A Novel 2D Z-Shaped Electromagnetic Bandgap Structure

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***Abstract*—This paper researches a novel 2D Z-shaped Electromagnetic Band-Gap (EBG) structure, its dispersion diagram and application field. Based on a transmission line model, the dispersion equation is derived and theoretically investigated. In order to validate theoretical results, a full wave analysis is performed and the electromagnetic properties of the structure are revealed. The theoretical results show good agreement with the full wave simulation results. The frequency response of the structure is compared to the well know structures of Jerusalem cross and patch EBG. The results show the applicability of the proposed 2D Z-shaped EBG in microstrip patch antennas, microstrip filters and high speed switching circuits, where the suppression of parasitic surface wave is required.**

Keywords- Electronic Band-Gap (EBG) structures; microstrip patch antennas; microwave filters; high speed switching circuits.

I. INTRODUCTION

The concept of EBG structures originates from solid state physics and optics, where photonic crystals with forbidden band gaps were proposed in [1-3]. In the following years, photonic crystals have gained the interest of the scientific community, and a number of researches have been made upon them [4-6]. The terminology Photonic Band Gap (PBG) structures were used in these years. In recent years, structures, similar to the PBG, were studied in microwave frequencies [7]. The band gap attribute was first researched and documented in the early 1990's [8]. Since then, many researches and applications for this novel technology have been applied to microwave devices, reducing the switching noise in high speed switching circuits, reducing the surface wave in planar microstrip antennas, giving forbidden frequency bands in microwave filters, and used in other types of microwave devices, like power amplifiers, dividers, mixers etc. [1-14].

The EBG structures can be divided into three major categories – volumetric 3D structures, 2D planar structures, and 1D transmission line structures. The 1D transmission line structures have been analyzed as a periodic array of drilled holes in the dielectric substrate under the transmission line [13] or as a composite right-left handed transmission line [14]. Another classification of the EBG also consist of mushroom-type [1] or uni-planar type [15]. The main difference is the via to the ground metalized plane, that can lead to significant change in the structure's behavior.

The design of EBG structures can be performed by two different methods: the transmission line method and the full-wave analysis method. The transmission line method approximates the structure with transmission lines and their physical parameters. The dispersion equation of the structure can be derived according to the circuit theory using the transmission line matrix representation. The transmission line method is preferred when an approximate solution to given structures is necessary. It is of lower computational complexity and it is faster than the other methods used. The transmission line method however, suffers from approximation errors.

The full-wave method of analysis is the other method, used in the analysis and simulation of EBG structures. It solves the Maxwell equations with periodic boundary conditions to a unit cell. It gives more accurate results compared to the transmission line method. Different computational methods for full wave analysis are implemented in the software products. The most used of them are the finite difference time domain (FDTD) and frequency domain (FDFD) methods, the method of moments (MoM) and the finite element method (FEM). Depending on the topology of the periodic structure and its application, different techniques may be used in different design scenarios. A more detailed survey of the different types of full-wave computational electromagnetic analysis methods can be found in [17].

In this paper, a novel Z-shaped EBG periodic structure is proposed. A theoretical model based on transmission line theory is presented and a closed form dispersion equation for the structure is derived. The properties of the structure are investigated using the k-β diagrams. In order to validate the theoretical results, a finite difference time domain (FDTD) based full wave simulation is performed. The theoretical and simulation results show good agreement in the cut-off frequencies of the bandgaps of the structure. The frequency response of the proposed structure is compared to Jerusalem cross and patch EBG and it shows similar characteristics and applicability in microwave devices.

II. TRANSMISSION LINE MODEL AND DISPERSION DIAGRAM

The transmission line method, applied for the novel Z-shaped EBG structure consists of two 90 degree rotated, Z-shaped segments, interconnected and via grounded in the center. It is represented by a section of main transmission line and open end arms in both ends. The arms of one unit cell form a coupled lines with the adjacent unit cells in x and y direction. The Z-shaped 2x2 unit cells and the important points of the structure are shown in Figure 1. From point A to point B is the length of the main transmission line of the Z-shaped structure l_a. The line from point B to point C forms the coupling with the adjacent cell with length l_c. The space period is denoted with d.

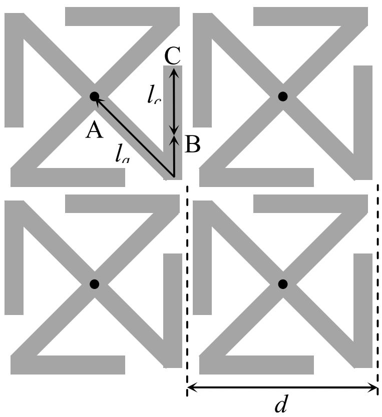

Fig. 1. 2x2 periodic unit cells Z-shaped EBG structure.

In order to derive the structure dispersion diagram is necessary to evaluate the complete ABCD matrix of one unit cells in x or y direction. A unit cell is shown in Figure 2, which is presented with the equivalent transmission line matrices in each direction.

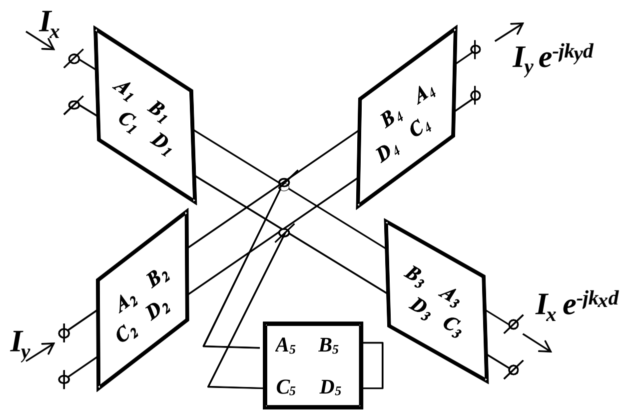

Fig. 2. Unit cell of a periodic structure, presented with the equivalent transmission matrices

The structure is modeled with its equivalent circuit, shown in Figure 3. Opposite open ended coupled lines can be represented by their T-equivalent circuit. The dashed line shows the line of symmetry of the unit cell. The coupled lines can be divided into two identical L sections.

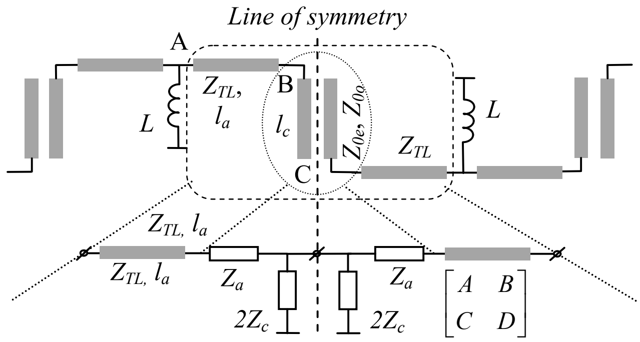

Fig. 3. Transmission line model of the Z-shaped EBG.

The ABCD matrix of the L section is [19]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{CL} = \begin{bmatrix} 1 & Z_a \\ \dfrac{1}{2Z_c} & 1+\dfrac{Z_a}{2Z_c} \end{bmatrix} \quad (1)$$

where

$$Z_a = -j\frac{Z_{0e}-Z_{0o}}{2}\cot(\beta l_c) + j\frac{Z_{0e}-Z_{0o}}{2}\frac{1}{\sin(\beta l_c)}$$

$$Z_c = -j\frac{Z_{0e}-Z_{0o}}{2}\frac{1}{\sin(\beta l_c)} \quad (2)$$

Z_{0e} and Z_{0o} are the even and odd impedances of the coupled lines, β is the propagation constant. The second part is the main transmission line, from point A to B. The ABCD matrix of a transmission line is [19]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{TL} = \begin{bmatrix} \cos(\beta l_a) & jZ_{TL}\sin(\beta l_a) \\ \dfrac{1}{jZ_{TL}}\sin(\beta l_a) & \cos(\beta l_a) \end{bmatrix}$$

where Z_{TL} is the characteristic impedance of the microstrip line.

The complete ABCD matrix is a product of both matrices in x or y direction:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{CL} \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{TL} =$$

$$= \begin{bmatrix} \cos(\beta l_a) + \dfrac{Z_a \sin(\beta l_a)}{jZ_{TL}} & jZ_{TL}\sin(\beta l_a) + Z_a \cos(\beta l_a) \\ \dfrac{\cos(\beta l_a)}{2Z_c} + \left(1 + \dfrac{Z_a}{2Z_c}\right)\dfrac{\sin(\beta l_a)}{jZ_{TL}} & \dfrac{jZ_{TL}\sin(\beta l_a)}{2Z_c} + \left(1 + \dfrac{Z_a}{2Z_c}\right)\cos(\beta l_a) \end{bmatrix} \quad (3)$$

According to the structure line of symmetry shown on Figure 2 , it can be written:

$$\begin{aligned} &A_1 = A_2 = A_3 = A_4 = A \\ &B_1 = B_2 = B_3 = B_4 = B \\ &C_1 = C_2 = C_3 = C_4 = C \qquad (4) \\ &D_1 = D_2 = D_3 = D_4 = B \\ &D_5 = 1 \quad B_5 = j\omega L \end{aligned}$$

The dispersion equation can be obtained, if the determinant of the matrix is set to zero. For the Z-shaped structure, applying the equations in [14, 18], the dispersion equation is derived as:

$$\cos(k_x d) + \cos(k_y d) = -2 + 4AD + BD\frac{1}{j\omega L} \quad (5)$$

where k_x and k_y are the wave numbers for x and y direction, and L is the inductivity of the via hole.

III. ANALYSIS AND RESULTS FOR THE Z-SHAPED 2D EBG STRUCTURE

A Z-shaped structure has been analyzed in order to verify the derived dispersion equation based on the transmission line method. The normalized parameters of the structure are given in Table I for *f=1.14GHz*.

TABLE I. NORMALIZED PARAMETERS (1.14 GHZ)

Parameters	l_c/λ	l_a/λ	a/λ	d/λ	$Z_{0e},[\Omega]$	$Z_{0o},[\Omega]$
Values	0.185	0.3	0.56	0.118	59.45	37.54

The diameter of grounding via is 0.75 mm. The solution of the dispersion equation is graphically represented in the Brillouin diagram, which shows the propagation of the electromagnetic wave in the *x*, *y* and diagonal direction. The dispersion diagram of the analyzed structure is shown in Figure 4.

The Z-shaped structure has a bandpass behavior, because of the opposite open ended coupled lines [19]. Thus the structure suppresses the low frequencies from DC to its first resonance. As the unit cell is a resonating structure, the passband and stopband alternatively changes. The main drawback of the transmission line model is that it loses accuracy at higher frequencies, where higher modes appear. In order to verify the applicability of the transmission line model, a full wave FDTD simulation of infinite periodic structure consists of Z-shaped unit cells is performed in Ansoft HFSS.

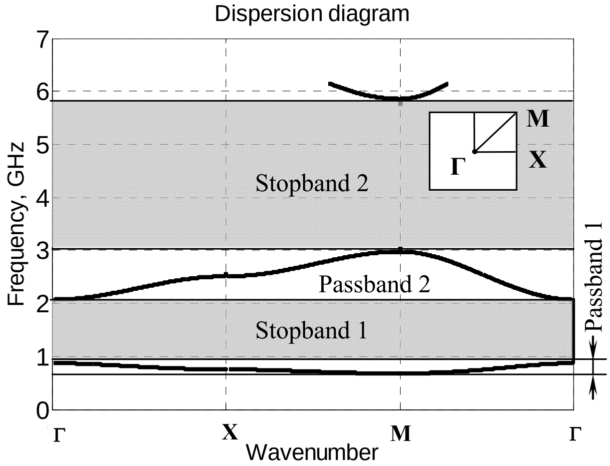

Fig. 4. Dispersion diagram for Z-shaped structure.

IV. FULL WAVE ANALYSIS OF Z-SHAPED 2D EBG STRUCTURE

Performing FDTD full wave simulations to the infinite 2D Z-shaped structure, the scattering parameters of the structure are analyzed. The dielectric substrate used in the simulations is FR-4, h=1.5mm, ε_r=4.4, tgδ=0.02. Figure 4 shows the reflection coefficient S_{11} and the transmission coefficient S_{21}. In the structure, the center resonance frequencies for both stopbands are located at 1.8 GHz and at 5.78 GHz, with S_{21} dropping to -39dB at the first band and to -43dB at the second stopband. The frequency response of the periodic structure is shown in Figure 5.

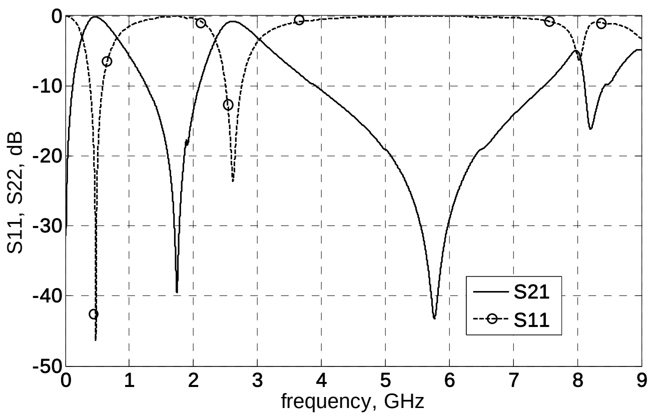

Fig. 5. Scattering parameters of the structure.

As expected the transmission line equivalent model of Z-shaped structure suffers from accuracy at higher frequencies, because of the higher modes. In order to define the applicability of the proposed Z-shaped structure, it is simulative compared to other known periodic structures [14] that exhibits bandpass characteristics. Figure 6 shows a comparison between full wave FDTD simulations of Z-shaped structure, Jerusalem cross and a patch EBG [14]. The Z-shaped structure has the same response behavior as the Jerusalem cross but at lower frequencies, because its topology. The patch EBG has another response behavior with wider stopband compared to the other two structures. This is due to the different coupling mechanism between the unit cells.

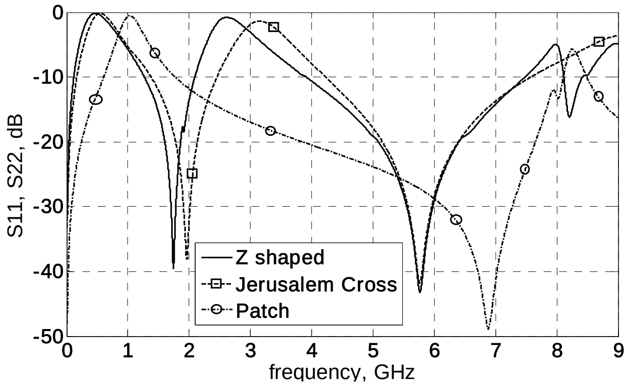

Fig. 6. Comparison of different EBG structures.

V. CONCLUSION

In this paper, a novel 2D Z-shaped EBG structure topology, dispersion equation and research is proposed. The structure exhibits two suppression bands and two passbands. A theoretical model, based on transmission line theory is proposed that allows analysis and synthesis of Z-shaped structures for different design requirements. The results from the theoretical and full wave FDTD simulations show good agreement at low frequencies. The comparison of the simulation results with two known structures show the applicability of Z-shaped structures in microstrip patch antennas, microstrip filters and high speed switching circuits where the suppression of parasitic surface wave is required.

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