tion without starting from a close estimate of the original configuration.

4. CONCLUSION
An electromagnetic approach for the detection and reconstruction of elliptic dielectric cylinders has been extended to the case of perfect conducting elliptic cylinders. This approach is based on the inverse-scattering problem and on an analytical-series solution for the forward-scattering computation. A memetic algorithm is applied as a global optimization tool. The inverse method has been tested with reference to real data collected by an experimental setup that is based on the modulated scattering technique. In this preliminary assessment, the approach has shown good capabilities in localizing and shaping the perfect conducting elliptic cylinder, due to the ability of the memetic algorithm to deal with the multimodality inherent to the inverse scattering problem and also due to the good accuracy of the input data collected by the experimental prototype. However, further evaluations are needed, in particular, a consideration of the coated cylinders, in which conducting and dielectric materials are contemporarily present.

ACKNOWLEDGMENT
The authors wish to thank Dr. Johan Wettergreen for providing the subroutines for the computation of the Mathieu functions.

REFERENCES

© 2004 Wiley Periodicals, Inc.

NOVEL MICROWAVE MICROSTRIP FILTERS USING PHOTONIC BANDGAP GROUND PLANE WITH FrACTAL PERIODIC PATTERN

K. Siakavara
Aristotle University of Thessaloniki
Department of Physics
Radiocommunications Laboratory
Thessaloniki, Greece

Received 18 April 2004

ABSTRACT: Photonic bandgap (PBG) structures with slots etched in their ground plane have been proposed recently as a good choice for the design of printed microwave filters, absorbers, reflectors, and antennas for many modern applications. In the present work, a microstrip PBG filter was designed to operate as a multifrequency bandstop filter. The conventional profile of the slot patterns used in previous works was either discrete (with circles), continuous sinusoidal, or triangular. These geometries guide the structure to operate as a single wideband filter. In this work, a different periodic pattern of slots is introduced. The configuration is designed using the fractal technique. The self-similarity of the fractal geometry is found to excite the PBG structure to act as a wide stop-band filter in more than one frequency region. © 2004 Wiley Periodicals, Inc. Microwave Opt Technol Lett 43: 273–276, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20443

Key words: photonic bandgap (PBG) structures; fractal patterns; microstrip filters

1. INTRODUCTION
Photonic bandgap (PBG) structures are periodic structures in which the propagation of electromagnetic waves is prohibited in some frequency bands or directions. The realization of this operation was obtained initially by a class of periodic dielectrics that is the photonic analogous of semiconductors and were used in optical regions [1]. However, PBG properties are scalable and applicable to the microwave and millimetric-wave range, finding multiple applications, such as the improvement of antenna radiation features [2, 3], use as broadband absorbers and reflectors, and the design of broadband filters and high efficiency amplifiers, power dividers, and so forth.

In microstrip technology, for the microwave frequency range, a PBG structure is obtained by creating a proper periodic pattern drilled in the substrate or etched in the ground plane. The planar-etched PBG configurations proposed in the literature [4–8] have attracted interest due to their ease of implementation and their compatibility with microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs).

Several works in the literature have introduced the use and proved the efficiency of periodic patterns of slots etched on the ground plane of the microstrip structure, when a frequency range pass or rejection of the transmitted signal is needed. The slots in the ground plane may have either a circular shape [4–8] or a sinusoidal or a triangular profile [7]. The operational characteristics of the filters are controlled by the size and the distance of the ground slots [4–8]; in this case, their pattern is uniform. A nonuniform configuration where the slot dimensions are varied proportionally to the binomial or Chebyshev polynomial distributions can improve their performance [6].

The PBG structures presented in the abovementioned studies act as low-pass filters and furthermore have a band-stop behavior.
in a wide range of frequencies. This range, which is unique and wide, depends on the geometrical features of the slot array.

In the present work, a PBG microstrip filter is designed by considering an array of etched apertures in the ground plane. Each slot is synthesized by the fractal algorithm of the Minkowski curve.

The fractal technique has already been used for the design of printed antennas [9–13], in which attractive operational features, were realized. In the present work, it is proved that similar properties of fractal geometries that enable an antenna to have multi-frequency operation also lead to similar performances when used in the design of apertures in the ground plane of a PBG structure.

2. MULTI-WIDEBAND PBG MICROSTRIP STRUCTURE DESIGNED BY FRACTAL TECHNIQUE

The PBG structure selected is a planar configuration, as shown in Figure 1. The dielectric substrate has $\varepsilon_r = 10.2$ and height $h = 0.5$ mm, and the microstrip line is 0.5-mm wide and has a characteristic impedance $Z_0 = \frac{50}{\sqrt{\mu}}$. The slots are considered to be etched in the ground plane and are designed by the Minkowski fractal algorithm. The generator slot, from which the higher stages of the fractal curve are produced via iterations, is a straight slot of length 5.6 mm [Fig. 2(a)]. The first stage was generated by dividing its length in four segments and then composing a new aperture by using eight of these smaller slots, positioned as shown in Figure 2(b). At the next iteration, guiding to the second stage, each one of the eight segments of the previous configuration was also divided into four even smaller segments and eight of them, arranged as previously, replaced each segment of the first stage [Fig. 2(c)]. Following this algorithm, all higher stages can be derived and the length of the curve will tend to infinity, as at each iteration the length of each segment is divided by four and the number of segments is multiplied by eight; hence, the total curve length is twice the length of previous stage. In the present work, the first-stage slots only gave satisfactory results.

3. RESULTS

In order to investigate the multiple stop-band effect of the newly proposed PBG structure, three circuits were composed and simulated. Nine apertures of the second fractal stage were positioned at different distances in each circuit. The results of the reflection ($S_{11}$) and transmission ($S_{12}$) coefficients are shown in Figures 3–5 and it can be seen that multiple stop-band performance was obtained. In all three cases, one of the stop-band regions appears at a frequency of about $f_0$, which is a function of the period of the

![Figure 1](image1.png)

**Figure 1** Three-dimensional view of the proposed PBG structure with second-stage Minkowski curves apertures etched in the ground plane ($\varepsilon_r = 10.2, h = 0.5$ mm)

![Figure 2](image2.png)

**Figure 2** Stages of the Minkowski curved aperture: (a) generator slot of length 5.6 mm; (b) first stage; (c) second stage

![Figure 3](image3.png)

**Figure 3** Simulated $S_{11}$ and $S_{12}$ parameters for the PBG microstrip structure with nine Minkowski apertures ($d_m = 5.6$ mm, $D = 6.5$ mm)
structure, and is calculated approximately with the following expression:

\[ kd = \pi, \]  

(1)

where \( d \) is the period of the PBG pattern (Fig. 1), and \( k \) is the wave number in the dielectric slab, defined by

\[ k = \frac{2 \pi f_0}{c} \sqrt{\varepsilon_{\text{eff}}}, \]  

(2)

where \( f_0 \) is the center frequency of the stop-band, \( \varepsilon_{\text{eff}} \) is the effective relative permittivity of the dielectric slab, and \( c \) is the speed of light in free space.

Additional stop-band regions appear near the frequency or its multiples, at which each aperture appears as a self-resonance. To verify this, a geometry composed of only one aperture in the ground plane, the dielectric slab, and the microstrip line was considered to operate as an antenna, and was fed via its proximity to the line. The power gain of this configuration is shown in Figure 6. As can be seen, two maximum values appear at frequencies \( f_1 = 6.73 \text{ GHz} \) and \( f_2 = 12.946 \text{ GHz} \). They are not greater than 0 dB, but are satisfactorily high enough to introduce a perturbation and frequency rejection at the operation of the filter.

The frequency responses of \( S_{11} \) and \( S_{12} \) of the PBG structure, where the distance between the apertures is 6.5 mm, is presented in Figure 3. In this case, the center frequency calculated via Eqs. (1) and (2) is \( f_0 = 7.926 \text{ GHz} \) and a stop-band frequency appears. The center frequencies of the other two bands are 6.34 and 12.9 GHz, corresponding to the self-resonances of each aperture in accordance with Figure 6. In Figure 4, the curves for \( S_{11} \) and \( S_{12} \) versus frequency when \( d_m = 10 \text{ mm} \) are presented. The center frequency due to the periodicity of the aperture pattern is \( f_0 = 5.15 \text{ GHz} \) and a corresponding stop-band region appears. Another stop-band appears at 10.7 GHz, corresponding to \( 2f_0 \), and two more bands appear at 6.9 GHz (=\( f_1 \)) and 13 GHz (=\( f_2 \)), due to the self-resonances of the apertures.

The results of Figure 5 were obtained with a distance between the slots \( d_w = 14 \text{ mm} \). In this case, the central frequency of the periodic pattern, as calculated by Eqs. (1) and (2), is \( f_0 = 3.68 \text{ GHz} \). As can be seen, four stop-band regions related to \( f_0 \) appear. The first is at 3.69 GHz (=\( f_0 \)), and the others are at 7.6 GHz (=\( 2f_0 \)), 10.89 GHz (=\( 3f_0 \)), and 15.13 GHz (=\( 4f_0 \)), respectively. Due to the self-resonance of the slots, the stop-band regions appear at 6.82 GHz (=\( f_1 \)) and 12.85 GHz (=\( f_2 \)), as expected.

In all three cases, the frequency rejection bands were wide and the rejection level was satisfactory.

4. CONCLUSION
A novel PBG microstrip structure with an array of fractal Minkowski curve apertures etched in the ground plane has been presented. The configuration acts as a multifrequency filter, instead of single-range band-stop filter. The center frequency of the stop-band ranges are controlled via the geometry of the fractal aperture array. Wide rejection bands with a high rejection level and satisfactory low ripple outside the stop frequency regions were obtained.

REFERENCES
3. Y. Qian, R. Coccioi, D. Sievenpiper, V. Radisic, E. Tablonovitch, and
ABSTRACT: This paper presents an accurate and robust 3D time-domain electromagnetic model for hybrid and monolithic microwave and optoelectronic integrated circuits. The time-domain model has been validated for different structures, such as metallic waveguides and planar lines under harmonic-oscillation excitation. The simulation results demonstrate that this approach is suitable for modeling microwave components of integrated circuits. 

Key words: electromagnetic effects; microwave circuits; high frequencies; numerical simulation; waveguide

1. INTRODUCTION

In the last few years, the dramatic demand of more and more sophisticated hybrid and monolithic microwave and optoelectronic integrated circuits highlight the crucial need for fast, accurate, and robust CAD tools. Due to their complexity, such circuits must be designed using advanced CAD techniques. These techniques must be able to simulate the interaction of electromagnetic (EM) waves with interconnects and passive components where the dimensions become important, and where major difficulties lie.

The objective of this paper is to develop a comprehensive, systematic, and generic approach for global full-wave simulation of 3D electromagnetic structures. The technique is based on the rigorous solution of Maxwell’s equations using explicit finite-difference method in the time domain (the FDTD method). Several absorbing boundary conditions (ABCs) are used to truncate the computational domain [1, 2]. This approach has several advantages compared to other previous works [3–5]. The 3D time-domain model is suitable for implementation in a massively parallel processing (MPP) machine, and can be used for hybrid and monolithic circuits in microwave as well as optical frequency ranges.

2. ELECTROMAGNETIC MODEL

EM wave propagation can be completely characterized by solving Maxwell’s equations. In a natural unity system, assuming a uniform isotropic medium for the dielectric and magnetic relations, Maxwell’s equations are given by

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{and} \quad \nabla \times \mathbf{B} = \mu \epsilon \mathbf{E} \]

These systems of equations are hyperbolic and symmetric. It can be seen that the dielectric \( \epsilon \) and permeability \( \mu \) appear only in source terms. This system of equations can be also written as

\[ \frac{\partial \mathbf{U}}{\partial t} + \mathbf{A} \frac{\partial \mathbf{U}}{\partial x} + \mathbf{B} \frac{\partial \mathbf{U}}{\partial y} + \mathbf{C} \frac{\partial \mathbf{U}}{\partial z} = \mathbf{F}, \]

where \( \mathbf{U} = (E_x, E_y, E_z, B_x, B_y, B_z) \), \( \mathbf{F} = (-j\mu/c \sqrt{\epsilon} E_x, -j\mu/c \sqrt{\epsilon} E_y, -j\mu/c \sqrt{\epsilon} E_z) \), and matrices \( \mathbf{A}, \mathbf{B}, \text{and} \mathbf{C} \) are the real coefficients, and \( c \) denotes the speed of light. The numerical resolution of Maxwell’s equations is based on an explicit finite-difference technique in which \( \mathbf{E} \) and \( \mathbf{B} \) are unknowns. We have applied the Mac–Cormak numerical scheme, which is a modified Lax–Wendroff scheme with two increments in time and in the form of predictor–corrector. The predictor provides an estimate of the solution and the corrector decreases the error produced by the predictor and gives a more accurate result.

In this scheme, \( \mathbf{E} \) and \( \mathbf{B} \) are calculated at the same point and same time and they are situated at the centre of a space mesh, as shown in Figure 1. This scheme is adopted to study nonlinear