Verification, enhancement and mathematical analysis of EBG structure using complex geometrical shapes and eigenmode analysis approach

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Abstract

The study presents the enhancement in analysis formulae and its verification for Electromagnetic Band Gap (EBG) structure using the Eigenmode analysis method. Eigenmode analysis of EBG structure is a compact and prolific method for obtaining its performance parameters like surface bandgap (bandwidth) and resonant frequency. The enhancement in mathematical expressions of the gap width, the capacitance, and the bandwidth is carried out using the simple geometrical shapes like square, circle, and hexagon. The verification of the enhanced formulae of the EBG structure is conducted using complex shapes. The theoretical and simulated results agree with each other up to 94% accuracy.

Keywords Unit cell · EBG structure · Surface bandgap

1 Introduction

In the recent past, microstrip antenna with EBG structure was popular due to its peculiar features like surface wave suppression, bandwidth enhancement, and improvement in the efficiency of antenna [1–5]. The characterization of EBG structure is obtained using techniques like plane-wave-expansion method [6–8], finite-difference method [9], finite-element method [10, 11], and transfer-matrix method [12, 13]. A variety of other techniques are also used, such as the effective medium theory [14], phased-array method [15], Eigenmode expansion method [16], array scanning method [17], and hybrid methods [18, 19], Full-wave simulation, Finite Domain Time Difference (FDTD) method and circuit model-based method [20]. The full-wave simulation method based on a diffraction grating is developed for a finite number of periodical layers of the EBG structure [21].

Generalized-pencil-of-function (GPOF) algorithm is developed as a post-processing procedure in the finite-difference time-domain (FDTD) method for EBG structure

analysis. The technique reduces the computational burden by reducing an excessive number of time steps [22]. The circuit model is build up using the patches and meander lines as connecting bridges based on the rigorous analysis of the propagation effects for each unit cell of the EBG structure [23].

The circuit model for the hybrid structure consisting of resistance, which represents the permeability losses due to the ferrite layer is proposed. It is also demonstrated that both the inductor and resistor components are frequency-dependent [24].

The research of any technology relies on mathematical modeling and reaches up-to computational simulation. In this paper, the computational simulation method is used to enhance the basic analysis formulae. The FDTD based Eigenmode analysis is used to simulate the unit cells of various shapes of the EBG structure. These simulated results are put into a mathematical model, and the enhancement of formulae like the gap width, capacitance and surface bandgap are achieved.

The major contributions of this paper are focused on,

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- Investigation and validation of the expressions of the capacitance and bandwidth for considered geometrical shapes like circle, hexagon, and complex designs like circular fractal shapes where the gap-width is not constant at every point on the edge of cells.
- The analysis is carried out using the Eigenmode analysis approach, and the expressions of bandwidth and capacitance are validated and enhanced.

The paper organization is as follows. In Sect. 2, a model of EBG structure and its mathematical analysis is demonstrated. Section 3 discusses the Eigenmode analysis approach using the simulation setup for EBG analysis. Section 4 focuses on simulations of various shapes, while Sect. 5 elaborates on results, and suggestions regarding the enhancements in the analysis of the bandwidth expressions. Section 6 describes the brief conclusions.

2 EBG structure and its mathematical analysis

EBG structure is a modified ground surface with the metallic patches printed on the substrate. These patches are known as cells which are either periodic or non-periodic. These cells are separated by a particular gap width [25–28]. The dimensions of a patch and gap width are much less than the operating frequency (λ) of an antenna [3, 29–31]. The EBG cells are shorted to the ground surface using conducting pins or wires, which are called vias [32–34]. The geometry of EBG structure, typically Sivenpiper's Mushroom structure, is shown in Fig. 1.

Fig. 1 Geometry of Mushroom like Sivenpiper's EBG structure

A Sivenpiper's mushroom EBG cell comprises a metallic patch of width ' w ' which is separated from another patch by the distance ' g ', which is called gap width. The via is present between EBG cell and ground surface, and its height is ' h '. The patch width of EBG cell, gap width, and height of via form the effective capacitance and inductance [20, 32, 35, 36]. Figure 2 shows the side view of mushroom, like Sivenpiper's EBG structure showing the dimensions of the EBG structure.

LC resonating circuit model best describes the structure, and its effective capacitance and inductance values are evaluated with the help of Eqs. (1) and (2),

$$C = \frac{w\epsilon_0(1 + \epsilon_r)}{\pi} \cosh^{-1} \left(\frac{w + g}{g} \right) \quad (1)$$

$$L = \mu h \quad (2)$$

where ' w ' is a unit cell patch width, ' ϵ_0 ' is free space permittivity, ' ϵ_r ' is relative permittivity of the substrate, ' g ' is a gap width, ' μ_r ' is the relative permeability of the substrate, ' μ_0 ' is free space permeability ($\mu = \mu_0\mu_r$), and ' h ' is the height of the substrate. The physical parameters of the EBG cell are shown in Fig. 3a. The conducting via has the height of h , and its radius is r . Figure 3b shows the equivalent capacitance ' C ' and inductance ' L '.

The EBG structure's for the calculation of bandwidth, resonant frequency, and impedance of EBG structure are derived as follows [20, 32, 36].

Let Z_s be the surface impedance of the EBG structure. The reflection coefficient Γ and the reflection phase can be computed as:

$$Z_s = jX \quad (3)$$

Fig. 2 Mushroom-like electromagnetic bandgap (EBG) structure's side view

Fig. 3 **a** Physical parameters of the EBG cell and **b** Equivalent LC model

$$\Gamma = \frac{(Z_S - \eta_0)}{(Z_S + \eta_0)} \quad (4)$$

$$|\Gamma| = 1 \quad (5)$$

$$\angle \Gamma = \pi - 2 \tan^{-1} \left(\frac{X}{\eta_0} \right) \quad (6)$$

The bandwidth of the EBG structure is defined as the band of frequencies where the reflection phase is between $+90^\circ$ and -90° . The condition of the surface bandwidth can be found as:

$$-90^\circ \leq \angle \Gamma \leq +90^\circ \quad (7)$$

Using Eqs. 6 and 7, it can be written as,

$$-\eta_0 \geq X \geq +\eta_0 \quad (8)$$

Let ω_1 be the angular frequency where $X = \eta_0$, so

$$Z_S = j\eta_0 \quad (9)$$

Further,

$$Z_S = \frac{j\omega_1 L}{1 - \left(\frac{\omega_1}{\omega_0} \right)^2} \quad (10)$$

$$\therefore \omega_0^2 - \omega_1^2 = \frac{(\omega_0^2 L \omega_1)}{\eta_0} \quad (11)$$

Let ω_2 be the angular frequency when $X = -\eta_0$. From Eqs. (10) and (11),

$$BW = \omega_2 - \omega_1 = \frac{\omega_0^2 L}{\eta_0} = \frac{1}{120\pi} \sqrt{\frac{L}{C}} \quad (12)$$

From Eq. (12), it can be observed that the bandwidth given in the relevant literature is equal to the mathematical expression derived [36].

The equations from (1)–(12) are used to find the performance parameters of the EBG structure like bandwidth, resonant frequency, and the surface impedance. These equations are derived for a square-shaped EBG cell where the gap width 'g' is constant between adjacent cells.

3 Eigenmode approach for EBG Structure

The EBG structure is analyzed using full-wave simulation methods like Finite Element Method (FEM) and Method of Moments (MOM). The full-wave simulation methods require huge memory and time for their execution.

Finite Difference Time Domain (FDTD)-Periodic Boundary Condition (PBC) is widely used to analyze the EBG structure. It gives a wide visibility of performance using a simple simulation setup [37, 38]. The method helps to predict the performance of the EBG structure by simulating a single cell of the EBG structure. Figure 4 depicts the simulation setup of Eigenmode analysis.

FDTD-PBC based unit cell analysis method is carried out using two approaches viz. scattering mode analysis and Eigenmode analysis. For the first one, an EBG cell is placed with an airbox of finite size, the sidewalls of the air box are applied with Periodic Boundary Condition (PBC). The upper surface of the air box is applied with a floquet port. The scattering analysis gives a reflection and transmission curves for the selected frequency range, and the surface band is predicted.

For Eigenmode analysis, the EBG cell is placed in the airbox of a height six times more than the height of the substrate. A Perfectly Matched Layer (PML) boundary is applied to terminate the airbox. This airbox is enclosed in another airbox whose sidewalls are applied with PBC along x and y directions. The phase shift along the transverse direction is kept at 0° , while the phase along the direction of propagation is varied from 0° to 180° .

The dispersion curve and the surface band gap for various modes obtained using Eigenmode analysis and a graphical method [39, 40].

Fig. 4 Simulation Setup design of FDTD/PBC based Eigenmode analysis

The following steps are carried out for analysis of EBG structure using the FDTD-PBC method wherein the electromagnetic fields are calculated using the following technique [20].

- The electromagnetic (EM) fields in the interior of the EBG cell in free space are updated Yee's scheme.
- Equations (13) and (14) are used to calculate EM fields on the periodic boundaries of a computational domain.

$$E(x = 0, y, z, t) = E(x = p, y, z, t)e^{ipk_x} \quad (13)$$

$$H(x = 0, y, z, t) = H(x = p, y, z, t)e^{ipk_x} \quad (14)$$

where the periodicity of EBG cells is p .

- The elimination of the reflections in the Perfectly Matched Layer (PML) region is possible by setting the material properties as per (15) (16), (17), and (18).

$$\bar{s} = \begin{bmatrix} s_x^{-1} & 0 & 0 \\ 0 & s_x & 0 \\ 0 & 0 & s_x \end{bmatrix} \cdot \begin{bmatrix} s_y & 0 & 0 \\ 0 & s_y^{-1} & 0 \\ 0 & 0 & s_y \end{bmatrix} \cdot \begin{bmatrix} s_z & 0 & 0 \\ 0 & s_z & 0 \\ 0 & 0 & s_z^{-1} \end{bmatrix} \quad (15)$$

$$s_x = 1 + \frac{\sigma_x}{j\omega\epsilon_0} \quad (16)$$

$$s_y = 1 + \frac{\sigma_y}{j\omega\epsilon_0} \quad (17)$$

$$\left(s_z = 1 + \frac{\sigma_z}{j\omega\epsilon_0} \right) \quad (18)$$

The following procedure is carried out to implement a constant k_x method.

- The propagation constant $k_x(\beta)$ is obtained.
- Acquired results are plotted in k_x -frequency plane.
- The Eigen frequencies are identified for the propagation constants in x and y directions.
- The extraction of the resonant frequencies of surface waves is undertaken.
- The Dispersion is plotted to obtain the surface band gap [20, 41].

In this research work, Eigenmode analysis approach is applied to obtain the bandwidth and the center frequency of the unit EBG cell. This empirical bandwidth is verified using a mathematical approach, and an enhancement in its formulation is suggested for an improvement in results.

4 Simulation of experiments for various shapes of EBG cell

In this section, the simulations are carried out for the basic geometrical shapes using Eigenmode analysis. The simulations are conducted using High-Frequency Simulation Software version 11 (HFSS 11). The EBG cells of the same footprint and gap widths are taken into consideration. The effect of gap width for complex shapes and its expression is enhanced using fractal shapes.

Fig. 5 Dimensions of **a** Square, **b** Circular and **c** Hexagonal unit cell for Eigen Analysis

Initially, the square-shaped EBG cell is simulated using the dimensions as $w=6$ mm, $h=1.6$ mm, $g=1$ mm, $\epsilon_r=4.4$, $r=0.1$ mm. The geometry and dimensions of the square-shaped EBG cell is shown in Fig. 5a. For circle and hexagonal shapes, the width or footprint of the cell is kept as $w_{\text{EBG}}=6$ mm, $h=1.6$ mm, $\epsilon_r=4.4$, $r=0.1$ mm. The gap width g , for circular and hexagonal shapes, is considered between the two nearest points of adjacent EBG cells, as shown in Fig. 5b and c.

Table 1 describes the bandwidths and center frequencies obtained using Eigenmode analysis. From Table 1, it is observed that though the dimensions of the EBG cells are the same and the corresponding bandwidths and center frequencies are different for each case. This variation is due to the shape of the EBG cell, which offers different gap width values between the adjacent cells.

It is observed from Eqs. (1) and (12) that the gap width plays a vital role in deciding the capacitance of the EBG structure as well as its bandwidth.

To study and observe the effect of the gap width for circle and hexagon shape, the gap widths between them are measured at different points, as shown in Figs. 6 and 7. The gap widths g_1 and g_2 are considered between the two nearest points and farthest points, respectively, for these two shapes. There are an infinite number of values of gap width between g_1 and g_2 .

Therefore, for accurate analysis of such complex shapes, there is a need to modify the gap width equation. Various gap widths should be considered between the adjacent cells. The gap width for such shapes is selected in such a way that the average gap width is found to be equal to 1 mm for the verification of practical and simulated results.

Exhaustive computational simulations are carried out by varying the gap width for the validation of the equation. The equivalent gap width is calculated using averaging of discrete samples of the available gap widths as described in Eq. (19),

$$g_{\text{avg}} = \frac{1}{n} \sum_{n=1}^n g_n \quad (19)$$

Equation (19) is validated for various sizes of circular and hexagonal shapes. To further investigate the performance

Table 1 Comparison of band-gaps and center frequencies for three basic shapes

Shape of unit cell	Width of patch w (mm)	Gap width g (mm)	Surface band-gap (GHz)	Center frequency f_r (GHz)
Square	6	1	1.83–3.26	2.545
Circle	6	1	2.08–4.83	3.455
Hexagon	6	1	2.11–4.72	3.415

Fig. 6 Geometry of Circular EBG cell and its corresponding dimensions

Fig. 7 Geometry of Hexagonal EBG cell and its corresponding dimensions

of this equation, complex shapes with more number of intermediate gap widths are designed, simulated, and tested. Figure 8 shows the circular fractal shaped EBG cell with one iteration where the width or footprint of the cell is kept 6 mm constant throughout. The gap widths are different at different points but are adjusted to the values such that the average gap width, g_{avg} , is equal to 1 mm.

Two iterations based circular fractal shaped EBG cell is designed having a footprint size of 6 mm and simulated using Eigenmode analysis approach.

Fig. 8 Geometry of circular-shaped fractal unit cell with one iteration

Fig. 9 Geometry of circular-shaped fractal unit cell with 2 iterations

Figure 9 shows the geometry and dimensions of a circular-shaped fractal unit cell with two iterations. The parameters obtained after simulation are tabulated in Table 2.

Table 2 clearly states that even for the same width of patch and gap-width, variation in the parameters for various shapes is obtained. The gap-width is kept as 1 mm in all cases, but for square shape, it was constant for every point on adjacent edges. The gap width for other shapes is not the same throughout the curvature. It is, therefore, needed to enhance the theoretical expression for capacitance as it depends on a gap-width.

Table 2 Parameters for circular fractal shaped EBG cell

Shape of unit cell of fractal shape	Width of patch w (mm)	Gap width g_{avg} (mm)	Surface band-gap (GHz)	Center frequency f_r (GHz)
Circle	6	1	2.11–4.72	3.415
Circle with 1st iteration	6	1	1.8–5.21	3.505
Circle with 2nd iteration	6	1	1.1–6.32	3.71

Table 3 Theoretical and practical values of parameters of square-shaped EBG structure

Patch width W (mm)	Height of substrate h (mm)	Gap width G (mm)	Theoretical inductance L (nH)	Theoretical inductance C (pF)	Theoretical Band-width BW (Hz)	Band-gap using Eigen-mode analysis approach (GHz)
4	1.6	0.5	2.0112	0.162827	0.294953146	2.9801
4	1.6	1	2.0112	0.129281	0.331015708	4.4345
4	1.6	2	2.0112	0.09941	0.377486817	7.1025
6	1.6	0.5	2.0112	0.275485	0.226760828	1.2043
6	1.6	1	2.0112	0.222809	0.252144925	1.6559
6	1.6	2	2.0112	0.000169179	9.150464168	701441.9
8	1.6	0.5	2.0112	0.0000563929	15.84910154	5062117.6
8	1.6	1	2.0112	0.000112785	11.20703169	146948.3
8	1.6	2	2.0112	0.000225568	7.924605745	417133.7

5 Discussions on the results

This section focuses on the need for improvement in bandwidth expression of the EBG structure. The improvement is suggested based on the simulation results of fractal shapes of EBG cells obtained using FDTD-PBC analysis method.

The enhanced capacitance expression can be given as per Eq. (20),

$$C = \frac{w\epsilon_0(1 + \epsilon_r)}{\pi} \cosh^{-1} \left(\frac{w + g_{avg}}{g_{avg}} \right) \quad (20)$$

The following steps are carried out for investigating the validity of bandwidth expression.

- Mathematical analysis is carried out considering the square-shaped EBG cell with various patch widths and gap widths.
- The corresponding equivalent, capacitance, inductance, and bandwidth are calculated.

Several iterations of simulations are conducted to obtain the modified expression for the bandwidth. The simulations are conducted for various gap widths and patch widths of the EBG cells. The results of a few of the simulations are tabulated in Table 3. The theoretical as well as simulated results obtained for square-shaped unit cells for various widths

Table 4 Theoretical and practical values of parameters of complex shapes of EBG

Shape of unit cell	Width of patch w (mm)	Surface band-gap bandwidth (GHz)	Calculated bandwidth using enhanced formula in GHz
Square	6	1.48	1.4692
Hexagon	6	2.75	2.6987
Circle	6	2.61	2.581
Fractal circle with 1st iteration	6	3.41	3.395
Fractal circle with 2nd iteration	6	5.22	5.183

Fig. 10 Plot of error in simulated and calculated results for various shapes

of patch and gap widths are shown in Table 3. It can be observed that there is a remarkable difference in theoretical and simulated bandwidth results. Hence, there is a requirement to modify the formula for bandwidth. The enhanced expression for bandwidth which is stated in Eq. (21),

$$BW = \frac{L^{1.5}}{\pi C^{1.8}} \quad (21)$$

The Eq. (21) is formalized using regression analysis and based on an empirical method. The validation is carried out for circle, hexagon, and circular fractal shapes, and the results are tabulated in Table 4.

From Table 4, it is observed that simulated and calculated bandwidths agree with each other up to 94% accuracy. Figure 10 shows the plot of percentage error in theoretical and practical results concerning the shapes of EBG cells.

The strong agreement between the simulated and calculated results (obtained from the enhanced formula of bandwidth) is the achievement of the research. The earlier research has focused on the new techniques of EBG structure analysis. While this paper discusses enhancing the traditional analysis formulae so that the accurate mathematical analysis can be carried out.

6 Conclusion

The modern tools for the analysis of complex designs of microstrip antenna and EBG structure are useful for the prediction of their performance. The Eigenmode based analysis method proves to be efficient for the verification of mathematical analysis and enhancement of expressions used for the analysis. The gap width for some geometrical shapes

like circular and hexagonal unit cells is not uniform at every point between the adjacent cells. Therefore, an improvement in gap-width calculation based on sampling and averaging method is suggested. This improvement is validated with practical results obtained using FDTD-PBC based Eigenmode analysis approach. The equation for gap width is verified for complex shapes based on circular fractal shapes of EBG cells. Further, the analytical formulation of capacitance is enhanced using regression analysis and verified with simulated results. The Eigenmode analysis can be further investigated for exploring different parameters of EBG structure and similar materials like Artificial Magnetic Materials (AMC), High Impedance Surface (HIS), Photonic Band Gap (PBG) materials.

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Conflict of interest The authors declare that they have no conflict of interest.

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