

Dispersion Diagram of a Novel Multi Band EBG Structure Using FDTD/GPOF Technique

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Abstract— The problem of surface waves usually degrades the performance of planar circuits and antennas, to reduce its effects, the electromagnetic band gap (EBG) structures are applied to suppress these undesired waves at certain bands. In this paper a novel multi band planar structure is simulated using finite difference time domain where the eigen frequencies are captured using the generalized pencil of function (GPOF) technique. By plotting the dispersion diagram of the structure, a surface wave propagation at 1.92-3.05GHz, 3.77-4.48GHz and 4.65-5.78GHz bands is prohibited, thus making the proposed structure suitable for WLAN requirements.

Keywords— Dual band electromagnetic band gap (EBG) structure, finite difference time domain (FDTD), generalized pencil of function (GPOF), eigen frequencies, dispersion diagram.

I. INTRODUCTION

Surface waves propagating along the substrate in planar circuits and antenna arrays usually produce undesired coupling effects and performance degradation, for example, these waves reduce antenna efficiency and gain, increase the side lobe levels, and increase the mutual coupling levels in antenna arrays[1]. Introducing electromagnetic band gap structures prove to be useful in reducing these effects.

EBG structures are "artificial periodic (or sometimes non-periodic) objects that prevent/assist the propagation of electromagnetic waves in a specified band of frequency for all incident angles and all polarization states "[1]. In addition to the property of suppressing surface waves, EBG structures also can simulate artificial magnetic conductor (AMC) at certain frequency band where an incident wave on such surface will be reflected in-phase, this desirable property can help in reducing antenna profile.

It is to be noted that the most widely used form of the EBG structure is the planar EBG [2,3] suitable to be integrated with planar microwave circuits, these structures may have fixed structure geometry and hence fixed frequency response or may be reconfigurable or tuned using varactor diodes [4], PIN diodes [5] or micro-electromechanical systems [6]. EBG structures have many applications other than enhancing the operation of antennas, these structures are also used to build planar filters [5], integrated with MRI RF antennas [7], integrated with CMOS chips for noise suppression [8], and also in suppressing ground plane noise in high speed digital circuits [9].

EBG structures are in most cases complex but they can be analyzed and simulated using various techniques. Full-wave techniques are accurate in studying these structures.

Finite difference time domain [10], finite element method [11] and the method of moments [12] are used to accurately analyze EBG structures. Lumped elements and transmission line equivalent models [13,14] are less accurate but they are much simpler and faster in calculations.

In order to reduce the required time to obtain the eigen frequencies, many techniques are used to predict these frequencies accurately using only early time domain data. Such techniques include the generalized pencil of function (GPOF) [15], Prony [16] and the auto-regressive moving average (ARMA) [17] techniques, the former technique did not draw the deserved attention in EBG eigen frequency estimation, so in this paper the procedure of FDTD/GPOF is discussed in some detail.

In this paper a novel multiband planar EBG structure is introduced. Its operation is based on resonance effects produced by its various capacitive and inductive parts. A unit cell of this structure is analyzed using the FDTD full wave technique for the dispersion diagram. To obtain the complete dispersion diagram the analysis is performed many times, each time with a fixed wavenumber, and the GPOF technique is used to estimate the eigen frequencies using the early time response of the fields. The obtained dispersion diagram is verified using HFSS software and the wave suppression property is further illustrated using the suspended microstrip line technique.

In section II, the numerical schemes to be used in this paper are reviewed. Section III presents in some detail the procedure to be followed for detecting the eigen frequencies and plotting the dispersion diagram. In section IV a novel dual band EBG structure is presented and analyzed using the presented procedure, then the propagation suppression property is verified using suspended microstrip line.

II. OVERVIEW OF THE NUMERICAL TECHNIQUES USED IN THIS WORK

A. Finite difference time domain FDTD

FDTD scheme first proposed by Yee [18] now become a widely used numerical technique in simulating metamaterials because of many advantages such as simplicity, flexibility, and performing calculations in time domain which allows wide band characterization in a single simulation[1].

FDTD technique is based on discretizing Maxwell's equations both in space and time based on central difference approximation of space and time derivatives, where all the six field components are updated step by step in time until

the end of a required simulation time. The step in x-direction is denoted by Δx , and similarly in y-direction denoted by Δy and in z-direction by Δz while the step in time is denoted by Δt . To ensure good resolution and accuracy of the discretization, the space steps should be small compared to the shortest wavelength in the spectrum of interest and also small compared to the minimum dimension in the structure. To ensure stability, Δt should obey the following criteria [19]:

$$\Delta t \leq \frac{1}{c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (1)$$

Where c is the speed of light in free space .

There are two issues regarding the simulation of the proposed EBG unit cell; the interface between substrate and air, and the simulation of thin conductor sheets. For the first issue, the average value of the substrate and the air permittivities is used in the update equations of the tangential components of the electric field components at the interface [19]. Similarly, for the second issue the thin conductor sheets can be modeled by using the perfect conductor conductivity in the update equations of the tangential electric field components on these sheets [19].

Because computer resources are limited the solution space in FDTD should be truncated, but we are faced with many problems of interest in open regions. To solve this problem the space is truncated using absorbing boundaries, that are boundaries that should absorb as perfect as possible incident waves at all frequencies and angles of incidence.

Convolutional perfectly matched layer (CPML) introduced in [20] is one of the best techniques in implementing absorbing boundaries where it is a finite thickness layer of a hypothetical anisotropic material with electric and magnetic conductivities assigned to it where the fields updating equations are modified accordingly [19]. This layer is matched to the inside space material to prevent unwanted reflections while attenuating the penetrating waves in a direction normal to the interface.

B. Periodic boundary conditions PBC

As in the case of open regions, simulating infinite periodic structures of repeated structures is impossible because of limited computer resources. It is sufficient to study only one cell and then the periodic boundary conditions are used to truncate the space and simulate an infinite structure.

For example, assuming a material with periodicity P_x along x-direction, the electric fields at the boundaries $x = 0$ and $x = P_x$ are related in frequency domain by [1]:

$$\vec{E}(0, y, z) = \vec{E}(P_x, y, z) \exp(jk_x P_x) \quad (2)$$

Where k_x is the propagation constant in the x-direction.

Transforming (2) to time domain results in a formula that violates causality [1]. Assuming that the propagation constant k_x is a constant in (2) will lead to a formula in time

domain which is causal since the exponential term is now a constant [1]. In time domain, equation (2) becomes :

$$\vec{E}(0, y, z, t) = \vec{E}(P_x, y, z, t) \exp(jk_x P_x) \quad (3)$$

Similarly, to account for periodicity in y-direction, the electric field at the boundaries along y-direction can be updated using :

$$\vec{E}(x, 0, z, t) = \vec{E}(x, P_y, z, t) \exp(jk_y P_y) \quad (4)$$

Where k_y is the propagation constant along y-direction.

C. Generalized pencil of function GPOF

The original idea of the process of extracting eigen modes requires long time to wait for decaying the non-eigen modes and extracting the eigen modes using Fourier transformation. GPOF is a method to shorten the simulation time of extracting the eigen frequencies by using a short segment of FDTD simulations to predict the late response as a sum of complex exponentials [21], one method to do that is to use the GPOF technique [15].

In general, we can approximate a time response $y(t)$ as:

$$y(t) \approx \sum_{i=1}^M R_i \exp(s_i t) \quad (5)$$

Where R_i are the residues of the complex exponentials, M is the number of modes, and s_i are the complex poles.

Given that the signal sampled every δt we have:

$$y(k) = y(k\delta t) \approx \sum_{i=1}^M R_i \exp(s_i k\delta t) \quad (6)$$

Where $k = 0, 1, 2, \dots, N-1$, N is the number of samples, and note that δt will not in general equal the time step Δt in FDTD simulation, but it is an integer multiple of Δt where the multiplication factor d is called the decimation. Hence,

$$\delta t = d\Delta t \quad (7)$$

The general objective in GPOF method is to get the best estimates of M , R_i s and s_i s [21], but the procedure followed in this paper is to assume a reasonable assumption of M and using the GPOF method to estimate the complex poles only since they are the quantities of interest.

We can define two matrices $[Y_1]$ and $[Y_2]$ as [21]:

$$[Y_1] = \begin{bmatrix} y(0) & y(1) & \dots & y(L-1) \\ y(1) & y(2) & \dots & y(L) \\ \vdots & \vdots & & \vdots \\ y(N-L-1) & y(N-L) & \dots & y(N-2) \end{bmatrix} \quad (8)$$

$$[Y_2] = \begin{bmatrix} y(1) & y(2) & \dots & y(L) \\ y(2) & y(3) & \dots & y(L+1) \\ \vdots & \vdots & & \vdots \\ y(N-L) & y(N-L+1) & \dots & y(N-1) \end{bmatrix} \quad (9)$$

Where L is called the pencil parameter, the value of L is estimated as a fraction of N . Using singular value decomposition, $[Y_1]$ can be written as [15]:

$$[Y_1] = [U][D][V]^H \quad (10)$$

Truncating the matrices $[U]$, $[D]$, and $[V]$ using M and defining a matrix $[Z]$ as [15]:

$$[Z] = [D_M]^{-1}[U_M]^H[Y_2][V_M] \quad (11)$$

And from z_i the eigen values of the matrix $[Z]$ we can find the complex poles using [15]:

$$s_i = \frac{\ln(z_i)}{\delta t} \quad (12)$$

Where the eigen frequencies can be obtained from these poles. But the GPOF may result in erroneous eigen frequencies and some correction criterions were presented in [15] to reject those frequencies; among them the criterion Q is found after many trials to be sufficient and it is the only one to be used in this work. This criterion is based on calculating the following quality factors and comparing them to a predefined threshold:

$$Q_i = \frac{\text{Im}(s_i)}{\text{Re}(s_i)} \quad (13)$$

III. DESCRIPTION OF THE PROCEDURE FOLLOWED TO OBTAIN THE DISPERSION DIAGRAM

The main parts of the simulation space are shown in fig.1; the planar EBG structure backed with PEC layer is shown at the bottom of the space, the four side boundaries are PBC to simulate periodicity, and the top layer is CPML to simulate open space above the EBG structure and it should be noted that the four PBC boundaries extends in the CPML layer. The electric and magnetic field components inside the space are updated using Yee algorithm while the fields at CPML layer or on the side boundaries are updated using the appropriate equations [19][22]. It is noted that the CPML layer is located some distance above the substrate.

On the vertical axis of the dispersion diagram to be plotted we have the eigen frequencies of the various modes. On the horizontal axis we have three critical points which are called Γ , X, and M respectively. At the Γ point both k_x and k_y are equal to zero, at the X point $k_x = \pi/P_x$ while k_y is zero, and at the M point $k_x = \pi/P_x$, $k_y = \pi/P_y$. Between Γ and X points k_y is kept fixed while k_x is increased from zero to π/P_x , between X and M points k_x is kept fixed while k_y is increased from zero to π/P_y , and from M to Γ point again both k_x and k_y values are decreased gradually to zero.

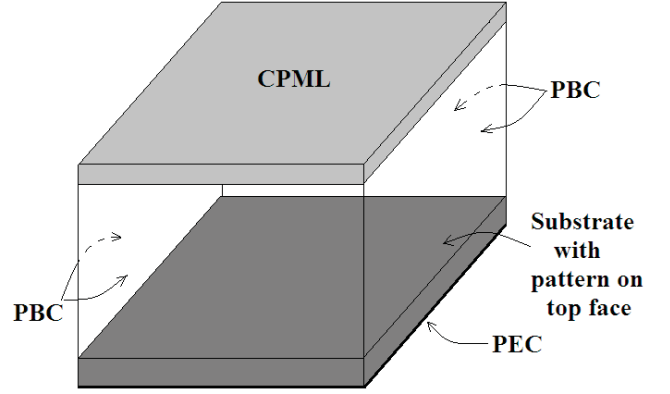


Fig. 1. The simulation space with main parts shown.

Before starting FDTD simulation, a fixed values of k_x and k_y should be defined according to the sequence defined above.

The substrate is excited by many sources with different polarizations distributed randomly to excite all possible modes. The spectrum of the excitation signal should cover all the desired bandwidth. A suitable waveform for this purpose is the modulated Gaussian pulse [1]:

$$f(t) = \exp\left[-\frac{(t-t_0)^2}{2\sigma_t^2}\right] \exp[j2\pi f_0 t] \quad (14)$$

Where t_0 denotes the time delay required to shift the center of the Gaussian pulse from time zero since the simulation starts at zero, σ_t defines the pulse width, and f_0 is the center frequency of the resulting spectrum.

Probing points that record the electric field values with different polarizations should be located in the substrate at random locations and their density should be sufficient to detect all possible modes.

The recording of the probe points should be once every d time steps and should start after excitation stage is finished at suitable time step denoted by n_i , the simulation should continue for sufficient time and terminated at a time step denoted by N_{max} . The required sequence $y(k)$ is taken as the average of all probe records.

The GPOF technique will give M values of complex poles from which the eigen frequencies are those which have an absolute value of Q greater than a predefined threshold. Then the whole procedure should be repeated for a new pair (k_x, k_y) and so on, until the whole dispersion diagram is completed. The band gaps are those frequency bands which are empty of any modes.

IV. THE PROPOSED STRUCTURE AND DISPERSION ANALYSIS

The proposed structure is shown in fig.2a together with the classic uniplanar EBG structure [3] in fig. 2b. The main advantage of these structures that they are completely planar and no need for vias that complicate the fabrication process.

The structure shown in fig. 2b has many resonance frequencies at which the structure prohibits surface waves. These resonance effects can be observed by noticing that the thin strips produce inductive effects while the patches

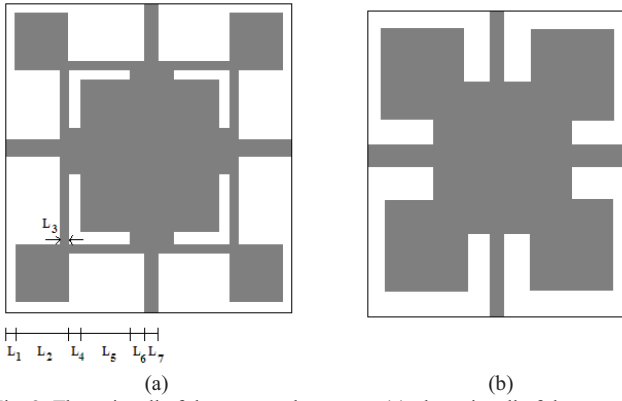


Fig. 2. The unit cell of the proposed structure (a), the unit cell of the conventional uniplanar EBG.

produce capacitive effects; first resonance occurs between the strips and the entire patches together as a single patch, the central patch is responsible of the second resonance, and a third resonance is produced by the strips and the corner patches [23].

The proposed structure in fig. 2a is designed to use the same principle of strips and patches to obtain multiple resonances.

The substrate used in this design has a substrate thickness of 1.27mm and a dielectric constant of 6.15. The proposed pattern dimensions of this structures are given in table I where all dimensions are in mm.

TABLE I. DIMENSIONS OF THE STRUCTURE IN FIG. 2a TO MEET THE DESIGN REQUIREMENTS

L_1	L_2	L_3	L_4	L_5	L_6	L_7
0.4	3.0	0.4	0.6	3.8	1.4	0.4

To simulate this structure, a single cell is simulated in the solution space similar to that of fig. 1. Standard finite difference time domain with $\Delta x = \Delta y = 0.2\text{mm}$, $\Delta z = 0.127\text{mm}$, and $\Delta t = 0.314\text{ps}$, the structure was excited with 36 source points with different polarizations distributed in the substrate, while the fields were recorded with 36 probing points that record different polarizations also distributed randomly in the substrate.

The electric and magnetic fields are updated in time until a sufficient number of steps can be used to obtain eigen frequencies using the GPOF technique. The parameters of the GPOF technique which were found to be good after many trials are given in table II and used in this work.

TABLE II. THE GPOF PARAMETERS TO BE USED IN EXTRACTING THE EIGEN FREQUENCIES

n_i	N_{max}	M	d	L/N
3500	10000	16	14	0.35

The number of modes M is set here to be 16 although the real number of modes is unknown before the simulation, this is not a problem since it is found that the false modes will in general have a low value of Q defined in (13). The threshold value of Q used to extract the correct eigen frequencies is 40, where the absolute values of Q_s will be compared to this threshold.

The resulting dispersion diagram is plotted in fig. 3 together with data computed using HFSS for comparison, which shows clearly a three distinct band gaps at 1.92-3.05GHz, 3.77-4.48GHz, and 4.65-5.78GHz where the first and third gaps are compatible with the WLAN requirements. Fig. 3 shows a very good agreement between the FDTD/GPOF procedure and HFSS, hence, the procedure is validated.

Some few notes can be drawn from fig. 3, first, it can be seen that the procedure failed in distinguishing two closely spaced eigen frequencies and returns only one point, second, we have at least one false point in the diagram, finally, fig. 3 shows the tendency of HFSS curves to bend downward following the light line while the FDTD curves does not bend, a result also obtained in comparing dispersion diagrams in [24] and [25].

The wave suppression property of the proposed EBG structure can be further investigated using the suspended microstrip line technique [26], the method is illustrated in fig. 4 where the ground plane of a microstrip line is replaced with a planar array of EBG cells. Although an infinite number of EBG cells is required to show the band gap characteristics of fig. 3, but even a small number of cells is enough to show some of these properties. At the forbidden frequencies the EBG structure will block the propagation and the transmission between ports 1 and 2 in fig. 4 will be highly attenuated [27].

A 2×4 array of the proposed structure is used here with a microstrip placed 0.635mm above the array on a supporting material with relative permittivity of 6.15. The structure is simulated using HFSS and the magnitude of S_{21} is plotted in fig. 5 together with the magnitude of S_{21} for the normal case of conductor ground for comparison. In fig. 5 it is observed that the transmission is very good for the normal case, but in the case of EBG ground the transmission is highly attenuated at frequency bands compatible with that obtained in fig. 3 except for the presence of a band gap around 3.2GHz not very clear in fig. 3.

V. CONCLUSION

A novel multiband uniplanar EBG structure has been proposed in this paper, each band gap is produced as a result of resonance effects resulting from various inductive and capacitive parts of the structure. The structure has been analyzed using FDTD for a relatively short time and the GPOF technique has been used to extract the eigen frequencies. The results obtained using FDTD/GPOF procedure has been validated by comparison with HFSS simulation results where the two results showed a good agreement. The obtained results have been also investigated using a suspended microstrip line method and results compatible with those obtained in the dispersion diagram have been obtained.

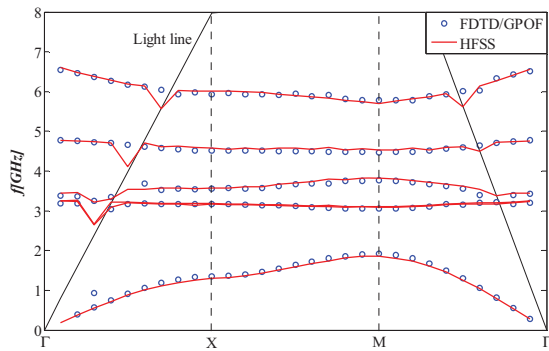


Fig. 3. Dispersion diagram of the proposed structure computed using the FDTD/GPOF technique and HFSS.

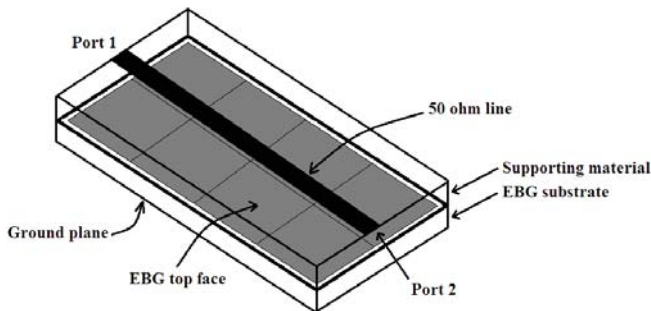


Fig. 4. Suspended microstrip line on a 2×4 array of the proposed EBG structure

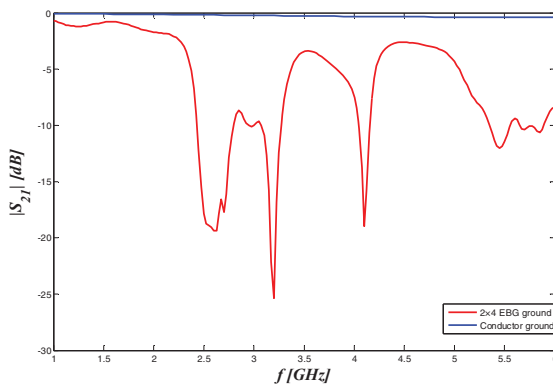


Fig. 5. Simulated $|S_{21}|$ for the case of conductor grounded microstrip line and the case of 2×4 EBG ground

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