Investigation of EBG array performance on decreasing the mutual coupling and improve shield factor

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Abstract

In this paper EBG structures including parallel plates of EBGs are being used to reduce the mutual coupling between the two omni-directional antennas. Here, we have chosen the Discone antennas as omni directional antennas and comparisons between uniform and non-uniform structure with conventional array of antenna is presented, and compared with the fractal structure for designing ultra wide band structure. The multi-layer EBG structure have been designed and simulated based on EBG metamaterial characteristics. Our aim is to reduce coupling or reduction of $S_{21}$ to have better coupling reduction and shielding effectiveness for applying the structure as an absorber or shield and shielding bandwidth in non uniform structure is increased up to 16 GHz.

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1. Introduction

One of the most important topics that are being concerned in many circuits especially with shortly separated elements is the coupling between the elements which results in the electromagnetic interference among the adjacent elements in different structures. Thus, reducing the coupling and achieving the ways for decreasing it more efficiently, is a problem that is always discussed in EMI topics. For this purpose, absorbers and common structures can be used for decreasing the coupling but there are usually discussions about their longevity, mechanical damages and other characteristics about them. Metamaterial structures are artificial materials containing periodic element and act as an efficient environment that have permittivity and permeability smaller than zero. These materials have been used in different applications in electromagnetic for their special characteristics. Using metamaterial structures in electromagnetic shields and absorbers for prevention of electromagnetic waves propagation, have been discussed in

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several papers (Lovat et al., 2008; Watts et al., 2012; Azarbar and Ghalibafan, 2011; Moghadasi et al., 2008). Using different metamaterial structures to decrease the coupling has been the subject of many researches. MNG’s metamaterial is used as a flat EBG to reduce coupling between microstrip patch antennas, which causes a −18 dB loss and also 60% loss in radiated power (Salehi and Tavakoli, 2006). Coupling between microstrip antenna arrays, is a problem that has always existed and leads to surface wave and reduction of performance of the antenna and disturbance the pattern shape. To solve this problem, meta-materials are used to reduce coupling between arrays in substrate of rectangular patch antenna arrays (Yang and Rahmat-Samii, 2003; Mirhadi and Kamyab, 2010; Xie et al., 2011). Frequency band gap structure, is a class of meta-materials that is actually artificial periodic materials (sometime non periodic) for preventing the propagation of electromagnetic waves in a defined frequency band in all directions of radiation and also for all types of polarization. EBG structures are the most famous periodic structures. It consists of metal or dielectric elements showing the band pass or band stop characteristics (Islam and Alam, 2013; Kim et al., 2011). These structures have been also used in other applications for decreasing the coupling up to 20 dB between two waveguides with parallel plate and eliminating surface waves between other structures (Mohajer-Iravani et al., 2006). Different planar EBG structures like mushroom and fractal shape are provided in order to develop the bandwidth, phase characteristics and coupling decreasing characteristics. Some studies have been also performed by modeling equivalent circuits (Farahani et al., 2010; Mohajer-Iravani and Ramahi, 2010; Kern and Werner, 2006).

Different types of slots like H and I that have been studied for reducing the coupling, can also reduce the total size. Fractal model have been studied as an effective method for reduce coupling and compact absorber design (Elsheakh et al., 2010; Cheng et al., 2009).

The EBGs printed on a multilayer dielectric substrate is used in microstrip antenna array to decrease the coupling and eliminate the surface waves (Rajo-Iglesias et al., 2008). The coupling coefficient is calculated by the following equation (Saenz et al., 2010):

$$|C|^2 = \frac{|S_{21}|^2}{(1 - |S_{11}|^2) - (1 - |S_{22}|^2)}$$

(1)

2. FEM model for EBG structure and Floquet expansion

Nowadays many full wave theoretical methods have been presented for analysis of EBG structure such as FDTD, FEM, MOM (Xiaoying and Lezhu, 2005). HFSS is full wave FEM simulator and available as a commercial software. In a general in homogeneous medium wave propagation shown with (2) and (3).

$$\nabla^2 E + k^2 E = j\omega\mu J + \frac{1}{\varepsilon}\nabla \varrho$$

(2)

$$\nabla^2 H + k^2 H = -\nabla \times J$$

(3)

$$E(r) = \int \int \int_V \left[-j\omega\mu J(r') - \frac{1}{\varepsilon}\nabla' \varrho(r')\right]G_0(r, r')dV'$$

(4)

$$E(r) = \int \int \int_V \left[\nabla' \times J(r')\right]G_0(r, r')dV'$$

(5)

where $G_0(r, r')$ denotes the point-source response, known as the scalar Green’s. Finite element method for three-dimensional structure at total condition defined with (6) (Li, 2010):

$$-\frac{\partial}{\partial x} \left(a_x \frac{\partial \Phi}{\partial x}\right) - \frac{\partial}{\partial y} \left(a_y \frac{\partial \Phi}{\partial y}\right) - \frac{\partial}{\partial z} \left(a_z \frac{\partial \Phi}{\partial z}\right) + \beta \Phi = f$$

(6)

via Galerkin weighted residual method for periodic structure we are able to calculate the periodic part of indicate wave as shown in (7)–(13) where $N$ is known as Galerkin weighted function:

$$r = \frac{\partial}{\partial x} \left(a_x \frac{\partial \Phi}{\partial x}\right) - \frac{\partial}{\partial y} \left(a_y \frac{\partial \Phi}{\partial y}\right) - \frac{\partial}{\partial z} \left(a_z \frac{\partial \Phi}{\partial z}\right) + \beta \Phi - f$$

(7)
and thus the weighted residual integral for element $e$ is

$$R^e_i = \iiint_{V^e} N^e_i r dv \quad \text{for} \quad i = 1, 2, 3, 4.$$  \hspace{1cm} (8)

$$R^e_i = \iiint_{V^e} N^e_i \left[ -\frac{\partial}{\partial x} \left( a_x \frac{\partial \Phi}{\partial x} \right) - \frac{\partial}{\partial y} \left( a_y \frac{\partial \Phi}{\partial y} \right) - \frac{\partial}{\partial z} \left( a_z \frac{\partial \Phi}{\partial z} \right) + \beta \Phi - f \right] dv$$  \hspace{1cm} (9)

$$R^e_i = \iiint_{V^e} \left( a_x \frac{\partial N^e_i}{\partial x} \frac{\partial \Phi^e}{\partial x} + a_y \frac{\partial N^e_i}{\partial y} \frac{\partial \Phi^e}{\partial y} + a_z \frac{\partial N^e_i}{\partial z} \frac{\partial \Phi^e}{\partial z} + \beta N^e_i \Phi^e \right) dv - \iiint_{V^e} N^e_i f dv - \hat{\Phi}_i N^e_i D \hat{r}^e ds$$  \hspace{1cm} (10)

$$D = a_x \frac{\partial \Phi}{\partial x} + a_y \frac{\partial \Phi}{\partial y} + a_z \frac{\partial \Phi}{\partial z}$$  \hspace{1cm} (11)

$$R^e_i = \sum_{j=1}^{4} \Phi_j x \left( a_x \frac{\partial N^e_j}{\partial x} \frac{\partial \Phi^e}{\partial x} + a_y \frac{\partial N^e_j}{\partial y} \frac{\partial \Phi^e}{\partial y} + a_z \frac{\partial N^e_j}{\partial z} \frac{\partial \Phi^e}{\partial z} + \beta N^e_j \Phi^e \right) dv$$

$$- \iiint_{V^e} N^e_i f dv - \hat{\Phi}_i N^e_i D \hat{r}^e ds$$  \hspace{1cm} (12)

which can be written in matrix form as

$$\{ R^e \} = \{ K^e \} \{ \Phi^e \} - \{ b^e \} - \{ g^e \}$$  \hspace{1cm} (13)

For periodic structure as shown by Mias et al. FEM modeling will be responsible for Floquet structure (Cai and Mias, 2009).  

3. Theory of metamaterials and EBG modeling

Providing and improving the accuracy of extracting effective value of $\varepsilon$ and $\mu$ using the scattering parameters have been the purpose of many researches. Presented methods are generally similar, but might be different in details because of the basic assumptions and environmental conditions.

Most of the methods and efficient parameters are based on the Nicolson–Rose method in which the wave meets the blade of material in a perpendicular direction and by this the refractive index, $n$, and impedance, $z$, can be obtained.

$$z = \pm \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}$$  \hspace{1cm} (14)

$$n = \frac{1}{k_0 d} \left[ \frac{\text{Im}(\ln\ln(e^{jknzd}))}{2m\pi} - j \text{Re}(\ln\ln(e^{jknzd})) \right]$$  \hspace{1cm} (15)

where $d$ is the cell thickness, $k_0$ represent wave number in the air and $m$ is an integer number related to phase in $\text{Re}(n)$. The $\varepsilon_r$ and $\mu_r$, then can be found according to (16) and (17) (Chen et al., 2004).

$$\varepsilon_r = \frac{n}{z}$$  \hspace{1cm} (16)

$$\mu_r = nz$$  \hspace{1cm} (17)

With considering a passive environment, we should have $\text{Im}(n) \geq 0$ and $\text{Re}(z) \geq 0$. It should be mentioned that the condition of $\text{Im}(n) \geq 0$ is taken into account only when the time factor is considered as $e^{-j\omega t}$. Otherwise, this value should be negative.

In most proposed methods the structure is considered homogeneous and isotropic. The blade (effectively homogeneous) is assumed to be very thin. It means that the direction from which the wave passes perpendicular in the metamaterial supposed to be short, so the branch points can be neglected. The correct choice of these branch points is the most important part of the task. Choosing the correct value of $m$ is very important for the sensitivity of the answer to the small value of $S_{11}$ and $S_{12}$. One of the methods for correctly choosing the $m$ value is using the continuity of $\varepsilon$ and $\mu$ as a function of frequency.
As presented in Fig. 1, the values of the inductance, $L$, and the capacitance, $C$, are determined by the characteristics of the EBG pattern and show the resonance behavior to explain the band gap feature of EBG structures. This model is very easy to understand but because of simple approximation of $L$ and $C$, the results are not very accurate.

The parameters of EBG structures are shown in Fig. 1 in which $w$ is the patch width, $g$ is the gap width, $h$ is the thickness of substrate, $\varepsilon_r$ is the dielectric constant, and $r$ is radius of Vias. When periodicity of $w + g$ is small compared to the wavelength, mechanism of EBG structure can be explained by the equivalent model of the lumped LC element. As it is shown above in Fig. 1, the equivalent capacitance and inductance is due to the gap between the patches and the current on the patches, respectively (Bell and Iskander, 2008).

Impedance of a parallel LC resonant circuit and the resonant frequency can be obtained as follows:

$$Z = \frac{j\omega L}{1 - \omega^2 LC}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

In low frequencies, the impedance is inductive and can pass the TM surface waves, but in high frequencies, the impedances will be capacitive and pass the TE surface waves. Near the resonant frequency, $\omega_0$, the impedance is very high and the EBG structure do not pass any surface wave that leads to frequency band gap region. Also the high surface impedance ensures that a radiated surface wave can be reflected without reversing the phase. This phenomenon happens on a perfect electrical conductor. Edge capacity and inductance for a narrow slit are obtained by the following equations (Grelier et al., 2011):

$$C = \frac{W\varepsilon_0(1 + \varepsilon_r)}{\pi} \cosh^{-1} \left( \frac{W + g}{g} \right)$$

$$L = \mu h$$

### 4. Structures and the simulation results

In this paper, the EBG structures, which consist of EBG parallel plates to decrease the coupling between two omni directional antennas, have been used. Here, we have chosen the Discone antennas as omni directional antennas. All simulations have been performed based on the finite element methods in HFSS. Final structure will be suitable for X and Ku band in radar applications and by proposed non-uniform structure it has been attempted to improve bandwidth of structure. The proposed structure has been compared with 3-layer fractal structure and proposed multilayer structure in.

#### 4.1. Discone without EBG

In Fig. 2 the array structure is shown which consists of two Discone antennas for UWB systems. In Fig. 3 return loss parameters for 8–16 GHz have been presented. As shown in Fig. 3, the $S_{21}$ for two antennas in array reach to maximum value of $\sim 26$ dB.
4.2. Discone with uniform and non-uniform EBG

In Fig. 4, sample EBG structure with 4 mm patch is illustrated. The dielectrics are laying with the dimension of $30 \times 5$ mm in 5 rows. The structures are designed on a Rogers/Duroid 5880 substrate with 1.6 mm thickness. The Vias diameters in all structures are 0.2 mm and also the space between the rows is 2.4 mm. The structure is located between the two omni-directional antennas. Fig. 5 showed a comparison between $S_{11}$ and $S_{12}$ parameters of the antenna.
structures. As it is shown in Fig. 5, in range of 9–14.5 GHz, we can see an acceptable loss in $S_{12}$ which is between $-20$ and $-47$ dB. In other words, here we can obtain up to maximum of $-24$ dB loss in $S_{21}$. But the $S_{12}$ is increasing in the frequency range of 14.5–16 GHz, which is due to the uniform structure. For this reason, the non-uniform structure has been proposed in Fig. 6.

Non-uniform structure shown in Fig. 6 is consisting of 3 mm patches in the edge of the structure. This structure has some advantages and disadvantages. This new structure modifies the bandwidth reduction of $S_{12}$ in high frequencies, and also reduces the loss of $S_{12}$ up to $-67$ dB, but leads to relative increase in $S_{12}$ value in low frequencies, as shown in Fig. 7.

4.3. Discone with uniform EBGs by 2.4 mm patches

Here, a uniform structure, including 2.4 mm patches, has been presented. This structure was used in a paper in planar form to decrease the coupling between two waveguides (Mohajer-Iravani et al., 2006). This structure is shown in Fig. 8. The comparison of $S_{11}$ and $S_{12}$ parameters for the structure of antenna is then illustrated in Fig. 9. As can be seen, the structure cannot show the desired performance in the X-band and lower frequencies of the Ku-band.
Fig. 7. Comparison of $S_{11}$ and $S_{12}$ for the non-uniform structure.

Fig. 8. Uniform structure with 2.4 mm patches.

Fig. 9. Comparison of $S_{11}$ and $S_{12}$ for uniform structure with 2.4 mm patch.
Fig. 10. Fractal structure with 1 mm × 1 mm slots.

Fig. 11. Comparison of $S_{11}$ and $S_{12}$ for fractal structure.

Fig. 12. EBG patch structure with PBC condition.
Fig. 13. Reflection phase comparison for (a) 3 mm patch; (b) 4 mm patch; (c) and fractal patch.
Fig. 14. Real part permittivity and permeability parameter (a) real permittivity for uniform structure; (b) real permeability for uniform structure; (c) real permittivity for non-uniform; (d) real permeability for non-uniform; (e) real permittivity for fractal structure; (f) real permeability for fractal structure.
4.4. Discone with fractal EBGs

In Fig. 10, a fractal structure has been used for uniform EBGs, which actually consists of slots with the dimension of 1 mm × 1 mm. The comparison of $S_{11}$ and $S_{12}$ of the antennas is shown in Fig. 11 for the proposed structure. As can be seen the $S_{11}$ and $S_{12}$ values have not changed a lot compared to initial uniform structure proposed in Fig. 4.

5. Reflection phase diagram

Periodic boundary condition (PBC) with Floquet port or perfect E condition (PEC) and perfect M condition (PMC) walls with wave port are conventional ways for simulation of the reflection phase from EBG structure in HFSS. Fig. 12 shows the EBG patch structure with PBC condition and Floquet port in HFSS. In here we compared reflection phase between EBG structures with 3 mm and 4 mm size for patch and 0.4 mm radius for Via and also it compared with fractal geometry in here. This comparison has been presented in Fig. 13 and shown in here. Fig. 13a shows reflection phase for 3 mm patch and it is occurring at 19 GHz and Fig. 13b and c presented reflection phase for 4 mm patch and fractal condition and in both situation reflection phase shows similar manner and it is occurring at 13.7 GHz. Exactly they show the same manner in EBG arrays as shown in Figs. 5 and 11 and it is emphasized by reflection phase comparison.

6. Material parameter

Nicolson–Rose method shows in (2) and (3) a conventional mathematical method for the calculation of metamaterials. Here this method has been executed in Matlab by numerical simulations for 3 difference EBG arrays model. In here have been extracted result for Uniform array with 4 mm patches and also compared with non-uniform structure and Fractal arrangement with Eqs. (22) and (23) where $v_1 = S_{21} + S_{11}$, $v_2 = S_{21} - S_{11}$, $k_0 = \frac{c}{f}$ and $d$ is the thickness of the layer (Majid et al., 2009).

$$\varepsilon_r \approx \frac{2}{jk_0d} \frac{1 - V_1}{1 + V_1}$$  \hfill (22)

$$\mu_r \approx \frac{2}{jk_0d} \frac{1 - V_2}{1 + V_2}$$  \hfill (23)

Fig. 14 shows the real part permittivity and permeability parameter for uniform, non-uniform and fractal structure. As shown in here the EBG shows the ENG, MNG or DNG in difference frequencies and this condition helps to reduce coupling by metamaterial structure. And in other hand uniform structures show similar characteristic like fractal arrangement. So here we demonstrated that metamaterial properties are same as reflection phase in non-uniform and fractal structures.

7. Shielding effectiveness

Generally shielding is for two aims, to prevent emission of electronic product to outer bounds and to avoid external radiation of reaching the product. So, fundamentally shield prevents transmission of electromagnetic field. Shielding effectiveness is defined as ratio of electric (magnetic) field magnitude incident to shield wall to electric (magnetic) field magnitude passes through shield wall. Also we can define it as the ratio of incident electric (magnetic) field in case of without shield to electric (magnetic) field in the presence of shield.

The field at 15 mm distance from the structure for case of with and without shield has been calculated. Shielding effectiveness for uniform and non-uniform structure is calculated and shown in Table 1. For non-uniform structure the shielding effectiveness has increased with increase in frequency in comparison to uniform structure.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>16 GHz</th>
<th>14 GHz</th>
<th>12 GHz</th>
<th>8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>−1.47 dB</td>
<td>6.91 dB</td>
<td>6.86 dB</td>
<td>−4.89 dB</td>
</tr>
<tr>
<td>Non uniform</td>
<td>7.61 dB</td>
<td>7.64 dB</td>
<td>6.45 dB</td>
<td>−6.08 dB</td>
</tr>
</tbody>
</table>
Obviously by implementation of non-uniform arrangement the shield factor is improved more than 8 dB at 16 GHz so here more band width for shield is achieved.

8. Conclusion

In this paper, EBG structures consisting EBG parallel plates have been used to reduce the coupling between two omni directional antennas. All simulations have been done based on full wave method in HFSS. The final structure has been tried to be appropriate for X and Ku band radar application. Here comparison between uniform and non-uniform structure with conventional array of antenna was presented, and compared with the fractal structure for designing ultra wide band structure. Also have been presented material parameter and proved that the structures has metamaterial characteristic and also reflection phase comparison. By implementation of non-uniform arrangement the shield factor is improved more than 8 dB at 16 GHz and loss of $S_{12}$ up to $-67$ dB.

References


