopband with a much larger bandwidth and higher attenuation than that shown by a conventional EBG structure only with patches etched in the ground plane. It was used in a class-AB power amplifier to improve its output power and power-added efficiency (PAE). A similar structure adopted tapering technique was proposed in [147]. Double layer microstrip structure is also found in the low-loss high-impedance structure with backside aperture that is developed in [148].

2.2.3 Tapering Techniques

1-D planar EBG microstrip structures show promising filtering capability in the stopband, which makes it attractive to filter designers. However, the ripple level in the passband of the EBG structures with uniform distribution is high due to the intrinsic periodicity of the structure. Tapering techniques are effective means

Figure 2.52: Schematic of a meander 1-D planar EBG microstrip structure with tapered circles [112]

to eliminate ripples. They are widely employed in the design, development, and optimization of planar EBG structures.

In some tapered EBG structures, tapering techniques are applied by directly adopting tapering functions (such as Kaiser [149]) to modify the dimension of the periodic patches. Fig. 2.52 shows the schematic of a meander 1-D EBG microstrip structure whose dimension of the etched circle in the ground plane are tapered applying Hamming window [114]. The effects of Bartlett, Hanning, Hamming, Nuttall, and Kaiser tapering on a 1-D planar EBG microstrip structure are compared and studied in [9]. As the result of the comparison, Kaiser tapering is the best because the structure with Kaiser tapering is able to obtain a good compromise between the stopband and the passband performance. It is applied in the design of a EBG lowpass filter structure (Fig. 2.22) proposed in [9].

The other approach to taper EBG structures is base on low side lobe array theory [12] including Binomial array, Dolph-Tschebyscheff array (Chebyshev array), and Taylor array. The significant effects of Binomial and Chebyshev distribution on the passband performance of an EBG microstrip structure has been shown by Karmakar *et al* [10]. Fig. 2.53 shows the schematic of the 1-D EBG microstrip structure applying the tapering technique. The effect of the Taylor distribution on a 1-D EBG CPW structure with square wave perturbation geometry

Figure 2.53: Schematic of a meander 1-D planar EBG microstrip structure with tapered circles in [10]

was shown in [150].

2.2.4 Summary

In this chapter, both 2-D and 1-D planar EBG structures have been reviewed in detail. They show the ability to control the wave propagation with periodic structures arranged in one or several planes. Due to the planar structure, they all have easier fabrication process than electromagnetic crystals.

For suppression of surface waves caused by radiation elements such as patch antennas, 2-D planar EBG structures have good performance because they are able to prohibit the propagation of waves in the directions on a plane. For applications such as filters or reflectors, 1-D planar EBG microstrip structures show advantages of good stopband and passband performances, a relatively small circuit area, and the ease of implementation.

However, for the existing 1-D planar EBG microstrip structures, it is observed that a stopband with a large bandwidth and a high attenuation can only be obtained with the degradation of the performance in the passband. Moreover, an enhancement of the stopband is always achieved at the expense of a significant increase in the circuit area. The limitations of this type of EBG structures prevent them from being widely employed in circuit designs in modern communications.

2.2 Planar EBG Structures

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In this thesis, the aim is to seek a good compromise between the performances in the stopband and in the passband as well as a good compromise between the filtering functionality and the physical size of the structure.

The characteristics of traditional planar EBG structures are studied, which serves as the basis of this research. Novel configurations as following are proposed:

- 1) dual-plane EBG configuration
- 2) small-size EBG (S-EBG) structure
- 3) U-shape microstrip line geometry
- 4) meander microstrip line geometry

Figure 3.1: Layout of a five-cell 1-D EBG reflector with circles etched in the ground plane

3.2 Design Principle

Fig. 3.1 shows the layout of a typical 1-D planar EBG structure with five circles of uniform dimension etched in the ground plane of a microstrip line. This EBG microstrip structure has a prominent band-gap in the frequency response when it satisfies the Bragg reflection condition [8]. As can be seen in the figure, the distance between two adjacent circles a defines the period of the structure; r represents the radius of the circle; and w is the width of the microstrip line.

According to the Bragg condition, the period a is approximated by the following expression:

$$\beta \cdot a = \pi \quad (3.1)$$

where β is the guided wavenumber in the substrate material and described by the following equation:

$$\beta = \frac{2\pi}{\lambda_g} \quad (3.2)$$

λ_g is the guided wavelength where

$$\lambda_g = \frac{c}{f_0 \cdot \sqrt{\epsilon_{eff}}} \quad (3.3)$$

f_0 is the center frequency of the stopband, ϵ_{eff} is the effective permittivity of the

Chapter 3

Design Principle & Dielectric Material

3.1 Introduction

In this chapter, the design principles of 1-D planar EBG microstrip structure is presented. The effects of dielectric materials on the performance of a 1-D planar EBG reflector such as the stopband bandwidth, the stopband attenuation, the center frequency, and the ripple level of the passband, are examined and analyzed in detail. Three commercially available dielectric materials (Taconic, Quartz, and RT Duroid 6010.5) with different dielectric constants are used and two case studies are presented. Experimental results of the EBG structure using Taconic are also presented to verify the simulation results.

The aim of the study in this part is to seek a suitable material for the experiments in the thesis that is able to clearly demonstrate the band-gap phenomenon of the structure with the ease of fabrication and at low cost.

Table 3.1: Dielectric Materials

Material	Taconic	Quartz	RT Duroid 6010.5
dielectric constant, ϵ_r	2.43	3.8	10.5
thickness of the substrate, h (mils)	30	30	30
loss tangent, δ	1.5E-3	2E-5	2E-3

substrate material, and c is the speed of light in the free space. From (3.1) and (3.2), the period a equals half of the guided wavelength λ_g as following equation:

$$a = \frac{\lambda_g}{2} \tag{3.4}$$

Base on (3.3) and (3.4), it can be seen that the period of the structure a is determined by the center frequency of the stopband and the dielectric materials of the substrate. When (3.3) is substituted in (3.4), the expression can be obtained as following:

$$a = \frac{c}{2f_0 \cdot \sqrt{\epsilon_{eff}}} \tag{3.5}$$

therefore,

$$f_0 = \frac{c}{2a \cdot \sqrt{\epsilon_{eff}}} \tag{3.6}$$

From (3.6), the center frequency of the stopband f_0 is determined by two factors: the period of the structure, a ; ϵ_{eff} that ranges from 1 to ϵ_r (ϵ_r is the dielectric constant of the material). ϵ_{eff} can be estimated by the following equation:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12h/w}} \tag{3.7}$$

where h is the thickness of the substrate and w is the width of the microstrip line.

r/a is the filling factor of the EBG structure that indicates the size of the EBG unit with respect to the period of the structure. It has a range from 0 to

Table 3.2: Dimensions of EBG Structures

Material	Taconic	Quartz	RT Duroid 6010.5
Period of the structure, a (mm)	10.35	8.48	5.68
Radius, r (mm)	2.59	2.12	1.42
Width, w (mm)	2.29	1.72	0.68

0.5 in the case that there is no overlap between any two adjacent EBG units. The performance of an EBG microstrip structure is affected by the filling factor r/a . In [7], it is reported that the bandwidth and attenuation of the stopband and the ripple level of the passband increase as r/a increases. It is reported that the optimal r/a is 0.25.

For the effect of dielectric materials on the performance of a 1-D planar EBG structure (Fig. 3.1), it is examined and studied by using two bandstop filter design cases. One is with a fixed center frequency of 10 GHz and the other is with a constraint on the physical size. The dimensions of the three materials investigated in this study are tabulated in Table 3.1.

3.3 Case One - 10 GHz Bandstop Filter

In this case study, the center frequency of all the structures is identical and set to 10 GHz. According to the Bragg condition, for dielectric materials Taconic, Quartz and Duroid, a period of 10.35 mm, 8.47 mm and 5.41 mm are obtained, respectively. Two other structural variables; the thickness of the substrate; and the filling factor (r/a) is fixed to be 30 mils and 0.25, respectively. Table 3.2 shows the radius of the circle r , and the width of the microstrip line w corresponding to a characteristics impedance of 50Ω at 10 GHz in each case. As can be seen in the table, with identical center frequency of the stopband and filling factor, the structure with a large dielectric constant is small in both the longitudinal

3.3 Case One - 10 GHz Bandstop Filter

Figure 3.2: Simulated S-parameters of EBG structures using Taconic ($\epsilon_r = 2.43$, $h = 30$ mils), Quartz ($\epsilon_r = 3.8$, $h = 30$ mils), and RT Duroid 6010.5 ($\epsilon_r = 10.5$, $h = 30$ mils) in Case One

Table 3.3: Simulated Performances of 12-cell EBG Structures

EBG structure	10-dB BW (GHz)	Maximum attenuation (dB)	Ripple Level (dB)	
			Lower passband	Higher passband
Taconic	4.98	27.25	2.19	5.74
Quartz	4.41	24.90	1.69	4.19
Duroid 6010.5	1.81	14.52	1.11	3.58

dimension and the transversal direction due to the small period of the structure. The width of the transmission line in the structure with a large ϵ_r is also small.

Fig. 3.2 depicts the S_{21} (a) and the S_{11} (b) parameter for each design using different dielectric materials. As can be seen in Fig. 3.2(a), in each case, an intrinsic stopband appears and is centered at about 10 GHz, satisfying the design specification. The Taconic, Quartz, and Duroid 6010.5 EBG structure shows a 10 dB bandwidth of 4.98 GHz, 4.41 GHz, and 1.81 GHz, respectively, and the highest attenuation of 27.25 dB, 24.90 dB, and 14.52 dB, respectively. The Taconic EBG structure has the widest bandwidth and the highest attenuation of the three materials while the Duroid EBG structure has lower attenuation and smaller bandwidth as compared to the other two EBG structures.

Fig. 3.2(b) shows the reflection coefficient (S_{11}) of the three structures with the different materials. It is known that low level of the side lobes of the S_{11} parameter implies small ripple level in the passband. Fig. 3.2(b) shows that the Duroid EBG structure has the best performance in terms of ripple level as compared to the other structures although it has poorer bandwidth and attenuation performance.

Table 3.3 shows the performances of the three EBG structures studied in this case. As can be seen in Table 3.3, the 10-dB bandwidth, the maximum attenuation of the stopband, and the ripple levels in both the lower passband and the higher passband decrease as ϵ_r of the substrate material increases. It is observed that

3.4 Case Two - Design Constrained by Physical Size

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a highly attenuated stopband with a large bandwidth is accompanied by a large ripple level in the passband. The compromise between the stopband and passband performance in a 1-D planar EBG microstrip structure with uniform distribution is identified.

In this case, it demonstrates that the bandwidth and attenuation of the stopband can be tuned by changing the substrate material. The Taconic EBG structure performs well in terms of the bandwidth and the attenuation of the stopband while its ripple level in the passband is high. Due to the small dielectric constant, the dimension of the Taconic EBG structure is big, which introduces the ease of fabrication, although it occupies a big circuit area.

3.4 Case Two - Design Constrained by Physical Size

In the previous case study, the center frequency of the stopband in the EBG structure was fixed to 10 GHz. The change of the substrate material allows a size tuning and a tuning of the bandwidth and attenuation of the stopband in the EBG structure. The flexibility of designs brought by substrate materials is to be further demonstrated in the following case study where the physical size of the structure is constrained.

In this study, the physical size of the EBG structure was fixed while the dielectric material was changed. The same materials were used to examine the effect of dielectric materials on the band-gap of the 1-D planar EBG structure. The period of the structure a and the radius of the circle r were fixed to be 10.35 mm and 2.59 mm, respectively, corresponding to a filling factor (r/a) of 0.25. The thickness of the substrate was kept to be 30 mils. Therefore, the width of the microstrip line in each structure remains the same as that in the previous design, corresponding to a characteristics impedance of 50Ω at 10 GHz.

Fig. 3.3 shows the simulated S_{21} (a) and S_{11} (b) parameter for these three

(a)

(b)

Figure 3.3: Simulated S-parameters of EBG structures using Taconic ($\epsilon_r = 2.43$, $h = 30$ mils), Quartz ($\epsilon_r = 3.8$, $h = 30$ mils), and RT Duroid 6010.5 ($\epsilon_r = 10.5$, $h = 30$ mils) in Case Two

structures. As can be seen from Fig. 3.3 (a), the center frequency of the stopband is 10 GHz in the Taconic EBG structure. Using the same dimensions of a and r , for Quartz and Duroid, the center frequency is shifted to 8.44 GHz and 5.78 GHz, respectively. As indicated by the results, varying the dielectric constant of the substrate material efficiently tunes the center frequency without any change in the size or modification to the structure. Moreover, there is no large attenuation degradation or increase in the ripple level or decrease in the selectivity [10] when the center frequency is tuned in this way. The side lobes of the S_{11} parameter in Fig. 3.3 (b) show the ripple level in the passband in each structure.

As can be seen in the simulated results, there is a decrease in the bandwidth of the stopband when the center frequency shifts from high to low. The second harmonic is also observed in the frequency response of the Quartz and the Duroid EBG structure. These undesirable effects can be removed by means of minor structural changes. For example, the bandwidth of the stopband is possible to be increased by increasing r/a [7] and the second harmonic can be suppressed by adjusting r/a to be 0.35 [151].

3.5 Measurement Results

The five-cell 1-D planar EBG structure with circles etched in the ground plane was fabricated and tested using Taconic as the substrate material with a thickness of 30 mils. The period of the structure a is 10.35 mm and the radius of the circle is 2.59 mm, corresponding to a r/a ratio of 0.25. The width and length of the 50 Ω microstrip line w and L is 2.29 mm and 60 mm, respectively. Two subminiature A (SMA) connectors were connected to two ends of the transmission line. Fig. 3.4 shows the photographs of the front side and back side of the fabricated EBG structure.

(a) Front side

(b) Back side

Figure 3.4: Photographs of the fabricated EBG structure with $\epsilon_r = 2.43$, $h = 30$ mils, $a = 10.35$ mm, $r = 2.59$ mm, $w = 2.29$ mm, and $L = 60$ mm

Figure 3.5: Simulated and measured S-parameters of the fabricated five-cell EBG structure

Fig. 3.5 shows the simulated and measured S-parameters of the fabricated Taconic EBG structure. As can be seen from Fig. 3.5(a), the measured results of the EBG structure exhibits a stopband centered at 10.12 GHz with an attenuation of 35.13 dB and a 20 dB bandwidth of 3.36 GHz. As shown in the figure, the measurements are in excellent agreement with the simulation results. The difference is probably caused by the over etching, the lack of cell uniformity or material uniformity. The ability to control the wave propagation in EBG structures of other dielectric materials such as Quartz and Duroid can be validated in a similar way to the one we have just demonstrated.

3.6 Summary

In this chapter, the design principles of 1-D planar EBG microstrip structures have been presented. The effect of dielectric materials on the wave propagation in the five-cell 1-D planar EBG structure has been identified and it has been demonstrated using two practical bandstop filter designs.

In the filter design with a fixed center frequency of 10 GHz, it has been shown that the selection of the dielectric material allows a physical size tuning and a tuning of the bandwidth and the attenuation of the stopband in EBG structures while maintaining a constant center frequency. In the filter design constrained by the physical size, the variation of the dielectric constant of substrate materials introduces an efficient shifting of the center frequency over a wide frequency range with a fixed physical size structure. Due to their effects on EBG structures, properly selecting the dielectric material used as the substrate can be an efficient approach to control the behavior of wave propagation in an EBG structure to meet design specifications even with strict constraints. In this sense, substrate materials provide great additional design flexibility. The selection of substrate materials is a powerful tool that can be used in the design of EBG reflectors or filters to satisfy desired specifications.

Compare the three dielectric materials, at the same working frequency (in Case One), the Taconic EBG structure is able to demonstrate a prominent band-gap with the ease of fabrication. Taconic is used in the experiments in the later parts of the study.

Chapter 4

Tapering Techniques

4.1 Introduction

1-D planar EBG structures show a wide and deep band-gap in the direction where there are periodic elements. The ability to control the wave propagation makes them attractive to be employed to microwave circuits such as reflectors and filters.

However, at times, due to the periodicity in the EBG structure, a desirable wide stopband with high attenuation is obtained at the expense of high ripple level in the passband that results in poor transmission performance in the passband. Tapering techniques are widely adopted to improve the passband performance of the EBG structure. To date, two approaches have been introduced. One is based on apodization functions (known as tapering functions) such as Hamming, Kaiser, and Bartlett, etc. The effect of some of these tapering functions (Bartlett, Hanning, etc.) on the performance of EBG structures are presented and compared in [9]. The other approach is based on low side lobe array theory [12] that includes Binomial array and Dolph-Tschebyscheff array (Chebyshev array). It has been shown by Karmakar *et al* [10] that the tapering technique adopting the low side lobe array theory is able to significantly lower the ripple level in the passband. Ripples in

the passband can be eliminated by adopting tapering functions accompanied by degradation of stopband performance to a certain extent.

This chapter presents a study on the tapering techniques for 1-D planar EBG structures. The techniques based on the tapering functions and low side lobe array theory are both presented in the following sections. The effect of the tapering technique on the passband and stopband performance of a typical six-cell 1-D planar EBG microstrip structure with circles etched in the ground plane (Fig. 4.1) is examined, compared, and analyzed.

4.2 Tapering Functions and Low Side Lobe Array Theory

The first approach adopted to taper the dimension of cells in EBG structures is by applying tapering functions. They are functions that are used to bring an interferogram smoothly down to zero at the edges of the sampled region. Table 4.1 shows the function and plot of various types of popular tapering techniques. In the Kaiser function, $I_0(x)$ is the modified Bessel function of the first kind. The variance σ^2 in the Gaussian function is generally set to one for a normal distribution. According to the definition, the value of the function varies in the range of 0 to 1 corresponding to the $x \in [-1, 1]$ with the exception for Kaiser ($x \in [-\frac{1}{2}, \frac{1}{2}]$).

The second approach is based on Binomial array and Chebyshev array from the low side lobe theory [12]. The coefficients of a Binomial array are determined by the series binomial expansion of the function $(1+x)^{m-1}$ as shown below:

$$\begin{aligned} (1+x)^{m-1} = & 1 + (m-1)x + \frac{(m-1)(m-2)}{2!}x^2 \\ & + \frac{(m-1)(m-2)(m-3)}{3!}x^3 + \dots \end{aligned} \quad (4.1)$$

4.2 Tapering Functions and Low Side Lobe Array Theory

Table 4.1: Apodization function (tapering function)

Type	Apodization Function	Plot
	$x \in [-1, 1]; y \in [0, 1]; a = 1$	
Bartlett	$1 - \frac{ x }{a}$	
Blackman	$B_A(x) = 0.42 + 0.5 \cos(\frac{\pi x}{a}) + 0.08 \cos(\frac{2\pi x}{a})$	
Connes	$(1 - \frac{x^2}{a^2})^2$	
Cosine	$\cos(\frac{\pi x}{2a})$	
Gaussian	$e^{-x^2/(2\sigma^2)}$	
Hamming	$Hm_A(x) = 0.54 + 0.46 \cos(\frac{\pi x}{a})$	
Hanning	$Hn_A(x) = \cos^2(\frac{\pi x}{2a}) = \frac{1}{2}(1 + \cos(\frac{\pi x}{a}))$	
Kaiser	$\frac{I_0(4\sqrt{1-(2x)^2})}{I_0(4)} \quad x \in [-\frac{1}{2}, \frac{1}{2}]$	
Welch	$1 - \frac{x^2}{a^2}$	

Table 4.2: Array in Low Side Lobe Array Theory

Type	Polynomial	Plot (six-element array)
Binomial	$(1+x)^{m-1} = 1 + (m-1)x + \frac{(m-1)(m-2)}{2!}x^2 + \dots$	
Chebyshev	$T_m(z) = \cos(m \cdot \cos^{-1}(z))$ where $z \equiv \cos \theta$	

The positive coefficients of the series expansion for different values of m can be adopted to taper the dimension of cells in EBG structures. The Binomial array has wide variations between the coefficients, especially for an array with large number of elements. Thus, Chebyshev array was introduced as a compromise between uniform and binomial array. Its coefficients are related to Chebyshev polynomial that satisfies the recurrence relations expressed as following

$$T_m(z) = z \cdot T_{m-1}(z) - \sqrt{(1 - z^2)\{1 - [T_{m-1}(z)]^2\}} \tag{4.2}$$

$$T_m(z) = 2z \cdot T_{m-1}(z) - T_{m-2}(z) \tag{4.3}$$

where $T_1(z) = 1$. Letting $z \equiv \cos \theta$, $T_m(z)$ is expressed as

$$T_m(z) = \cos(m \cdot \theta) = \cos[m \cdot \cos^{-1}(z)] \tag{4.4}$$

Table 4.2 shows the polynomial and plot of coefficients corresponding to the six-element array of Binomial array and Chebyshev array (with a major-to-minor lobe ratio of 25 dB) correspondingly.

4.2 Tapering Functions and Low Side Lobe Array Theory

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For 1-D planar EBG microstrip structure with a column of m circles etched in the ground plane of a microstrip line, the distribution of the circle dimension follows the following expression:

$$b_i = b_c \cdot T(z_i) \quad (4.5)$$

when tapering functions are applied,

$$b_i = b_c \cdot a_i \quad (4.6)$$

when low side lobe array theory is applied. i is an integer with a range from 1 to $m/2$ in the case that m is an even number and from 1 to $(m+1)/2$ in the case that m is an odd number. b_i is the radius or the area of the i^{th} circle, b_c is the radius (or the area) of the central circle. In (4.5), $T(z)$ is the tapering function, and z_i is the normalized distance between the center of the i^{th} circle and the center point of the structure that can be determined by the following expression:

$$z_i = \frac{2d_i}{L_t} \quad (4.7)$$

where d_i is the distance between the center of the i^{th} circle and the center point of the microstrip line, and L_t is the total length of the EBG microstrip structure. In (4.6), a_i is the i^{th} coefficient in the array. In the case that the number of circles is even, the central circle doesn't exist but it is used to determine the dimension of the circle when employing tapering functions. Whereas when the low side lobe array theory is applied, the two circles at the center are regarded as central circles in the calculation [10].

Figure 4.1: Layout of six-cell 1-D EBG structures

Table 4.3: Values of Tapering Functions and Normalized Coefficients ($2n = 6$)

Type	$T(z_1)$	$T(z_2)$	$T(z_3)$
Bartlett	0.82	0.46	0.09
Blackman	0.87	0.27	0.01
Connes	0.94	0.49	0.03
Cosine	0.96	0.66	0.14
Gaussian	0.98	0.86	0.66
Hamming	0.93	0.48	0.10
Hanning	0.92	0.43	0.02
Welch	0.97	0.70	0.17
Kaiser	0.94	0.58	0.16
Type	a_1	a_2	a_3
Binomial	1	0.50	0.10
Chebyshev	1	0.73	0.39

Table 4.4: The Dimension of the Circle in the Tapered EBG Structures

Type	r_1	r_2	r_3
Bartlett	2.34	1.75	0.78
Blackman	2.41	1.34	0.26
Connes	2.51	1.81	0.45
Cosine	2.54	2.10	0.97
Gaussian	2.56	2.40	2.10
Hamming	2.50	1.79	0.82
Hanning	2.48	1.70	0.37
Welch	2.54	2.16	1.07
Kaiser	2.51	1.97	1.03
Binomial	2.59	1.83	0.82
Chebyshev	2.59	2.21	1.62

4.3 Tapered 1-D Planar EBG Structure

The 1-D planar EBG microstrip structure with six circles etched in the ground plane (Fig. 4.1(a)) is studied. Taconic with a dielectric constant (ϵ_r) of 2.43 and a thickness of 30 mils was used as the substrate material of the structure. The width of the microstrip line w is 2.29 mm corresponding to a characteristics impedance of 50 Ω . The center frequency of the stopband is 10 GHz giving a period of the structure $a=10.35$ mm, according to the Bragg reflection condition. All the tapering techniques aforementioned were separately adopted to taper the area of circles. To calculate the coefficients of the tapering functions, the values of x are set to [0.182, 0.545, 0.909] corresponding to the relative location of the EBG cell to the total length of a uniformly distributed six-cell EBG structure. To determine the coefficients in Binomial and Chebyshev array, the element number is set to six. For Chebyshev array, the major-to-minor lobe ratio is fixed at 25 dB. The normalized coefficients of every tapering type are tabulated in Table 4.3. Amplitude 1 corresponds to the area (πr_3^2) of the two center circles with a radius of

r_3 shown in Fig. 4.1(b). They both have a filling factor (r/a) of 0.25 [7]. The areas of the circles at two ends of the structure are tapered according to coefficients a_2 and a_3 shown in Table 4.3, resulting in smaller radius $r_1 < r_2 < r_3$. The dimension of the circle in the tapered EBG structures are tabulated in Table 4.4.

From the simulation results, it is found that each tapered EBG structure exhibits a stopband centered at 10 GHz although the bandwidth, attenuation within the stopband and ripple level in the passband varies from one to another. As can be observed from the simulation results, some structures show similar transmission characteristics, thus, these distributions are classified together to form two groups. Group One consist of Hanning, Connes, Binomial, Hamming, and Bartlett tapered EBG structure. Their simulated S-parameters are shown in Fig. 4.2. As can be seen from the S_{21} parameter in Fig. 4.2(a), the EBG structures in this group show a 10 dB bandwidth of about 3.9 GHz, an attenuation of 16 dB, a lower passband ripple level of 0.12 dB, and a higher passband ripple level of 2.6 dB. The ripple levels are also indicated by side lobe levels of S_{11} parameters in Fig. 4.2(b). Structures in this group are good in terms of ripple level performance but poor in terms of stopband performance.

Fig. 4.3 depict the simulated data of Group Two; Kaiser; Cosine; and Welch tapered EBG structure. Fig. 4.3 (a) and Fig. 4.3 (b) show the S_{21} and S_{11} parameter, respectively. Group Two has a similar 10 dB bandwidth of 4.1 GHz, with a better attenuation performance of 20 dB. The general performance of structures in this group is superior to those in Group one. The Kaiser tapered EBG structure in Group Two has the best ripple level performance of 0.08 dB in the lower stopband and 2.4 dB in the higher passband. Due to the extremely low ripple level in the passband, the Kaiser tapered EBG structure allows a compromise in the ripple level for an enhancement of the stopband. The performances of the tapered EBG structures in these two groups are tabulated in Table 4.5.

4.3 Tapered 1-D Planar EBG Structure

(a)

(b)

Figure 4.2: Simulated S-parameters of tapered EBG structures in Group One ($\epsilon_r = 2.43$, $h = 30$ miles, $a = 10.35$ mm, $w = 2.29$ mm, and $L_t = 70$ mm)

(a)

(b)

Figure 4.3: Simulated S-parameters of tapered EBG structures in Group Two ($\epsilon_r = 2.43$, $h = 30$ miles, $a = 10.35$ mm, $w = 2.29$ mm, and $L_t = 70$ mm)

Table 4.5: Performances of Tapered 1-D EBG Microstrip Structures

Group	Tapering Techniques	10-dB bandwidth	Attenuation (dB)	Ripple Level (dB)		Side Lobe Level	
				Lower	Higher	Lower	Higher
Group One	Hanning	3.8 ~ 4.0 GHz	15 ~ 17	0.08 ~ 0.16	2.3 ~ 2.9	> 21 dB	> 8 dB
	Connes						
	Binomial						
	Hamming						
	Bartlett						
Group Two	Kaiser	4.0 ~ 4.3 GHz	19 ~ 21	0.21 ~ 0.31	3.0 ~ 3.5	> 15 dB	> 9 dB
	Cosine			(except	(except	(except	(except
	Welch			Kaiser)	Kaiser)	Kaiser)	Kaiser)

Fig. 4.4 shows simulated S-parameters of Blackman, Binomial, Kaiser, Chebyshev, Gaussian tapered EBG structures and a uniformly distributed structure. Binomial is from Group one and Kaiser is from Group two. As shown in the figure, the uniformly distributed EBG structure displays a good 10 dB bandwidth of 5.0 GHz with an attenuation of 34.4 dB. Unfortunately, it exhibits a high ripple level of 2.8 dB in the lower passband, and 6.8 dB in the higher passband. As can be seen, all tapered structures have significantly reduced the ripple level in both passbands. However, this comes at the expense of a reduction in both the bandwidth and attenuation in the stopband. As compared to the uniformly distributed EBG structure, the Gaussian tapered EBG structure achieves a 64.3% and 26.5% reduction in the ripple level in the lower and higher passband, respectively. However, its bandwidth and attenuation is reduced to 4.7 GHz and 30.2 dB, respectively. The Blackman tapered EBG structure is able to obtain a very low ripple level in the passband (0.16 dB in the lower passband and 1.9 dB in the higher passband). However, the bandwidth and attenuation of this structure is greatly reduced to 3.1 GHz and 12.5 dB, respectively.

It is observed that for the performance of tapered EBG structures, the reduction in the passband ripple level is commonly proportional to the reduction in the bandwidth and attenuation of the stopband. Nevertheless, the Chebyshev

(a)

(b)

Figure 4.4: Simulated S-parameters of tapered EBG structures ($\epsilon_r = 2.43$, $h = 30$ miles, $a = 10.35$ mm, $w = 2.29$ mm, and $L_t = 70$ mm)

tapered EBG structure exhibits a 10 dB bandwidth of 4.3 GHz, an attenuation of 24.36 dB, a ripple level of 0.17 dB in the lower passband, and a ripple level of 2.9 dB in the higher passband. This is similar to the performance of the Kaiser tapered EBG structure in the sense that they are both able to obtain low ripple levels while maintaining a relatively wide and deep stopband. Although their stopband performances are not the best, the very low ripple level in the passband enables them to obtain a good trade-off between the ripple level in the passband and the bandwidth and attenuation of the stopband.

Besides the bandwidth and attenuation of the stopband and the passband ripple levels, selectivity is another crucial parameter to evaluate the performance of a filter. It can be approximated by the following equation [10]:

$$\xi = \frac{\alpha_{min} - \alpha_{max}}{f_s - f_p} \left(\frac{dB}{GHz} \right) \quad (4.8)$$

where ξ is selectivity in $\frac{dB}{GHz}$, α_{max} is the 3 dB attenuation point, α_{min} is the 20 dB attenuation point, f_s is 20 dB stopband frequency in GHz, and f_p is the 3 dB cutoff frequency in GHz.

As compared to the Kaiser tapered EBG structure, the Chebyshev structure has slightly higher ripple levels in both passbands, but its selectivity is higher than that shown by the Kaiser tapered EBG structure.

4.4 Measurement Results

The 1-D EBG microstrip structures with six circles etched in the ground plane adopted Kaiser and Chebyshev tapering technique is fabricated and tested. Fig. 4.5 shows the photographs of the ground plane of the fabricated uniformly distributed EBG structure, the Kaiser tapered EBG structure, and the Chebyshev tapered EBG structure. Fig. 4.6 shows the simulated and measured S-parameter

(a) Uniformly distributed EBG structure

(b) Kaiser tapered EBG structure (c) Chebyshev tapered EBG structure

Figure 4.5: Photograph of the ground plane of fabricated EBG microstrip structures ($\epsilon_r = 2.43$, $h = 30$ miles, $a = 10.35$ mm, $w = 2.29$ mm, and $L_t = 70$ mm)

Figure 4.6: Simulated and measured S-parameters of the Kaiser tapered EBG structure and the uniformly distributed EBG structure

of the fabricated Kaiser tapered EBG structure as well as those of the uniformly distributed EBG structure. Fig. 4.7 shows the simulated and measured data of the fabricated Chebyshev tapered EBG structure and that of the uniformly distributed structure as comparison. The measurement results are in good agreement with the simulation results. As can be seen in Fig. 4.6 (a) and Fig. 4.7 (a), the ripples in the stopbands of the measured S_{21} parameters are clearly observed while they are difficult to identified in the plots of S_{11} parameters in Fig. 4.6 (b) and Fig. 4.7 (b). The high ripple levels in the measurement results are possibly due to the non-ideal calibration in the measurement. As shown in Fig. 4.6 (b) and Fig. 4.7 (b), the difference in the passband between the measurement results and the simulation results is probably caused by the radiation loss, the dielectric loss, and the loss introduced by the SMA connectors and the soldering between the device and the connectors. The smoothness in the stopband of the measured S_{11} parameters is due to the small variation of the S_{11} parameter in the stopband.

As shown in Fig. 4.6 and Fig. 4.7, the fabricated uniformly distributed EBG structure shows a 10 dB bandwidth of 4.75 GHz, attenuation of 46.11 dB, a ripple level of 3.83 dB in the lower passband, and a ripple level of 6.63 dB in the higher passband. The fabricated Kaiser tapered EBG structure (Fig. 4.6) exhibits a bandwidth of 3.71 GHz, attenuation of 23.78 dB, a ripple level of 0.40 dB in the lower passband, and a ripple level of 5.76 dB in the higher passband. The ripple level of the Kaiser tapered EBG structure is significantly reduced by 89.56% and 13.12% of that shown by the uniformly distributed structure in the lower and higher passband, respectively yet its bandwidth and attenuation are maintained to be 78.10% and 51.57% of those in the uniformly distributed EBG structure, respectively.

In Fig. 4.7, the fabricated Chebyshev tapered EBG structure shows a 10 dB bandwidth of 3.92 GHz, attenuation of 31.95 dB, a ripple level of 1.25 dB in the

4.4 Measurement Results

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(a)

(b)

Figure 4.7: Simulated and measured S-parameters of the Chebyshev tapered EBG structure and the uniformly distributed EBG structure

Table 4.6: Measured Performances of Tapered EBG Microstrip Structures

EBG Structure	10 dB bandwidth	Attenuation	Ripple Level	
			(lower)	(higher)
Uniform	4.75 GHz	46.11 dB	3.83 dB	6.63 dB
Kaiser	3.71 GHz	23.78 dB	0.40 dB	5.76 dB
Chebyshev	3.92 GHz	31.95 dB	1.25 dB	5.28 dB

lower passband, and a ripple level of 5.28 dB in the higher passband. This tapered structure achieves a 67.36% reduction in the ripple level in the lower passband and a 20.36% reduction in the ripple level in the higher passband. The bandwidth and attenuation of the Chebyshev tapered EBG structure are 82.53% and 69.29% of those in the uniformly distributed EBG structure, respectively.

Table 4.6 shows the performances of the fabricated uniformly distributed and tapered EBG structures. As can be seen in the table, the Chebyshev tapered EBG structure has a better selectivity and stopband attenuation than that shown by the Kaiser tapered EBG structure. However, its ripple level in the lower passband is inferior. Nevertheless, the ripples in the Chebyshev tapered EBG structure are significantly eliminated as compared to that of the uniformly distributed EBG structure. Due to its good selectivity and its popularity in EBG filter designs, Chebyshev tapering technique (Chebyshev distribution) will be employed in the development of EBG structures in the later study.

The measurement results verify the promising ability of Kaiser and Chebyshev tapering technique to lower the passband ripple level while maintaining a relatively good stopband performance.

4.5 Summary

A comprehensive study on tapering techniques widely adopted to EBG structure designs is presented in this chapter. It demonstrates the tapering techniques based on tapering functions and low side lobe theory by showing their associated analytical expressions and plots. Their effects on the performance of a typical six-cell 1-D planar EBG filter structure are illustrated, analyzed, and compared.

From the characteristics of wave propagation of different tapered EBG structures, several important findings are obtained and listed as followed:

- The compromise between ripple level performance in the passband and the stopband performance is clearly identified.
- In all techniques, Kaiser and Chebyshev distribution are able to achieve significant reduction in ripple level in the passband while maintaining a relatively wide stopband with high attenuation. They can be applied together with other optimization techniques to further improve the performance of EBG filter designs.

This systematic study of the effects of tapering techniques can benefit, in general, the design and optimization of 1-D planar EBG structures for microwave applications. Chebyshev distribution will be applied to the designs of EBG structures in the later research stage for the optimization of structure performance.

Chapter 5

Dual-Plane 1-D EBG Microstrip Filter Structure

5.1 Introduction

1-D planar EBG microstrip structures are widely used to control the wave propagation in microstrip circuits. In the EBG structure of this category, a microstrip line with one single column of EBG cells etched in the ground plane exactly below the line exhibits a prominent band-gap in the direction along the conducting line. Due to the unique wide stopband with high attenuation, they are employed as high performance reflectors and filters [8]. The 1-D EBG microstrip filters show advantages of large rejection bandwidth, high attenuation, low insertion loss in the passband, compact in size, and compatibility with monolithic microwave integrated circuits (MMICs).

A band-gap can be controlled in the microstrip line when the geometry of the etched EBG cell is changed or when the periodic elements are introduced in the microstrip line [139] [142]. Defected ground structure (DGS) has the defect in the ground plane of a microstrip line with a dumbbell-shape geometry [125]. They

are also able to prohibit the propagation of waves in certain frequency bands. Even with a single unit, they are able to exhibit an attenuation pole in the frequency response.

In a traditional EBG structure with EBG cells in one plane (ground plane or microstrip line), conventionally, the desirable large rejection bandwidth and high attenuation can be obtained by increasing either the dimension or the number of EBG cells, which increases the physical size in the transversal and longitudinal dimensions, respectively.

Several approaches have been taken to enhance the stopband performance of 1-D planar microstrip EBG Bragg reflectors while maintaining a reasonable ripple level in the passband and keeping a small physical size. For example, in order to design a high performance bandstop filter that exhibits a wide stopband with high attenuation in a relatively small physical area, a meandering 1-D EBG microstrip line is proposed [113]. In [129], a compact EBG bandstop filter structure with a wide stopband was proposed by combining a 1-D periodic DGS and a modulated microstrip line. This structure is able to increase the bandwidth of the stopband while maintaining a small ripple level in the passband.

In this study, a dual-plane 1-D EBG microstrip structure is designed, implemented, and developed for the applications for microstrip bandstop filters. The first proposed structure named dual-plane compact EBG (DPC-EBG) structure exhibits wide stopband with high attenuation and small ripple levels in both passbands within six EBG cells. As compare to other EBG microstrip structures, this structure shows advantages of large bandwidth and high attenuation of the stopband, small insertion loss in each passband, compact physical size, and ease of fabrication. The DPC-EBG structure is further developed to be the three-cell small-size EBG (S-EBG) structure which is able to achieve significant reduction in physical size while having good filtering functionality.

Figure 5.1: Layout of a five-cell single-plane EBG structure with a modulated microstrip line

This chapter is to present the design, implementation, and applications of the two proposed dual-plane 1-D EBG microstrip structures. In the next section, the first proposed DPC-EBG bandstop filter design is presented followed by the S-EBG structure.

5.2 Single-Plane (SP) EBG Microstrip Structure

A typical single-plane (SP) EBG microstrip structure with circles etched in the ground plane was shown in Fig. 3.1 (five-cell) and Fig. 4.1(a) (six-cell). Its properties were studied and presented in Chapter 3 and 4.

Fig. 5.1 shows the layout of another single-plane 1-D EBG microstrip structure. It is a modulated microstrip line with rectangular patches periodically inserted in it. The structure satisfies the Bragg reflection condition and therefore, the period of the structure a can be determined by equation (3.4). Fig. 5.2 shows the simulated S-parameters of the SP-EBG structure with inserted patches (SP-five-patch) and the SP-EBG structure with six etched circles (SP-six-circle) when Taconic ($\epsilon_r = 2.43$, $h = 30$ mils) is used as the substrate material and the center frequency of the stopband, f_0 , is set to be 10 GHz. As can be seen in Fig. 5.2(a), the EBG structure with a modulated microstrip line (SP-five-patch) exhibits a stopband similar to that of the EBG structure with circles etched in the ground

Figure 5.2: Simulated S-parameters of the single-plane EBG structures in Fig. 4.1(a) and Fig. 5.1($a = 10.35$ mm, $w = 2.29$ mm, $r/a = 0.25$, $r = 2.59$ mm, $l_a = w_a = 5.18$ mm)

5.3 Dual-Plane Compact EBG (DPC-EBG) Microstrip Structure 95

plane (SP-six-circle) discussed in the previous chapter. Although this EBG structure with a modulated microstrip line shows a prominent stopband in the frequency response, it is different from a conventional stepped impedance microstrip lowpass filter structure [152] in terms of working principle and design.

The length and width of the patch is represented by l_a and w_a , respectively. The width of the microstrip line is w . In this EBG structure, the variation range of w_a is expressed as below:

$$w_a > w \quad (5.1)$$

With a width that is larger than the width of the microstrip line, the EBG unit increases the coupling between the microstrip line and the ground plane, and accordingly increases the capacitance.

5.3 Dual-Plane Compact EBG (DPC-EBG) Microstrip Structure

5.3.1 Design

Fig. 5.3(a) and Fig. 5.3 (b) show the 3-D view and the top view of the proposed DPC-EBG structure, respectively. As can be seen in Fig. 5.3(a), the proposed structure consists of two single-plane EBG structures introduced previously. The modulated microstrip line is on the top side and a perturbed ground plane is at the bottom side of a dielectric material with a relative permittivity of ϵ_r and a thickness of h .

As shown in Fig. 5.3(b), the etched circles in the ground plane are indicated by the dashed line. The period of this structure is a_1 and the radius of the circle is r . The modulated microstrip line on the top is outlined by the thick solid line in the same figure and has a period of a_2 . In this proposed structure, the center

(a) 3-D view

(b) top view

Figure 5.3: 3-D layout (a) and layout (b) of the six-cell dual-plane compact EBG DPC-EBG structure with uniform distribution

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frequency of the EBG structure on each plane is identical. According to equation (3.4), a_1 equals a_2 . As can be seen from the layout, by superposing these two single-plane EBG structures, the inserted rectangular patch increases the coupling between the microstrip line and the ground plane thus equivalently increasing the capacitance seen from the microstrip line whereas the etched circle in the ground plane increases the equivalent inductance of the microstrip line [148]. Therefore, the DPC-EBG structure enhances reactances in the longitudinal direction resulting in an enhancement of the stopband performance. In the DPC-EBG structure, the relative location between the single-plane EBG structures and the dimension of EBG cells are two key factors in the enhancement of the stopband performance.

Due to the special dual-plane configuration, the relative location of the EBG structure on each plane (d' and d) has significant effects on the performance of the proposed structure. The transversal alignment offset d' and the longitudinal offset d are as illustrated in Fig. 5.3(b). When d' equals 0, the column of circles is etched exactly below the modulated transmission line where the wave propagation is perturbed to the biggest extent due to the high confinement of electromagnetic fields under the microstrip line. As shown in the figure, d is defined as the short distance between the centers of the adjacent etched circle and rectangular patch in the longitudinal direction. It ranges from 0 to $a_1/2$ (or $a_2/2$), and periodically repeats anywhere else.

When $d = 0$, the etched circle in the ground plane overlap the inserted patch in the microstrip line, which causes a cancelation between the additional inductance and capacitance. The cancelation decreases as d increases. When $d = a_1/2$ (or $a_2/2$), the cancelation has a minimum value. By setting d to be $a_1/2$ (or $a_2/2$) and appropriately setting dimensions of EBG units, the variation of reactance can be greatly enhanced and good stopband performance for the structure is possible to obtain.

In this design, when $d = a_1/2$ (or $a_2/2$), the length of the rectangular patch l_a is determined by the following expression,

$$l_a \leq a - 2r \quad (5.2)$$

to avoid any overlap between the etched circle and the inserted patch. w_a equals l_a if condition in (5.1) can be satisfied.

5.3.2 Numerical Simulation

The proposed DPC-EBG structure shown in Fig. 5.3 was simulated. It consists of a microstrip line with five inserted square patches and the ground plane with six etched circles. The substrate used is Taconic with a dielectric constant (ϵ_r) of 2.43 and a thickness (h) of 30 mils. The width of the microstrip line is set to 2.29 mm, corresponding to a characteristics impedance of 50Ω at 10 GHz. To operate in the X-band range, the center frequency of each single-plane EBG structure is set to be 10 GHz. Therefore, the period of the EBG structure a_1 and a_2 are both 10.35 mm, according to the Bragg condition. In order to obtain good performance from the structure, the transversal alignment offset d' and the longitudinal offset d is set to be 0 mm and 5.18 mm, respectively. The filling factor (r/a) is set to be 0.25 to optimize the filter design [7]. By setting r/a to be 0.25, the radius of the circle is determined to be 2.59 mm. The length of the inserted rectangular patch in the microstrip line l_a is fixed to be 5 mm to avoid any overlap between the circle in the ground plane and the rectangular patch in the microstrip line so as to enhance the stopband. The width of the inserted patch w_a is set to be 5 mm.

For comparison, the single-plane EBG structure on each plane of the DPC-EBG structure is simulated separately; the modulated microstrip line on a unperturbed ground plane (SP-five-patch) shown in Fig. 5.1; and the microstrip line

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Figure 5.4: Simulated S-parameters of the DPC-EBG structure and two single-plane EBG structures

with six circles etched in the ground plane (SP-six-circle) shown in Fig. 4.1(a). Fig. 5.4(a) shows the S_{21} parameter and Fig. 5.4(b) shows the S_{11} parameter of all three structures. As we can see from Fig. 5.4(a), SP-five-patch EBG structure has a 10 dB bandwidth of 3.27 GHz with an attenuation of 20.17 dB, a ripple level of 1.60 dB in the lower passband, and a ripple level of 2.55 dB in the higher passband. The bandwidth performance of this structure is poor, however, its ripple level performance is very promising. The 10 dB bandwidth and attenuation of SP-six-circle EBG structure are 4.98 GHz and 34.24 dB, respectively, while its ripple level in the lower passband is 2.77 dB and that in the higher passband is 6.55 dB. This structure although performs well in terms of bandwidth, it is inferior in terms of ripple level. An ultra-wide stopband with high attenuation can clearly be observed in the performance of the proposed DPC-EBG structure when the two single-plane EBG structures are superposed in a compact dual-plane configuration (as shown in Fig. 5.3). The DPC-EBG structure shows a 10 dB bandwidth of 7.91 GHz with an attenuation of 50.72 dB that are much larger than those shown by the two single-plane EBG structures. With only six EBG cells, this proposed structure is able to achieve a 25 dB bandwidth of 7.00 GHz with a center frequency of 10 GHz. This is extremely difficult to realize by using any single-plane EBG structure with EBG cells of identical dimensions (Fig. 5.1, Fig. 4.1(a)). Although the DPC-EBG structure exhibits good stopband performance, it suffers from high ripple levels. In this structure, the ripple level increases to 3.97 dB in the lower passband and 6.82 dB in the higher passband. They are represented by the side lobe levels of the S_{11} parameter in Fig. 5.4(b). As can be seen, the DPC-EBG structure has higher side lobe levels in both the lower and higher passband as compared to those in the other two single-plane EBG structures.

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Figure 5.5: Layout of the tapered DPC-EBG structure with Chebyshev distribution

5.3.3 Analysis

Like many other conventional methods to enhance a stopband in an EBG structure, the proposed DPC-EBG structure introduces an increase in the bandwidth with high attenuation within the stopband at the expense of a high ripple level in the passband. Since the bandwidth and attenuation performance of the proposed structure are greatly enhanced, it allows a compromise in the stopband for a reduction in ripple level. As an effective mean to optimize the performance of an EBG structure in terms of its transmission in the passband, tapering techniques, which are discussed in Chapter 4, are applied here in order to tailor the high ripple level in the proposed DPC-EBG structure. The optimization of the proposed structure by employing tapering techniques is presented in the following section.

5.3.4 Tapered DPC-EBG Microstrip Structure

To eliminate the ripple in the passband due to the EBG periodicity in the DPC-EBG structure proposed in the last section (Fig.5.3), the Chebyshev distribution is adopted to taper the dimension of the etched circles at the two ends of the structure. Fig. 5.5 shows the layout of the tapered DPC-EBG structure. The coefficients of the six-element Chebyshev array obtained previously (Table 4.3) were used in the design. Amplitude 1 corresponds to the area of the two center

Figure 5.6: Simulated S-parameters of the tapered and uniform DPC-EBG structure

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circles with a filling factor (r/a) of 0.25. Accordingly, the radius of the circle from the left to the right is 1.61 mm, 2.21 mm, 2.59 mm, 2.59 mm, 2.21 mm, and 1.61 mm, respectively.

Fig. 5.6 shows the simulated S-parameters for the tapered DPC-EBG structure (Fig. 5.5) and the proposed uniform DPC-EBG structure (Fig. 5.3). As can be seen from Fig. 5.6(a), the tapered DPC-EBG structure has a 25 dB bandwidth of 6.05 GHz with an attenuation of 67.71 dB. This is a reduction of about 14% of bandwidth at 25 dB. However, its ripple level is significantly improved from 3.97 dB to 0.92 dB in the lower passband and from 6.82 dB to 3.42 dB in the higher passband. The stopband performance is slightly degraded by the adopted tapering technique; nevertheless, it is still much better than those shown by the single-plane EBG structures mentioned previously. On the other hand, in the tapered structure, the ripple level is significantly lowered, which implies an excellent transmission in the passband. The low ripple level of the tapered DPC-EBG structure is obviously indicated by the low side lobe level of the S_{11} parameter shown in Fig. 5.6(b).

5.3.5 Experimental Results

The proposed tapered five-patch-six-circle DPC-EBG microstrip structure with a 70-mm-long transmission line is fabricated and tested. Fig. 5.7 (a) and Fig. 5.7 (b) show the photograph of the microstrip line (top view) and the ground plane (bottom view) of the fabricated structure, respectively. Fig. 5.8 shows the simulated and measured S-parameters of the fabricated tapered DPC-EBG structure. As can be seen from the measurement results, the proposed structure is able to achieve a 25 dB bandwidth of 5.98 GHz at 10 GHz, with an attenuation of 39.00 dB, a ripple level of 1.56 dB in the lower passband, and a ripple level of 4.68 dB in the higher passband. An excellent agreement between the measurements and the simulation results has been obtained. The slight difference is probably due to

(a) Microstrip line (top view)

(b) Ground plane (bottom view)

Figure 5.7: Photographs of the fabricated tapered DPC-EBG microstrip structure ($\epsilon_r = 2.43$, $h = 30$ mils)

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Figure 5.8: Simulated and measured S-parameters of the fabricated tapered DPC-EBG structure

the effect of SMA connectors, the lack of material uniformity and cell uniformity, and the over etching.

The tapered DPC-EBG microstrip structure demonstrates the advantages of ultra-wide bandwidth, high attenuation, smooth passband, compact size, and ease of fabrication process. This proposed structure can be easily applied to circuit applications requiring broadband filtering functionality.

5.4 Five-cell Dual-plane Compact EBG Microstrip Structure

A five-cell tapered dual-plane compact EBG structure was fabricated and tested. Taconic ($\epsilon_r = 2.43$, $h = 30$ mils) was used and the center frequency of the stopband was set to be 10 GHz. The dimension of the etched circles in the ground plane was tapered by applying a five-element Chebyshev array. Fig. 5.9 shows the photographs of the fabricated structure and Table 5.1 shows the parameter set. Fig. 5.10 shows its simulated and measured S-parameters. The physical size of the five-cell DPC-EBG structure is smaller than that of the six-cell structure presented in the previous section due to the decrease of the number of EBG cells. The performance of the five-cell structure is inferior in terms of passband and stopband characteristics which is a trade-off of the reduction in the circuit area. As less cells are used in this structure, the corresponding ripple level in both the higher passband and the lower passband are reduced relative to the six-cell structure.

(a) Microstrip line

(b) Ground plane

Figure 5.9: Photographs of the fabricated tapered five-cell DPC-EBG microstrip structure

Table 5.1: The Parameters of the Five-cell DPC-EBG Microstrip Structure

Parameter	Dimension (mm)	Parameter	Dimension (mm)
a_1, a_2	10.35	r_1	1.62
w	2.29	r_2	2.31
l_a, w_a	5.18	r_3	2.59

(a)

(b)

Figure 5.10: Simulated and measured S-parameters of the fabricated tapered five-cell DPC-EBG microstrip structure

5.5 Three-Cell Small-Size EBG (S-EBG) Structure

The proposed dual-plane compact EBG (DPC-EBG) structure exhibits a wide stopband, high attenuation, and excellent transmission in the passband with six EBG cells. It is compact as compared to conventional single-plane 1-D EBG microstrip structures with the similar filtering functionalities.

Base on the design of this six-cell DPC-EBG structure, a three-cell dual-plane small-size EBG (S-EBG) microstrip structure [18] was proposed which has smaller physical size than that of the six-cell DPC-EBG structure yet maintaining similar performance. The design the S-EBG structure will be presented, followed by its implementation.

5.5.1 Small-Size EBG Filter Design

The layouts of the proposed dual-plane S-EBG structure are shown in Fig. 5.11. As shown in the 3-D layout in Fig. 5.11(a), at the top it is a three-cell 1-D EBG microstrip structure with rectangular patches inserted in the microstrip line, which is shown in Fig. 5.12 (a), while at the bottom it is another three-cell 1-D EBG structure shown in Fig. 5.12(b), where circles are etched in the ground plane. The dielectric material is between the transmission line and the ground plane with a dielectric constant of ϵ_r and a thickness of h .

Fig. 5.11(b) shows the dimension of the EBG cells in the microstrip line and the ground plane. a_1 is the period of the circles etched in the ground plane whereas a_2 is the period of the rectangular patches in the microstrip line. Similar to the parameter settings in the previously proposed six-cell DPC-EBG structure, the center frequencies of the two single-plane EBG structures are identical and therefore $a_1 = a_2$. d' is set to be 0 and d is set to be $a_1/2$ (or $a_2/2$) for good

(a) 3-D view

(b) Top view

Figure 5.11: Layout of the dual-plane small-size EBG (S-EBG) structure

(a) EBG microstrip structure with a modulated microstrip line

(b) EBG microstrip structure with three circles etched in the ground plane

Figure 5.12: Layout of the single-plane EBG microstrip structure

performance of the structure. The radius of the circle r_1 , r_2 , and r_3 are determined by the filling factor r/a . The width and length of the inserted patch w_a and l_a are decided using condition in (5.1) and (5.2), respectively.

Different from the design of the former DPC-EBG structure, the width of the microstrip line above the etched circles is reduced in order to further enhance contrast of reactance along the microstrip line. It results in $w > w_1$ and $w > w_2$. The enhancement of the stopband performance is expected.

To eliminate the ripple due to the EBG periodicity in the proposed S-EBG structure, Chebyshev distribution from the low side lobe array theory [12] was

adopted to taper the dimension of EBG cells in the ground plane. In this case, a three-element array with a major-to-minor lobe ratio of 25 dB was used for the three circles in the proposed structure. The normalized coefficients are determined to be 0.73, 1 and 0.73, where 1 corresponds to the area of the central circle. The reduction in width ($w-w_1$) and ($w-w_2$) of the modulated microstrip line was also tapered proportionally according to the Chebyshev distribution.

Taconic with a dielectric constant (ϵ_r) of 2.43 and a thickness (h) of 30 mils is used as the substrate of the structure. To operate in the X-band range, the center frequency of each single-plane EBG structure is set to be 10 GHz. Therefore, a_1 and a_2 are both 10.4 mm according to the Bragg reflection condition [153]. Correspondingly, d is determined to be 5.2 mm. The width of the microstrip line w is set to be 2.3 mm, corresponding to a characteristics impedance of 50 Ω at 10 GHz. r/a of the central circle is set to be 0.25 and the radius of the circle from left to right is determined to be 2.2 mm, 2.6 mm, and 2.2 mm, respectively. The length and width of the inserted rectangular patch in the microstrip line l_a and w_a were both fixed to 5 mm, satisfying conditions in (5.1) and (5.2). w_1 is set to be 0.3 mm and w_2 is determined to be 0.8 mm.

Fig. 5.13 shows the simulated S-parameters of the proposed dual-plane S-EBG structure and those of the two single-plane EBG structures; the modulated microstrip line on a perfect ground plane (Modulated MLIN) shown in Fig. 5.12(a) and the uniform microstrip line with three tapered circles etched in the defected ground plane (Perturbed GND) shown in Fig. 5.12(b). As we can see from Fig. 5.13(a), the perturbed GND EBG structure shows a shallow stopband, but its ripple level in the passband is very good (low side lobe level in Fig. 5.13(b)). As compared to the perturbed GND structure, the modulated microstrip line EBG structure performs much better in terms of bandwidth and attenuation in the stopband. However, its ripple level is higher than that of the perturbed GND

(a) S_{21}

(b) S_{11}

Figure 5.13: Simulated S -parameters of the dual-plane (S-EBG) structure and the two single-plane EBG structures

(a) S_{21}

(b) S_{11}

Figure 5.14: Simulated S -parameters of the tapered DPC-EBG structure and the S-EBG structure

structure. An ultra-wide stopband with high attenuation can clearly be observed in the performance of the proposed S-EBG structure when the two single-plane EBG structures are superposed in a compact dual-plane configuration. The S-EBG structure shows a 10 dB bandwidth of 10.1 GHz with attenuation of 36.2 dB. The ripple level is 0.5 dB in the lower passband and is 3.7 dB in the higher passband. The stopband performance of the proposed S-EBG structure is much better than those shown by the two single-plane EBG structures. Its filtering functionality is similar to that of the proposed structure in [129] yet is much smaller in terms of longitudinal and transversal physical size. With only three EBG cells, this proposed structure is able to obtain a 25 dB bandwidth of 7.4 GHz with low ripple levels. This is extremely difficult to realize using any single-plane EBG structure.

Fig. 5.14 compares the simulated S-parameters of the novel three-cell S-EBG structure and those of the six-cell DPC-EBG structure presented in the previous section. As can be seen in Fig. 5.14, within a much smaller circuit area, the S-EBG structure shows a stopband with a bigger bandwidth and a smaller ripple level in the lower passband as compared to those of the DPC-EBG structure. However, it is inferior in terms of attenuation in the stopband and the selectivity due to the large reduction in the number of EBG cells. As can be observed in Fig. 5.14, the attenuation of the stopband in the S-EBG structure can be maintained below 20 dB in the frequency range from 5.4 GHz to 13.9 GHz, which is attributed to the reduction in the width of the microstrip line above the etched circles in the ground plane. The proposed S-EBG structure is a successful exploration for compact high performance EBG microstrip filter design.

5.5.2 Measured Results

The proposed dual-plane three-cell S-EBG structure with a 44-mm-long transmission line was fabricated (Taconic with $\epsilon_r = 2.43$ and $h = 30$ mils) and tested.

(a) Microstrip line (top view)

(b) Ground plane (bottom view)

Figure 5.15: Photographs of the fabricated dual-plane S-EBG structure ($\epsilon_r = 2.43$, $h = 30$ mils)

Figure 5.16: Simulated and measured S-parameters of the fabricated dual-plane small-size EBG (S-EBG) structure

Fig. 5.15 shows the fabricated structure and Fig. 5.16 shows the simulated and measured S-parameters of this structure. As can be seen from the measurement results, the proposed structure is able to achieve a 25 dB bandwidth of 6.3 GHz with a center frequency of about 10 GHz, attenuation of 36.1 dB, a ripple level of 0.8 dB in the lower passband, and a ripple level of 6.4 dB in the higher passband. An excellent agreement between the measurement and the simulation results is obtained. The slight difference is possibly due to the lack of cell uniformity, the lack of material uniformity, over etching, and the calibration of vector network analyzer (VNA).

This proposed S-EBG structure demonstrates the advantages of ultra-wide bandwidth, high attenuation, smooth passband, compact size, and easy fabrication process. It can be easily applied to circuit applications requiring broadband filtering functionality.

Table 5.2: Performances & Physical Size of Dual-plane EBG Microstrip Structures

EBG Structure	25 dB bandwidth	Selectivity ($\frac{dB}{GHz}$)	Attenuation (dB)	Ripple Level		Physical size
				(lower)	(higher)	
Tapered six-cell DPC-EBG	5.98 GHz	27.98	39.00	1.56 dB	4.68 dB	$70 \times 21 \text{ mm}^2$
S-EBG	6.30 GHz	14.73	36.10	0.80 dB	6.40 dB	$48 \times 21 \text{ mm}^2$

Table 5.2 shows the performance and physical size of the fabricated three-cell S-EBG structure and the six-cell DPC-EBG structure. Comparing to the six-cell DPC-EBG structure, as can be seen in the table, the S-EBG structure achieves a 5.35% increase in the 25 dB bandwidth of the stopband, a 48.72% reduction in the ripple level of the lower passband, and a 31.43% reduction in the circuit area at the same time. As the trade-off of reduction in the number of EBG cells, its selectivity, its stopband attenuation, and its ripple level in the higher passband become inferior.

5.6 Summary

In this chapter, the design, implementation, and application of novel dual-plane 1-D EBG microstrip filter structures are presented.

Generally, a dual-plane EBG microstrip structure proposed in this study consists of two single-plane EBG structures arranged in a compact dual-plane configuration. One EBG structure is in the ground plane and the other is in the microstrip line. With the dual-plane arrangement, the variation of electromagnetic field along the microstrip line is greatly enhance resulting in a significant improvement of stopband performance in terms of bandwidth, attenuation, and steepness of the transition. Therefore, this unique configuration makes it possible for microstrip EBG structures to achieve good control of wave propagation within

a compact physical size.

A six-cell dual-plane compact EBG (DPC-EBG) structure is proposed providing deep and wide band-gap in the direction of wave propagation. Its ripples caused by the periodicity in the dual-plane structure are well eliminated by adopting Chebyshev distribution.

A three-cell dual-plane small-size EBG (S-EBG) structure with a large reduction in circuit area is also proposed. By modifying the microstrip line, the proposed S-EBG structure is able to obtain a significant reduction in the physical size while maintaining good filtering functionality.

The proposed dual-plane 1-D EBG microstrip filter structures show high performance in terms of the bandwidth and attenuation of the stopband and the transmission in the passband within a compact circuit area. Together with their easy fabrication and the compatibility with MMIC technology, they are promising circuit components to be used in applications for microwave circuits.

Chapter 6

Dual Planar EBG Structure with Special Microstrip Line Geometry

6.1 Introduction

In the preceding chapter, a dual-plane EBG configuration has been presented. The proposed dual-plane (dual planar) EBG microstrip structures shows excellent passband and stopband characteristics in a relatively small circuit area. However, its performance is degraded in terms of the selectivity and the attenuation in the stopband when the number of EBG cells is reduced for a smaller physical size.

In order to retain the compactness of EBG structures of this category while obtaining good filtering functionality, dual-plane 1-D EBG microstrip filter structures with a U-shape and a meander microstrip line geometry are proposed.

In this chapter, the design and implementation of two high performance compact EBG microstrip filter structures with a U-shaped microstrip line geometry and one with a meander geometry are presented.

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Figure 6.1: Layout of (a) a straight 1-D EBG microstrip structure, (b) a U-shaped microstrip line, and (c) a U-shaped EBG microstrip structure

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry

6.2.1 U-shaped 1-D EBG microstrip structure

The structure

Fig. 6.1(a) shows the layout a straight 1-D EBG structure with four square patches of area e^2 inserted with a period of a and Fig. 6.1(b) shows that of a U-shaped

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry 123

microstrip line where the distance between the two parallel sections is also a . Fig. 6.1(c) shows the layout of the U-shaped 1-D EBG microstrip structure used in the proposed high performance compact U-shaped dual planar EBG microstrip lowpass filter design. It is a combination of the structures in Fig. 6.1(a) and Fig. 6.1(b) with the 90° bending taking place at the center point of the second and third patch from left to right, resulting in the U-shape microstrip line geometry. The three structures are all single planar (SP).

The straight 1-D EBG structure in Fig. 6.1(a) satisfies the Bragg reflection condition which is expressed by equation (3.1). Therefore, its center frequency of the stopband is decided by

$$f_0 = \frac{c}{2a \cdot \sqrt{\epsilon_{eff}}} \quad (6.1)$$

It should be noted that the design proposed here is not a conventional filter design [152] since it is designed to satisfy the Bragg reflection condition. The edge of the inserted square patch ($l_a = w_a = e$) equals half of the period ($e = a/2$) which is equivalent to an optimal filling factor of 0.25 [7]. Comparing the geometry of the straight 1-D EBG microstrip structure to that of the proposed U-shaped microstrip line geometry, the later structure achieves enhancement of circuit compactness and possibly additional flexibility in circuit layout designs

For the U-shaped conventional microstrip line shown in Fig. 6.1(b), its geometry is essential to the performance of the proposed U-shaped EBG structure because of the existence of resonators which cause resonance in the transmission. The resonator in a microstrip line with multiple bends (≥ 2) is originated by reflections between two consecutive or nearby bends. Its resonant frequency is determined by its physical length. Base on a study on meander microstrip line

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[114], the length of the resonator can be approximated using (6.2):

$$L = n \frac{\lambda_g}{2} \quad (6.2)$$

where L is the physical length of the resonator in the microstrip line; n is an integer; and λ_g is guided wavelength corresponding to the resonant frequency f_r . λ_g is expressed as following:

$$\lambda_g = \frac{c}{f_r \cdot \sqrt{\epsilon_{eff}}} \quad (6.3)$$

where c is the speed of light in the free space and ϵ_{eff} is the effective dielectric constant. Hence,

$$L = n \frac{c}{2f_r \sqrt{\epsilon_{eff}}} \quad (6.4)$$

As can be seen in Fig. 6.1(b), the U-shaped conventional microstrip line contains two bends. Therefore, it has only one resonator with a length of a as shown by the shadowed area. According to (6.4), with n set to 1, its resonant frequency is the same as the center frequency of the stopband in the straight 1-D EBG structure (Fig. 6.1(a)) as approximated by equation (6.1). As compared to a meander microstrip structure in [114], a U-shaped microstrip line has less bends and thus fewer resonators. The length of the resonator is as short as one EBG period.

Numerical results of the U-shaped microstrip line

The transmission characteristics of an EBG microstrip structure with multiple bends is determined by the response the two individual structures; the corresponding straight EBG structure and the microstrip line with multiple bends. In order to study the proposed U-shaped 1-D EBG microstrip structure, the three structures in Fig. 6.1 are simulated. Taconic, with a dielectric constant (ϵ_r) of 2.43 and a thickness (h) of 30 mils, is used as the substrate. The center frequency f_0 is set

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry 125

(a) S_{21}

(b) S_{11}

Figure 6.2: Simulated S -parameters of structures in Fig. 6.1

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to 10 GHz resulting in a period of the structure (a) of 10.35 mm. The edge of the square patch (e) is set to be 5 mm which equals half of the period. The width of the microstrip line is 2.29 mm corresponding to a characteristic impedance of 50 Ω at 10 GHz. Fig. 6.2(a) and (b) show their simulated S_{21} and S_{11} parameter, respectively.

As can be seen in Fig. 6.2(a), the U-shaped microstrip line shows slight attenuation in the high frequency range of 6GHz and above. The small resonance in the transmission is due to the resonator where reflections take place in the bends at its two ends. With a physical length of 10.35 mm, the resonator causes slight resonance centered at about 10 GHz, which is the same as that predicted using equation (6.4). The straight EBG structure shows a prominent stopband in the frequency response. The U-shaped 1-D EBG microstrip structure (a combination of the above two mentioned structures) obtains a wider stopband with higher attenuation and an increase in selectivity yet with no compromise on the ripple level.

The results reveal that the U-shape microstrip line geometry is able to enhance the filtering functionality of the EBG structure. The enhancement is obtained without producing any unwanted ripple. This is mainly because of the absence of resonator with a length that is longer than the period of the EBG structure which avoids additional resonance at frequencies lower than the center frequency of the stopband. In an EBG structure with bends, the difference of the phase delay between a bent unitary period (shadowed area in Fig. 6.1(c)) and a straight one (meshed area in Fig. 6.1(c)) causes ripples in the passband [114]. As reported in [114], for the EBG microstrip structure with circular patches etched in the ground plane below a bent, the bent section introduces a phase delay, thus causing an increase in ripple level in the passband. Therefore, a study on the bent section as shown in Fig. 6.1(c) is performed. As indicated in Fig. 6.3, by inserting

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry 127

Figure 6.3: Simulated phase delay in the output wave with respect to the input wave in a bent unitary period and in a straight unitary period

square patched at the bent of the EBG structure (shadowed area in Fig. 6.1(c)), the phase delay over the entire frequency range from DC to 6.76GHz introduced by the bent is negligible as compared to a straight section (meshed area in Fig. 6.1(c)). Since the square patch inserted at the bent corrects the phase delay introduced by the bent with no square patch inserted, the U-shaped 1-D EBG microstrip structure introduced in Fig. 6.1(c) is able to perform better in terms of a wider stopband but yet not introduces higher ripple level.

In a microstrip structure with bends, there are additional power losses that are due to the radiation and scattering that take place in the bend. These can be estimated as a percentage using

$$\text{Radiation} + \text{Scattering} = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (6.5)$$

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Figure 6.4: Simulated radiation and scattering levels for the U-shaped 1-D EBG structure and the straight 1-D EBG structure

Fig. 6.4 shows the power losses in the straight (Fig. 6.1(a)) and U-shaped (Fig. 6.1(c)) modulated microstrip line. As can be seen in the figure, the power losses of the U-shaped 1-D EBG microstrip structure are similar to that shown by the straight one over the whole frequency range (2-12 GHz), which indicates that the square patch in the bend of the microstrip line is able to eliminate power losses caused by radiation and scattering.

Additionally, the small insertion loss in the passband is attributed to the small number of bends in the U-shape microstrip line geometry that alleviates radiation and scattering losses of the transmission. It is also due to the large distance between the parallel microstrip line sections which eliminates the mutual interference. In single planar EBG (SP-EBG) structures, the U-shaped 1-D EBG microstrip structure with periodically inserted patches in the microstrip line is a

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry 129

compact structure with high performance.

6.2.2 U-shaped dual planar EBG microstrip lowpass filter design

Fig. 6.5(a) shows the 3-D layout of the U-shaped dual planar EBG (DP-EBG) microstrip lowpass filter structure. As can be seen in the figure, the U-shaped 1-D EBG structure (Fig. 6.1(c)) is on the top plane and a perturbed ground plane is at the bottom with circles etched in the plane along the microstrip line, resulting in a dual planar configuration. Between these two planes, Taconic ($\epsilon_r = 2.43$, $h = 30\text{mils}$) is used as the substrate.

Fig. 6.5(b) shows the relative location of the patches and the circles and Fig. 6.5(c) shows their dimensions. As can be seen in Fig 6.5(b), the square patches are inserted at a period of a . According to Bragg reflection condition [153], a is determined to be 10.35 mm with a center frequency of 10 GHz. Circles are etched exactly below the microstrip line at the center point between the rectangular patches ($d = a/2$). The width of the microstrip line w is set to be 2.29 mm corresponding to a characteristics impedance of 50 Ω .

In Fig. 6.5(c), r_2 is set to be 2.59 mm with an optimal filling factor (r/a) of 0.25 [7]. To obtain a small ripple level in the passband, the area of the other two circles is tapered by adopting the Chebyshev distribution from low side lobe array theory [12]. A three-element Chebyshev array with a major-to-minor ratio of 25 dB is used for the circles. The normalized coefficients is determined to be 0.73, 1, and 0.73 and the radius of the tapered circle r_1 and r_3 is determined to be 2.21 mm. The edge length of the inserted square patch e is set to be 5 mm in order to satisfy conditions in (5.1) and (5.2) avoiding any overlap between the circle in the ground plane and the rectangular patch in the microstrip line.

Fig. 6.6 shows the simulated S-parameters of the proposed U-shaped dual

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(a) 3-D view

(b) Top view 1

(c) Top view 2

Figure 6.5: Layout of the dual planar EBG microstrip structure with a U-shape microstrip line geometry

6.2 DP-EBG Structure with a U-shape Microstrip Line Geometry 131

Figure 6.6: Simulated S -parameters of the single planar and dual planar U-shaped 1-D EBG structure

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planar EBG filter structure and those of the U-shape single planar EBG structure (Fig. 6.1(c)) for comparison. As can be seen in the Fig. 6.6(a), the single planar structure shows a selectivity of about 6.82 dB/GHz, a passband ripple level of 0.83 dB, and a stopband with S_{21} parameter above 20 dB in the interested frequency range. Within the same physical size as that of the single planar structure, the proposed dual planar structure exhibits a selectivity of about 10.83 dB/GHz, a passband ripple level of 0.83 dB, and a wide stopband where the S_{21} parameter is maintained below 20 dB in the frequency range of 6.9-above 12 GHz. Comparing to the single planar structure, this dual planar structure achieves a significant increase in the selectivity and the attenuation of the stopband while maintaining a similar ripple level in the passband. This is attributed to the tapered etched circles in the ground plane. As shown by the S_{11} parameters in Fig. 6.6(b), the dual planar EBG structure exhibits a similar side lobe level to that of the single planar structure, which clearly indicates the similarity in the passband transmission of the two structures.

6.3 Modified U-shaped dual planar EBG microstrip structure

Within a small circuit area, this proposed U-shaped dual planar EBG structure shows excellent lowpass filtering functionality with superior passband and stopband characteristics. As compared to the single planar EBG structure, the proposed design achieves significant improvement in the selectivity and attenuation of the stopband. However, the selectivity of the DP-EBG structure shown in the previous section is limited. In order to extend the applications of U-shaped DP-EBG filter structure, the structure is modified by reducing the width of the microstrip line above the etched circle in the ground plane to obtain improvement of filtering

functionality within the same physical size.

6.3.1 The design

Fig. 6.7(a) shows the 3-D layout of the proposed lowpass filter and Fig. 6.7(b) and Fig. 6.7(c) show the relative location and the dimension of EBG cells, respectively. The new structure is developed base on the design of the U-shaped dual planar EBG structure introduced in the last section (Fig. 6.5).

As shown in Fig. 6.7(a) and (c), the period and the size of the inserted square patches a , the relative location of the patches and the circles, and the size of the circles remain the same as those in the original U-shaped DP-EBG structure. The etched circles are able to enhance the contrast of reactance in a EBG cell resulting in better filtering functionality of the structure as shown. For the same purpose, in this modified structure, the width of the microstrip line above the etched circles is reduced to be w_{bi} (where $i = 1, 2, 3$). Therefore, w_{bi} is smaller than the width of the microstrip line w . Similar to the three-cell small-size EBG structure in Chapter 5, the reduction in the microstrip line $w - w_{bi}$ in the new structure is tapered applying the Chebyshev distribution to eliminate the ripples due to the periodicity. Taconic ($\epsilon_r = 2.43, h = 30$ mils) is used as the substrate of the structure and the center frequency of the stopband f_0 is set to be 10 GHz. Thus, other parameters are determined correspondingly and shown in Table 6.1.

6.3.2 Numerical results

Fig. 6.8 shows the simulated S-parameters of the modified U-shaped dual planar EBG filter structure proposed in this section and the original U-shaped DP-EBG structure in the last section. The first two rows in Table 6.5 show the performance of these two structures in terms of selectivity, 20 dB bandwidth of the stopband, passband ripple level. As can be seen in Fig. 6.2(a) as well as the table, the se-

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Figure 6.7: Layout of the modified U-shaped dual planar EBG microstrip lowpass filter structure

6.3 Modified U-shaped dual planar EBG microstrip structure 135

Figure 6.8: Simulated S -parameters of the proposed U-shaped dual planar EBG structure and the modified structure

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Table 6.1: Parameter Setting of the Modified U-shaped DP-EBG Microstrip Low-pass Filter Structure

Parameter	Dimension (mm)
w	2.29
a	10.35
d	5.18
e	5.00
r_1, r_3	2.21
r_2	2.59
w_{b1}, w_{b3}	0.83
w_{b2}	0.29

lectivity and the stopband bandwidth of the modified structure are increased by 41.18% and 32.94% and the ripple level is reduced by 0.26 dB. With the further modification on the width of the microstrip line, the modified structure obtains great improvement in selectivity, the attenuation of the stopband, and the passband transmission yet keeping the physical size unchanged.

6.3.3 Experimental results

The proposed meander dual-plane EBG lowpass filter structure with a total area of 30 mm×30 mm was fabricated and tested. The photographs in Fig. 6.9 show the top view and bottom view of the fabricated structure. It is observed that the input port and output port are allocated at the same side of the structure. During the experiment, two 12.5-mm-long cables were connected between the device and the network analyzer facilitating the measurement. Fig. 6.10 shows the measured and simulated S-parameters. As can be seen in the figure, the fabricated filter structure shows a selectivity of 13.08 dB/GHz, a 20 dB stopband bandwidth of 6.57 GHz, and a ripple level of 1.04 dB in the passband. The measurement results are in good agreement with the simulation results. The differences are possibly

(a) microstrip line (top view)

(b) ground plane (bottom view)

Figure 6.9: Photographs of the fabricated modified U-shaped dual planar EBG lowpass filter structure

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(a) S_{21}

(b) S_{11}

Figure 6.10: Simulated and measured S-parameters of the fabricated modified U-shaped dual planar EBG lowpass filter structure

caused by the over etching, the lack of cell or material uniformity. The noise in the measured data is probably due to the additional cables connected.

As shown by the measurement results, this modified U-shaped dual planar EBG microstrip structure shows superior lowpass filtering functionality. It exhibits advantages of deep and ultra-wide stopband, high selectivity, low ripple level in the passband, compact size, and easy fabrication process.

6.4 Four-cell modified U-shaped dual planar EBG structure

In order to further improve the performance of the U-shaped dual planar EBG filter structure, a new U-shaped EBG microstrip structure was proposed by adding one square patch into the microstrip line to the modified U-shaped dual planar EBG microstrip structure design in the last section.

With this additional inserted patch, the performance of the structure is improved without any increase in the circuit area. In the four-cell EBG structure, the square patches in the microstrip line are tapered by employing tapering techniques to obtain good transmission characteristic in the passband.

6.4.1 The design

Fig. 6.11(a) shows the 3-D layout of the four-cell U-shaped DP-EBG filter structure. Fig. 6.11(a) and Fig. 6.11 (c) show the 2-D layouts indicating the relative location and the dimension of the EBG cells (patches in the microstrip line and the circles in the ground plane), respectively.

As can be seen in the figure, the new U-shape dual planar EBG structure is constructed by adding one square patch to the microstrip line in the modified U-shaped dual planar EBG structure shown in Fig. 6.7, resulting in a periodic

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(a) 3-D view

(b) top view 1

(c) top view 2

Figure 6.11: Layout of the optimized modified U-shaped dual planar EBG microstrip lowpass filter structure

Table 6.2: Parameter Setting

Parameter	Dimension (mm)
w	2.32
a	13.78
d	6.89
e_1, e_4	6.89
e_2, e_3	4.79
r_1, r_3	2.94
r_2	3.44
w_{b1}, w_{b3}	0.85
w_{b2}	0.32

structure with four EBG cells with the same physical size to that of the original three-cell structure. To eliminate the ripples in the four-cell structure, the size of the four square patches are tapered by adopting Chebyshev distribution. A four element Chebyshev array is used in this case. The edges of the two central square patches e_2 and e_3 are determined to avoid any overlap between the patch in the microstrip line and the circle in the ground plane.

Taconic ($\epsilon_r = 2.43, h = 30$ mils) is used as the substrate of the structure and the center frequency of the stopband f_0 is set to be 7.5 GHz. Thus, other parameters are determined correspondingly and shown in Table 6.2.

6.4.2 Numerical and experimental results

The new four-cell U-shaped dual planar EBG microstrip structure was simulated, fabricated, and tested. Fig. 6.12 shows the photographs of the fabricated structure. Fig. 6.13 shows its simulated and measured S-parameters. As can be seen in Fig. 6.13, the experimental results show good agreement with the simulated results. It demonstrates a wide stopband with a 20 dB bandwidth of 8.6 GHz, a ripple level of 0.54dB in the passband, and a selectivity of 22.5dB/GHz.

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(a) Microstrip line (top view)

(b) Ground plane (bottom view)

Figure 6.12: Photographs of the fabricated four-cell U-shaped dual planar EBG microstrip lowpass filter structures

Figure 6.13: Simulated and measured S-parameters of the fabricated four-cell U-shaped dual planar EBG microstrip lowpass filter structures

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Comparing the performance of the four-cell structure to that of the previous modified U-shape DP-EBG structure in Table 6.5, its selectivity and 20 dB bandwidth increase by 47.16% and 26.84%, respectively. Meanwhile, it obtains a decrease in the ripple level in the passband yet maintaining the same small circuit area.

Within a small circuit area, this four-cell U-shaped DP-EBG structure shows excellent lowpass filtering functionality with superior passband and stopband characteristics. As compared to the previous work on EBG microstrip filters [9][86], the proposed design achieves significant improvement in the selectivity and a great reduction in both the physical size and the passband insertion losses.

The proposed structure is compact with excellent passband and stopband performance. This filter design can be easily applied to circuit applications requiring lowpass filtering functionality. The unique U-shaped microstrip line geometry provides additional flexibility for allocation of components in circuit designs thus improving the compactness of circuits.

6.5 Four-cell meander dual planar EBG microstrip structure

The proposed four-cell modified U-shaped dual planar EBG microstrip structure in the last section shows excellent lowpass filtering functionality in a small circuit area. With the U-shape microstrip line geometry, it provides flexibility for the layout design of microwave circuits. In order to provide another geometry of the microstrip line with the input port and the output port allocated at the opposite end of the structure while keeping the bends that are crucial for the good performance and compactness of the structure, a four-cell modified U-shaped dual planar EBG microstrip structure with a meander microstrip line geometry is proposed and

presented in this section.

6.5.1 1-D EBG structure with a meander microstrip line geometry

Fig. 6.14(a) shows the layout of a straight 1-D EBG microstrip structure with four square patches inserted in the microstrip line at a period of a and Fig. 6.14(b) shows that of a meander line where the distance between adjacent parallel lines is also a . Fig. 6.14(c) is the four-cell 1-D EBG microstrip structure with a meander microstrip line geometry. It is a combination of the structure in Fig. 6.14(a) and (b). As can be seen in Fig. 6.14(c), the 90° bend takes place at the center point of each patch, resulting in a similar structure as that of a meander line.

Taconic ($\epsilon_r = 2.43, h = 30$ mils) is used as the substrate. The center frequency f_0 is set to 7.5 GHz resulting in a period of the structure a of 13.8 mm according to the Bragg reflection condition. The edge of the square patch e is set to be 6.9 mm which equals half of the period. The width of the microstrip line is 2.3 mm corresponding to a characteristic impedance of 50Ω at 7.5 GHz.

Fig. 6.15(a) and Fig. 6.15 (b) show their simulated S_{21} and S_{11} parameter, respectively. As can be seen in Fig. 6.15 (a), the meander line shows a small stopband centered at about 8 GHz and slight attenuation in the lower frequency range. The prominent resonance in the transmission is due to the resonators which are originated by reflections between two consecutive or nearby bends. The two resonators existing in the meander line are indicated in Fig. 6.14(b). According to a study on resonant frequency of meander line [114], a resonator with a length a introduces resonance at about 7.5 GHz whereas a resonator with a length of $2a$ causes resonance at both 7.5 GHz and 3.75 GHz. As can be seen in the figure, the straight EBG structure shows a prominent stopband in the frequency response. The meander 1-D EBG structure (a combination of the above two mentioned

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(a)

(b)

(c)

Figure 6.14: Layout of (a) a straight 1-D EBG microstrip structure, (b) a meander microstrip line, and (c) a meander EBG microstrip structure

6.5 Four-cell meander dual planar EBG microstrip structure147

(a)

(b)

Figure 6.15: Simulated S-parameters of the structures in Fig. 6.14

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Figure 6.16: Simulated radiation and scattering levels for the meander 1-D EBG structure and the straight 1-D EBG structure

structures) obtains a wider stopband with higher attenuation and an increase in selectivity while its passband ripple level increases slightly.

The results reveal that the meander geometry of the microstrip line is able to enhance the filtering functionality of the EBG structure. The significant enhancement in terms of selectivity and attenuation is obtained with a small increase in the passband ripple level. The higher ripple level is caused by the resonators in the meander line as well as the bends that introduces additional radiation and scattering. The passband ripple level is clearly indicated by the side lobe levels of the S_{11} parameter in Fig. 6.15(b). As can be seen in the figure, the side lobe level of the meander 1-D EBG microstrip structure still remains close to that of the straight one. This is because the meander 1-D EBG microstrip structure with inserted square patches is able to obtain a similar level of power losses to that

Figure 6.17: Layout of (a) a U-shaped microstrip line, and (b) a four-cell U-shaped EBG microstrip structure

of the straight one, which is illustrated by the radiation and scattering levels in Fig. 6.16. Another reason is that the bent unitary period (shadowed area in Fig. 6.14(c)) has the same phase shift as that of a straight unitary period (shadowed area in Fig. 6.14(a)), which has been shown in Fig. 6.3.

Fig. 6.17 shows the layouts of a four-cell U-shaped 1-D EBG microstrip structure and the U-shaped microstrip line. Using the same Taconic and with all other parameters set to be the same as those of the four-cell meander 1-D EBG microstrip structure, the two structures are simulated. Fig. 6.18 shows the simulated S-parameters of the U-shaped and the meander structure. As can be seen in Fig. 6.18(a), the microstrip line with a meander microstrip line geometry shows a resonance at about 8 GHz with higher attenuation than that of the U-shaped microstrip line. This is because both resonators in the meander microstrip line (one is with a length of $2a$ and the other is with a length of a) contribute to the resonance. As the result of the high attenuation of the resonance, the meander 1-D EBG microstrip structure shows a deeper stopband as compared to that shown by the U-shaped EBG structure. Due to the resonator with a length of $2a$, the

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(a) S_{21}

(b) S_{11}

Figure 6.18: Simulated S-parameters of the structures in Fig. 6.14(b), (c) and Fig. 6.17

Figure 6.19: Layout of the four-cell meander dual planar EBG microstrip lowpass filter structure

meander microstrip line exhibits another resonance at lower frequency, which is clearly shown by the side lobe level of the S_{11} parameter in Fig. 6.18(b). This results in additional ripples in the passband of the meander EBG structure that can be seen in Fig. 6.18(b) as well.

6.5.2 The design

Fig. 6.19 shows the 2-D layout of the four-cell meander DP-EBG filter structure. The meander 1-D EBG microstrip structure is on the top plane and circles are etched in the ground plane along the transmission line giving rise to a EBG structure with dual planar configuration. Fig. 6.19(a) and (b) indicates the relative location and the dimension of the EBG cells (patches in the microstrip line and the circles in the ground plane), respectively.

As shown in 6.19(a), circles are etched exactly below the microstrip line at

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Table 6.3: Normalized Coefficients of Chebyshev Distribution

Chebyshev Distribution	Normalized Coefficients
Three-Element	0.73, 1, 0.73
Four-Element	0.48, 1, 1, 0.48

the center point between the rectangular patches ($d = a/2$). The etched circles are for enhancing the reactance contrast in the EBG cell thus improving the stopband performance of the structure. For the same purpose, the width of the microstrip line above the etched circle is reduced so as to further increase the bandwidth and attenuation of the stopband, resulting in $w_b < w$.

To eliminate ripples caused by the periodicity of the design, Chebyshev distribution was adopted to taper the area of the circle and the inserted square patch. It results in the corresponding radius r_1 , r_2 and r_3 and the corresponding length of the edge e_1 , e_2 , e_3 , and e_4 . An optimal filling factor (r/a) of 0.25 [7] is used to determine the radius of the central circle r_2 . The edge length of the two central squares is set to e_3 and e_4 to avoid any overlap between the circle in the ground plane and the rectangular patch in the microstrip line in order to ensure good performance of the filter. The effect of the reduction in the width of the microstrip line ($w - w_b$) has been studied and it is found that good performance can be obtained when $(w - w_b)$ is tapered. A 3-element and a 4-element Chebyshev array with a major-to-minor ratio of 25 dB are used for the proposed design and the normalized coefficients are tabulated and shown in Table 6.3. Table 6.4 shows the numerical values of the parameters set.

6.5.3 Numerical and experimental results

The proposed four-cell meander DP-EBG LPF structure was fabricated (Fig. 6.20) and tested. Fig. 6.21 shows its measured S-parameters as well as the simulation

(a) Microstrip line

(b) Ground plane

Figure 6.20: Photographs of the fabricated meander dual planar EBG microstrip lowpass filter structures

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Figure 6.21: Simulated and measured S-parameters of the fabricated meander dual planar EBG microstrip lowpass filter structures

6.5 Four-cell meander dual planar EBG microstrip structure155

Table 6.4: Parameter Setting of the Meander Dual Planar EBG Microstrip Lowpass Filter Structure

Parameter	Dimension (mm)
w	2.32
a	13.78
d	6.89
e_1, e_4	6.89
e_2, e_3	4.79
r_1, r_3	2.94
r_2	3.44
w_{b1}, w_{b3}	0.85
w_{b2}	0.32

results. As can be seen in Fig. 6.21, the experimental results show good agreement with the simulated results. It demonstrates a wide stopband with an attenuation. It shows a 20 dB bandwidth of 8.6 GHz, a selectivity of $25.19\text{ dB} \setminus \text{GHz}$, and a ripple level of 0.38 dB in the passband. The proposed structure is compact and is able to achieve excellent passband and stopband performance. This filter design can be easily applied to circuit applications requiring lowpass filtering functionality.

Comparing the four-cell meander structure to the previous four-cell U-shape DP-EBG structure in Table 6.5, its selectivity increases by 11.96% and its ripple level in the passband greatly decreases by 29.63% with the same 20 dB bandwidth. As revealed by the experimental results, the proposed four-cell meander DP-EBG structure achieves significant improvement of the filtering performance. It is an alternative in the layout design of microwave circuits with superior lowpass filtering functionality. The trade-off for the high performance in the meander DP-EBG structure is a slight increase in the physical size.

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Table 6.5: Performances and Circuit Area of DP-EBG Structures with Special Microstrip Line Geometry

EBG Structure	Selectivity ($\frac{dB}{GHz}$)	20 dB Rejection Bandwidth	Ripple Level (dB)	Circuit Area (mm ²)
three-cell straight 1-D EBG	3.55	-	0.76	22×44
three-cell U-shaped DP-EBG	10.83	5.10 GHz	0.83	33×30
three-cell modified U-shaped DP-EBG	15.29	6.78 GHz	0.57	33×30
four-cell modified U-shaped DP-EBG	22.50	8.18 GHz	0.54	33×30
four-cell modified meander DP-EBG	25.19	8.60 GHz	0.38	41×45

6.6 Summary

In this section, the dual planar EBG microstrip structure with a U-shape microstrip line geometry is proposed. Due to the unique U-shape geometry of the microstrip line, the performance of the dual planar EBG structure is significantly improved in terms of the filtering characteristics in the stopband and the transmission characteristics in the passband with a great reduction in the circuit area. Tapering techniques are employed in the design to eliminate ripples caused by the periodicity of the structure.

The novel U-shaped DP-EBG microstrip structure shows advantages of high selectivity, small ripple level in the passband, high attenuation of the stopband in a wide frequency range, compact physical size, easy fabrication, and compatibility with MMIC technology. They show superior filtering functionality as high performance compact lowpass microstrip filters.

To enhance the flexibility in circuit layout design when using the proposed

U-shaped DP-EBG structure, a high performance compact dual planar EBG microstrip lowpass filter structure with a meander microstrip line geometry is also proposed as an optional structure in applications.

Table 6.5 shows the performances and circuit area of the DP-EBG structures with special microstrip line geometry proposed in this chapter and that of the straight 1-D EBG microstrip structure (Fig. 6.1 (a)) as a reference. As shown in the table, significant improvement of the performance in the proposed structures is identified. With the same physical size, the four-cell U-shaped DP-EBG structure obtains the best performance in U-shaped structures. The meander DP-EBG structure exhibits better performance in terms of selectivity, the rejection bandwidth, and the passband ripple level than those shown by the U-shaped structures. However, it has larger circuit area than others.

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Chapter 7

Conclusions and Recommendations

7.1 Conclusions

In this thesis, electromagnetic band-gap (EBG) structures that control the propagation of electromagnetic waves in the microwave or the millimeter-wave frequency range are intensively studied. A detailed review on planar EBG microstrip structure is presented. The limitations in the development of planar EBG structures are identified that are due to the compromise between the stopband and the pass-band performance and the compromise between the stopband performance and the physical size of the structure. Solutions are proposed by proposing designs of novel structures.

Chapter 2 and Chapter 3 involve the study on the characteristics of conventional 1-D planar EBG microstrip structures. Dielectric materials used as the substrate of the 1-D planar EBG microstrip structures have been investigated. Three findings are obtained:

- When working in the same frequency range, dielectric materials have effects

on the passband ripple level, the selectivity, the stopband bandwidth, and the stopband attenuation.

- With the dimension of the EBG cell fixed, dielectric materials mainly affect the performance of the structure in terms of the center frequency and the bandwidth of the stopband.
- Taconic is suitable to be used in the experiments in the sense that it is able to show the band-gap characteristic and it is easy to fabricate at low price with high accuracy.

Different tapering techniques for the optimization of EBG structures have also been introduced. The effects of different tapering techniques on the performance of a 1-D EBG microstrip structure are examined, analyzed, and compared. Both the Kaiser and the Chebyshev tapered EBG structure are able to obtain relatively small ripple levels in both passbands and a wide stopband with high attenuation.

Chapter 4, Chapter 5, and Chapter 6 include the designs and implementations of the novel planar EBG structures delivered in this study.

1) A six-cell and a five-cell dual-plane compact EBG (DPC-EBG) structure are designed. The structures demonstrate the novel dual-plane configuration of EBG structures where two single-plane EBG structures are arranged in one structure. With this unique dual-plane arrangement, the reactance contrast in a EBG unit is significantly enhance therefore a great increase in the bandwidth and attenuation of the stopband can be obtained with a small number of EBG cells. Chebyshev distribution in these two DPC-EBG structures successfully eliminate ripples in the passband due to the periodicity of the structure. These structures are able to perform well in terms of selectivity, stopband attenuation, and passband ripple level within a relatively small circuit area as compared to conventional filter designs.

2) A three-cell small-size EBG (S-EBG) structure is proposed base on the DPC-EBG structure by reducing the width of the microstrip line above the etched circles in the ground plane. The reduction in the width of the microstrip line further enhance the contrast of reactance in a EBG unit thus relatively good filtering functionality is obtained with only three EBG cells. This structure was able to perform as well as the six-cell and five-cell DPC-EBG structure over only half the circuit area used.

3) A U-shaped and a meander dual planar EBG microstrip structure with improved filtering performance and a small number of EBG cells are proposed. Both the three-cell and the four-cell U-shaped dual planar EBG microstrip structure exhibit excellent lowpass filtering functionality within a small circuit area. To provide flexibility when employing the proposed lowpass filter structure, a four-cell meander dual planar EBG microstrip lowpass filter structure is also proposed. As compared to the U-shaped structure, the meander EBG structure shows better performance with a slight increase in circuit area.

In conclusion, the findings in this thesis are important that serve as the basic of the research. With the novel dual planar EBG configuration, and by introducing the U-shape microstrip line geometry to the design of EBG structures, better compromise between the stopband and the passband performance and the compromise between the stopband performance and the physical size of the structure are obtained than those in the literature. As the result, high performance compact planar EBG filter structures are realized exhibiting superior passband and stopband performances.

7.2 Recommendations

In this study, a dual-plane EBG configuration is proposed and it is employed in the designs of the novel EBG structures. By applying the proposed EBG configuration as well as certain tapering technique (Chebyshev distribution), structures shows excellent filtering performances such as a wide and deep stopband, high selectivity, and smooth passbands. Meanwhile, they are compact in physical size, easy to fabricate, and compatible with monolithic circuits. An accurate circuit model of the proposed structure should be necessary because it can pave its way towards wider applications for microwave circuits. Due to the time constrain, the modeling has not done yet, but the author believes that this is an important topic which is worth investigating following this study.

For the application of dual-plane EBG structures, other than filters, there are a number of other microwave circuits that are possible to be optimized by employing the dual-plane structure. For example, they can be used to reduce the cross talk between two close microstrip line without increasing the circuit area, or they can be used to construct a high-Q resonator with compact physical size by introducing a defect in the periodic structure. Both are believed to be promising. Moreover, with a wide and deep stopband, a dual-plane EBG structure is possibly used to construct high performance planar bandpass filters.

Appendix A

Author's Publications

Journal Papers

1. S. Y. Huang and Y. H. Lee, "Compact U-shaped dual planar EBG microstrip lowpass filter," *IEEE Transaction on Microwave Theory and Techniques*, vol. 53, no. 12, pp. 3799-3805, Dec, 2005, [20].
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Appendix B

Metallodielectric EC and Metallic EC

B.1 Metallodielectric EC

Metallodielectric EC's (MDEC's) consist of metallic elements periodically arranged in dielectric hosts (except air). Similar to dielectric EC's in the last section, based on the arrangement of periodic elements, MDEC's are divided into 3-D, 2-D, and 1-D structure.

A **3-D MDEC** consists of metal elements embedded in a dielectric host forming periodicity in the whole space. In [154], a stopband spanning about one octave was observed in a 3-D MDEC which is composed of a face-centered-cubic Bravais lattice of metal sphere supported by a low loss dielectric (Fig. B.1). Due to the 3-D configuration of periodic elements, the presented material exhibits an omnidirectional band-gap. This 3-D MDEC as well as a diamond structure (Fig. B.2) was further studied for the band structure and transmission properties using FDTD method in [155].

There are some studies on **2-D MDEC's** where metallic wires are period-

Figure B.1: Top view of a (111)-oriented fcc metallodielectric EC [152]

Figure B.2: Schematic of a diamond structure with metallic spheres [153]

ically arranged in a dielectric host medium. They were used as the substrate of patch antennas to reduce the surface wave loss thus to reduce the levels of side lobe radiation and to increase directivity [156]. The 2-D MDEC consisting of ferromagnetic nanowires embedded in polymer was proposed in a bandstop filter design [157]. The implants in 2-D MDEC's are wires which are small compared to the period of the cell. For a wire antenna in such an EC, in [158], a simple and explicit method was proposed to compute its radiation pattern. Besides, effective permittivity and permeability functions were developed for these type of EC's in [159].

A 1-D MDEC was proposed with vias in the microstrip line, which is for the design of broadband reflectors or short circuits with enhanced behavior at high frequencies [160].

Figure B.3: Schematic of the 3-D metallic EC with a network topology [162]

B.2 Metallic Photonic Band-gap (MPBG) Structure

The dielectric host used in the metallodielectric EC's can be Teflon ($\epsilon = 2.1$)[155], polymer [157], or other dielectric materials. If the host medium is air, they are metallic EC's. Metallic EC's are mainly made up of metal and air. Most of them consist of metallic elements periodically arranged in the air. There is another type of metallic EC's that are metals with periodic air holes. Although they are not the main stream of the research in this field, they were proposed for some specific application [161].

Base on the number of propagation directions in which there is a band-gap, they are also divided into 3-D metallic EC's (3-D MPBG), 2-D metallic EC's (2-D MPBG), and 1-D metallic EC's (1-D MPBG). Similar to dielectric EC's, **1-D metallic EC's** are commonly used for theoretical study such as the derivation of formulas [162] or the investigation of the material properties that affects the wave propagation (such as wave impedance and refractive index)[163].

Figure B.4: The schematic of a 2-D metallic EC mixed with dielectric Bragg mirror [172]

B.2.1 Main Difference of Metallic EC from Dielectric EC

3-D metallic EC's are artificial medium with metallic periodic scatters in the air. Due to the periodic element which is PEC, metallic EC's are frequency dependent, which is one of the two main differences of metallic EC's from dielectric EC's. The other major difference is the change of wave propagation characteristics of metallic EC's with a network topology which is shown in Fig. B.3 [164]. The metallic EC with a cermet topology consists of isolated scatters and exhibits a prominent band-gap which is similar to that of dielectric EC's. For the frequency response of the metallic EC with a network topology, there are no propagation modes for frequencies that are smaller than a cutoff frequency, which does not exist in the dielectric EC with connected periodic elements.

Not only the 3-D metallic EC with a network topology but also does the 2-D metallic EC consisting of infinitely long metallic cylinders (wires) have the cutoff frequency. The band-gap structure of the 3-D and 2-D metallic EC's were studied [165][166].

B.2.2 2-D Metallic EC and Metallic EC with Wires

2-D metallic EC's have attracted a lot of attention [167] [168] [169] and have been widely employed in microwave circuits. They are used in the design of wire

Figure B.5: The schematic of a 3-D metallic EC with short wires

Figure B.6: Schematic of the metallic photonic band-gap (MPBG) structure

antennas to improve their performance such as the reduction of grating lobes [170]. Theoretical studies on such antenna were carried out [171]. An efficient method was proposed to obtain the radiation characteristics of the wire antenna in the 2-D metallic EC in [172]. The 2-D metallic EC was modified for various applications. In [173], EC's with difference periods were combined to realize beam splitting. It was mixed with dielectric Bragg mirror in the way shown in Fig. B.4 to design a bandpass filter with very narrow bandwidth [174]. It was also used in the middle layer of the parallel-plate waveguide to guide and suppress surface waves in the design of an asymmetric parallel-plate waveguide Luneburg lens (APWLL) in [175].

For a 2-D metallic EC, it has been found that the wave propagation behavior

Figure B.7: A periodic array of electrically active elements arranged on a circuit board and the equivalent RLC circuits of the switch at the discontinuity [176]

becomes similar to that of a 3-D metallic EC with a cermet topology when the length of the wire is shorter than a wavelength. Therefore, for structures that are comprised of short wires (or cylinders) as shown in Fig. B.5, they are 3-D metallic EC's. [176] presents a hybrid method to efficiently calculate the band structure of the three types of 3-D metallic EC's that have been introduced, including the 3-D metallic EC with a cermet topology, the one with a network topology, and those with short wires. Formulas were proposed to obtain the radiation characteristics of an antenna in 3-D metallic EC with short wires [177].

Fig. B.6 shows the schematic of the wire metallic EC's that have been introduced. A 2-D metallic EC consists of periodic continuous wires of infinite length (with respect to the wavelength) whereas a 3-D metallic EC is comprised of short wires. As can be seen in the figure, it shows the possibility of constructing the 3-D structure by cutting those long wires in the 2-D one. Thus, physically they are able to transfer from one to the other. It implies the possibility to obtain the switch of the two different wave propagation behaviors exhibited by the 2-D and 3-D wire structure.

Figure B.8: Active structure geometry [177]

B.2.3 Controllable Metallic EC (Active Metallic PBG)

Electronic or electro-mechanical switches were used to replace the discontinuity in the 3-D metallic EC to achieve controllable metallic EC's which is also named active metallic PBG (AMPBG).

Fig. B.7 shows the schematic of a periodic array of electrically active metallic EC elements and its equivalent circuit model proposed in [178]. The electronic switches used to replace the discontinuity is fast *p-i-n* diodes because they are technologically more mature than fast electromechanical switches and commercially available at low price.

This electrically controllable Metallic EC can be fabricated using printed circuit technology. The metallic wires can be printed on periodic stacked circuit boards where *p-i-n* diodes are assembled in the printed arrays (Fig. B.7).

When the diodes are on, the AMPBG is a 2-D Metallic EC exhibiting a cutoff frequency in the reflection coefficient and it becomes a 3-D Metallic EC showing a band-gap when the diodes are off. The AMPBG can be applied to dipole antennas to be a beam shaper. When an antenna is placed in a Metallic EC with active wire (Fig. B.8), its beam radiation can be turned on or be turned off or switched from a wide to a narrow one [179]. However, the application of

the active Metallic EC is limited to the microwave band because the implementation becomes difficult when it is extended to the (sub)millimeter-wave regime due to the less availability of active electrical devices and the higher complexity of their integration. At millimeter wavelengths, controllable EC's are realized using dielectric materials [178].

Appendix C

1-D Planar EBG CPW Structure

1-D planar EBG structures are applied to coplanar waveguide (CPW). Fig. C.1 shows the schematic of a conventional 1-D planar EBG CPW structure [180]. As can be seen in the figure, the ground plane is perturbed by varying the distance between the center strip (of constant width) and the ground plane.

This EBG CPW structure is employed in the design of a CPW bandpass filter in [181]. The new CPW bandpass filter is shown in Fig. C.2. As can be seen, the filter design is based on capacitively coupled resonators with square wave perturbation geometry in the ground plane. Therefore, the proposed filter is able to reject frequency parasitics through the reflection properties of the the

Figure C.1: Top-view of a conventional 1-D planar EBG CPW structure

Figure C.2: Top-view of a 1-D planar EBG CPW bandpass filter based on capacitive coupled resonators and 1-D EBG CPW structure

EBG periodic structure. Moreover, its physical size becomes smaller than the conventional structure due to the slow-wave effect associated with the periodicity. The EBG CPW structure is also used to construct a resonator with high Q factor by inserting a defect in the middle of the EBG CPW reflectors [180] [182]. The resonant frequency can be tuned when a varactor is mounted in the resonator [183].

1-D planar EBG CPW structures can realize both frequency tuning and multistopband with some additionally loaded varactor diodes or shunt capacitances [184] [185]. On the other hand, there are some variants (Fig. C.3-Fig. C.5) proposed with a wide rejection bandwidth. Fig. C.3 shows the double tapered PBG (DT-PBG) structure with EBG perturbations etched in both the ground plane and the signal line [186] and Fig. C.4 shows the 1-D planar EBG structure with butterfly-radial slots (BRS) in the ground plane in stead of rectangular patches [187]. The spiral-shaped EBG CPW structure (Fig. C.5) that was proposed in [188] has much more rapidly increased slow-wave factor with an increase in operating frequency than that shown by the structure with rectangular geometry.

There is another type of 1-D planar EBG CPW structures called DGS CPW structures. Fig. C.6 shows the schematic of the DGS CPW structure proposed in [189]. As can be seen in the figure, the defect in the ground plane is composed

Figure C.3: Double tapered-PBG (DT-PBG) structure

Figure C.4: Butterfly-radial slots (BRS) EBG CPW structure

of a square patch and a narrow slot between the the etched patch and the gap, which has a similar shape to that of DGS in microstrip circuits. They are used to feed a loop slot antenna for harmonic suppression [190] or to improve the roll-off characteristics of the bandpass filter [191]. With some modifications on the shape of the defects in the ground plane, performance improvements of the structure are possible to obtained [192]. In [193], a variant of the DGS CPW structure achieves high impedance and is used in the design of Wilkinson power divider.

Other than the two types of 1-D planar EBG CPW structures, a T-shaped CPW filter structure as shown in Fig. C.7 was proposed in [194]. In [195], it was combined with a stepped-impedance filter to realize the filter with huge band-gap (Fig. C.8).

Figure C.5: Spiral-shaped EBG CPW structure [186]

Figure C.6: Schematic of a DGS CPW structure

Figure C.7: Schematic of a T-shaped CPW structure

Figure C.8: Schematic of a dual EBG-CPW filter [193]

There are other periodic 1-D planar EBG CPW structures that are not governed by the Bragg reflection condition, such as the corrugated EBG CPW structure [196] [197] whose center frequency is determined by the slot depth. Some EBG CPW structures are constructed by periodically loading varactors instead of etching patches in the ground plane [198] [199].

Appendix D

High-Impedance Electromagnetic Surface

High-impedance electromagnetic surface is considered as a combination of the EC and the planar EBG structure. It consists of a lattice of metal plates and conducting vias in the dielectric substrate to connect the plate to a solid metal sheet.

Fig. D.1 shows the cross sectional view and the top view of a high-impedance electromagnetic surface proposed in [43]. As shown in the figure, it consists of an array of metal protrusions on a flat metal sheet. They are arranged in a 2-D lattice. They can be visualized as mushrooms or thumbtacks protruding from the surface at the bottom in Fig. D.1(a). The geometry is analogous to a corrugated metal surface in which the corrugations have been folded up into lumped-circuit elements, and distributed in a two-dimension lattice. From the figure, it can be seen that it is a combination of a 2-D planar EBG structure (the structure on the top layer) and a 2-D metallodielectric electromagnetic crystal (the structure in the dielectric substrate).

This high-impedance surface has high surface impedance within a frequency band. It does not support propagating surface waves, and its image currents are

Figure D.1: (a) Cross section of a high-impedance surface. The structure consists of a lattice of metal plate, connected to a solid metal sheet by vertical conducting vias. (b) Top view of the high-impedance surface, showing a triangular lattice of hexagonal metal plates [41]

not phase reversed. It functions as a ground plane for low-profile antennas such as circularly polarized curl antenna [200] and planar inverted-F antenna [201]. Another advantage to apply this surface for an antenna is that the radiation of the antenna is smooth and free from the effects of multipath interference along the ground plane because the surface is able to suppress surface waves due to the forbidden frequency band.

In [202] and [203], the gaps between the metal patches are replaced by intercrossed capacitors as shown in Fig. D.2 to obtain larger capacitance. The proposed surface has compact size than the conventional structure. In [204], the center frequency of the band-gap can be tuned for fix periodicity when the uniform metal-

Figure D.2: (a) Square metal plate in conventional high-impedance surface (b) Geometry of the metallic layout with air gap replaced by intercrossed capacitors [201]

Figure D.3: Change of unit geometry in the polarization-dependent electromagnetic band-gap (PDEBG) structure

lic element is replaced by convoluted or interleaved element. The polarization-dependent high-impedance surface was proposed in [205]. This polarization-dependent surface is realized by changing the unit geometry. Fig. D.3 shows several proposed changes.

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