Reduction of Mutual Coupling between Radiating Elements of an Array Antenna Using EBG Electromagnetic Band Structures

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***Abstract*—In this paper, a new array antenna configuration based on Electromagnetic Band Gap (EBG) structures has been proposed for 3.5GHz wireless communication systems. The proposed slotted EBG structure, high impedance surface (SHI), consists of three squares and a square ring deposited on a substrate (Rogers RO4350) which has a relative permittivity of 10.2 and a thickness of 1.27mm. Initially a matrix of 3×7 unit cells of EBG structures is introduced between two patches of an array and then a matrix of 3×14 unit cell of EBG structures is integrated between eight patches, which resonate around 3.5GHz (Wi MAX). The insertion of these structures between the radiating elements of an array antenna reduces the mutual coupling and antenna dimensions by approximately (8dB, 11%) and (12 dB, 5%) respectively for two, eight elements array antenna. In addition, the directivity has been slightly improved in the presence of EBG structures, from 4.52dB to 6.09dB for a two-element array antenna, and from 8.18dB to 8.4dB for an eight-element antenna.**

***Index Terms*—Antenna array, electromagnetic band gap structure, mutual coupling, radiation pattern**

I. Introduction

Several scientific studies have been conducted to improve the radiation performance of antenna arrays. The antenna printed on an isotropic substrate has been the subject of a certain number of research works during the last decades, the concept of the radiating structure was first studied by Deschamps in 1950 [1], [2]. The development of methods to reduce the mutual coupling between radiating sources has become a topical issue. Microstrip antenna array is widely used in several communication systems such as mobile telephony, wireless multimedia systems (WiFi, Bluetooth) and also space communications, and radar applications. However, as the separations between the array elements are reduced, the mutual coupling between the antennas caused by surface waves becomes stronger. Therefore, the use of high impedance surface (SHI) type electromagnetic band gap structures may be a solution. The SHI (high impedance surface) structure was proposed by Sievenpiper in [3], it consists of four parts: a ground plane, a dielectric substrate, metal plates and connection vias. To analyze the characteristics of the SHI (high impedance surface) structure, different methods have been implemented. These methods can be classified into three categories: a model based on the equivalent circuit [4], [5], a model based on the transmission line [6]-[8] and a model based on the periodic boundary conditions [9]. The model of the equivalent circuit is the simplest one, which describes the SHI structure as an LC resonant circuit. The values of inductance L and capacitance C are determined by the SHI (high impedance surface) geometry, and its resonance behavior is used to explain the band gap characteristic of the SHI structure. This model is simple to understand, but the results are not very accurate due to the simplified approximation of L and C.

This structure has interesting behaviors in microwave frequencies [3], [10], it is applied to reject frequency bands [11] and avoid unwanted electromagnetic waves from propagating [12]. The suppression of surface waves helps to improve the performance of an antenna by increasing the antenna gain and reducing the return radiation [13]. Various SHI (high impedance surface) structures have been extensively studied in the last decade [14]-[16]. Other types of structures can play the same role. For example in references [17] and [18], there is about 16 dB of mutual coupling attenuation obtained by inserting slots in the ground plane Defected Ground Structure (DGS), but the back-lobe radiation is increased due to the existence of the slots in the ground plane, whereas Electromagnetic Band Gap (EBG) structures are a good choice for mutual coupling reduction between the radiating elements [19]-[22], which in turn improves antenna performance.

This paper focuses on the one hand on reducing the mutual coupling between two antenna arrays each containing four microstrip patch antennas and on the other hand on improving array antenna performance by using EBG electromagnetic band gap structures as shown in Fig. 1.

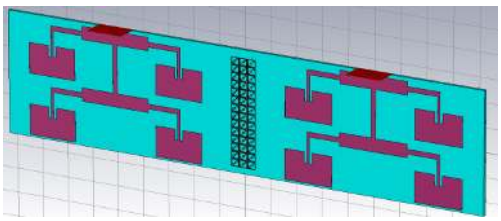

Fig. 1. The integration of the EBG and the antenna array

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The proposed structure is printed on a Rogers RO4350 substrate with a dielectric constant of 10.2 and thickness h=1.27mm. We present in this paper the results of the simulations which will be discussed in Section II, III and Section IV.

II. Configuration and Design of the EBG Structure

The slot-loaded EBG structure is a new type of electromagnetic band gap structures which are designed by adding some slots in the metal plates of conventional mushroom like EBG. These slots affect the one hand the current distribution on the patches resulting in a longer current path, and on the other hand they create additional capacitance formed between the edges of the slots. In this paper, we designed a new EBG slotted structure by introducing three squares and a square ring deposited on a substrate (Rogers RO4350) which has a relative permittivity 10.2 and a thickness of 1.27mm. The width of the three squares is 0.8mm, while 0.3mm is the width of the ring. The unit cell of the EBG structure is illustrated in Fig. 2 and the summary of the parametric values of this cell is presented in the Table I.

The equivalent circuit model describes the EBG structure as an LC resonant circuit. An electromagnetic wave which strikes the structure causes electric fields to cover the narrow spaces between the neighboring metal plates and this causes the accumulation of charges on the ends of the metal patches, which can be described as an effective capacitance C. The charges which go back, circulate around the conducting paths through the vias and the ground plane, describing an inductance L associated with the conduction currents. The whole forms a parallel resonant circuit which dictates the electromagnetic behavior of the EBG structure as shown in Fig. 3.

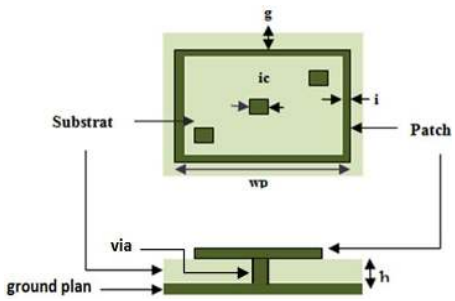


Fig. 2. Configuration of the EBG unit cell (top and side views)

TABLE I: DESCRIBES THE SUMMARY OF THE PARAMETRIC VALUES OF THE EBG UNIT CELL

Parameters	description	Values (mm)
i_c	thickness of interior squares	0.8
i	thickness of the square ring	0.3
g	The space between the unit cells	0.2
W_p	Length or width (W_p) of the unit cell	6.4
h	Substrate thickness	1.27
m	Ground plane thickness	0.0175
r	Via radius	0.5

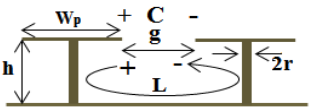


Fig. 3. Equivalent electric model.

The initial inductance L and capacitance C of the conventional mushroom-like EBG structure are [23]:

$$L = \mu_0 \mu_r h \tag{1}$$

$$C = \frac{w\varepsilon_0(1+\varepsilon_r)}{\pi}\cosh^{-1}\left(\frac{w+g}{g}\right) \tag{2}$$

where ε_0 and μ_0 are the permittivity and permeability of the free space respectively, the parameter g represents the gap between the elements of the EBG structure and w represents the width of the patch.

The inductance and capacitance equivalents are equal to the inductance and capacitance of the conventional mushroom-like structure, in addition to the new L and C which are created by the slots. Thus by inserting the slots the initial value of L and C remains unchanged while the value of equivalent L and C will increase and cause a lower resonant frequency and finally a compact structure.

The resonance frequency of the equivalent circuit is given by

$$\omega = \frac{1}{\sqrt{LC}} \tag{3}$$

And the bandwidth of the band gap frequency is expressed as

$$B_W = \frac{\Delta\omega}{\omega} = \frac{1}{\eta}\sqrt{\frac{L}{C}} \tag{4}$$

where η is the impedance of the free space.

The surface impedance being defined by effective equivalent circuit parameters which are determined by the geometry of the surface texture. Capacitors are formed by fringed electric fields between adjacent metal patches. The inductance is fixed by the thickness of the structure. According to Sievenpiper [12], the surface impedance is given by the following expression:

$$Z = \frac{j\omega L}{1-\omega^2 LC} \tag{5}$$

To get the accurate band gap characteristics, the design parameters of the unit cell illustrated in Fig. 2 have been optimized so that the band gap frequency interval contains the Wi MAX band. See Fig. 4.

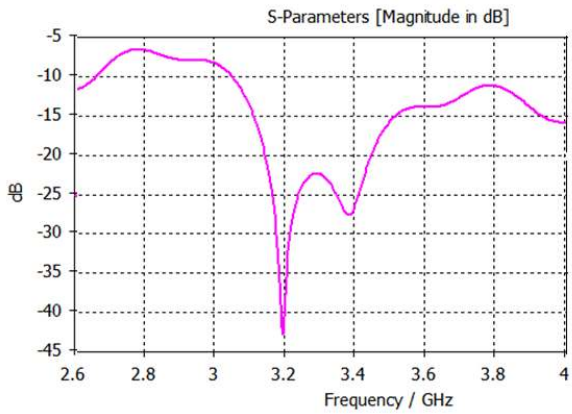


Fig. 4. Transmission coefficient S_{21} of the EBG unit cell.

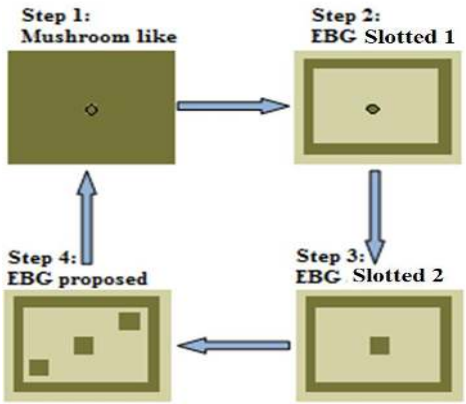


Fig. 5. Designing steps of the EBG unit cell.

From Fig. 4 we can see that the transmission coefficient S_{21} is less that −20dB, between 3.2GHz and 3.4GHz, indicates the behavior of the EBG structure that acts like a stop band filter in order to obtain a rejection around these frequencies.

The proposed EBG was obtained in four successive steps as demonstrated by Fig. 5. It is clear that the proposed EBG is designed by creating three squares and a square ring in the metal plates of conventional mushroom like EBG. These slots are created to achieve better antenna performance parameters. (See Fig. 9 in the section III-B).

III. Two-Element Array Antenna with and Without EBG Structure

A. Two-Element Array Antenna Design

Printed antennas are widely used in wireless communications because of their advantages: low profile, light weight, planar structure and low cost, they also have some disadvantages, such as narrow bandwidth and low gain. To meet the requirements of long distance communication, it is necessary to design antennas with very high gain. The array antenna model is considered to be one of the simplest ways to improve gain and bandwidth, but these improvements introduce mutual coupling between patches, which can reduce array efficiency. To see the effect of the EBG structure SHI-type on the coupling between antennas, we must first study the coupling between two printed antennas resonating at 3.5GHz. The array antenna geometry and parameters are illustrated in Fig. 6

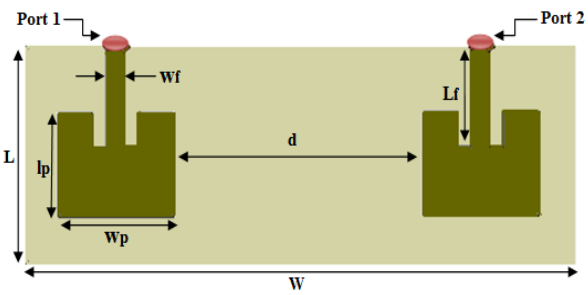


Fig. 6. Two patches resonating at 3.5GHz on a substrate of ε_r =10.2, W= 70mm, L = 25.3mm, l_p =12.65mm, w_p = 18.11 mm, w_f = 1mm, L_f= 8mm, d = 26.86mm (d=1 $\lambda_{3.5}$).

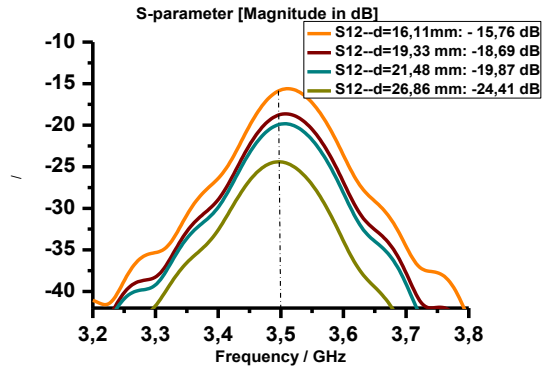


Fig. 7. Variation of mutual coupling depending on the distance d between two array antennas.

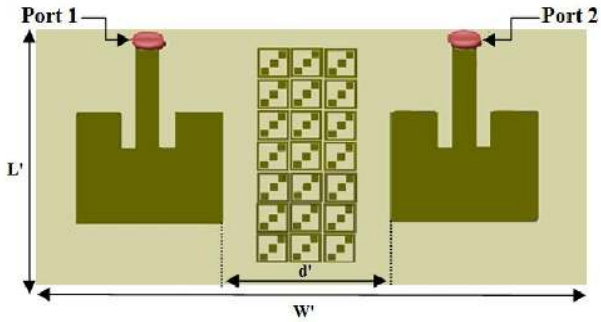


Fig. 8. Over view of the EBG structure, W'=62.37mm, L'=L= 25.3mm, d'= 19.33mm (d= 0.72$\lambda_{3.5}$).

B. Reduction of Mutual Coupling Using Slotted EBG

To study the variation of the mutual coupling as a function of the distance d between the two radiating elements, first we take a distance d = 26.86mm (1.0 $\lambda_{3.5}$ GHz) between the two antennas, a weak mutual coupling exists between radiant elements.

Then for d=21.48mm (0.8 $\lambda_{3.5}$ GHz), d = 19.33mm (0.72 $\lambda_{3.5}$ GHz) and d = 16.11mm (0.6 $\lambda_{3.5}$ GHz), it can be seen from Fig.7 that as the distance between the two array elements decreases, the mutual coupling increases. In conclusion, the mutual coupling between two radiating elements depends on the distance between them.

The surface waves generated have a significant effect on the mutual coupling between the elements of the antenna array. Especially in the case of array elements on high permittivity substrates. The introduction of the EBG structure between the array elements has shown its ability to suppress surface waves and to reduce mutual coupling at the resonant frequency, knowing that the distance between the two elements is reduced to d=19.33mm (this distance is chosen because it gives a better reduction of mutual coupling between the radiating elements). A matrix of 3×7 unit cells of EBG structures are inserted between two patch antennas to reduce mutual coupling, as shown in Fig. 8. From Fig. 8 we can see that the antenna dimension is reduced around 11%.

In a first step we insert between the two radiating elements, a matrix of 3×7 unit cells of EBG mushroom like, then a matrix of 3×7 unit cells of EBG slotted 1, EBG slotted 2, EBG proposed, in order to make a Mutual coupling comparison of the four steps of EBG.

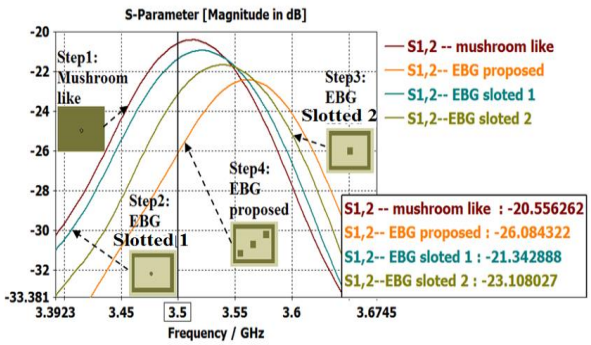


Fig. 9. Mutual coupling (S_{12}) comparaison for the design steps between two elements.

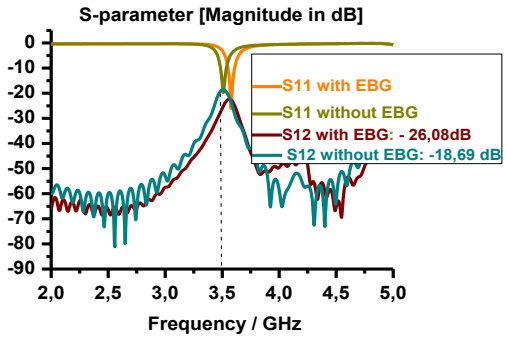


Fig. 10. Mutual coupling and reflection coefficient of array antenna with and without EBG structure.

Fig. 9 illustrates the S_{12} (mutual coupling) comparison between two radiating elements for the four involved steps in designing EBG structure. It is obvious that the step-by-step modification improves the antenna performance in terms of S_{12}. We can see from Fig. 9 that in the fourth step we achieve around 6 dB reduction of the mutual coupling compared to the first step, hence the choice of our proposed EBG.

From Fig. 10 it can be seen that in both cases (with and without EBG) the reflection coefficient is less than −10dB around 3.5GHz, and with the EBG structure the mutual coupling between two radiating elements is reduced by around 8dB compared to a configuration without EBG structures ($|S_{12}|=-18$dB).

The two antennas are designed on the Rogers RO4350 substrate (due to several factors such as low noise and excellent stability against temperature variations, adaptation to high frequencies and their availability on the market) [17] relative permittivity 10.2mm and 1.27mm thick. The two antennas are excited by a line of microstrip of 50 ohm of 1mm × 8mm. The distance between the two patch antennas is d=19.33mm (0.72 λ3.5 GHz), which is less than the wavelength in free space at 3.5 GHz.

The radiation patterns for the two array configurations with and without EBG structure are presented in Fig. 11 and Fig. 12. These figures show that the radiation patterns are not disturbed in the presence of the EBG structures, on the contrary they are slightly improved.

Fig. 13 shows the gain and directivity curve in Cartesian coordinate system to better observe this slight increase obtained in the direction where the gain and directivity are maximum.

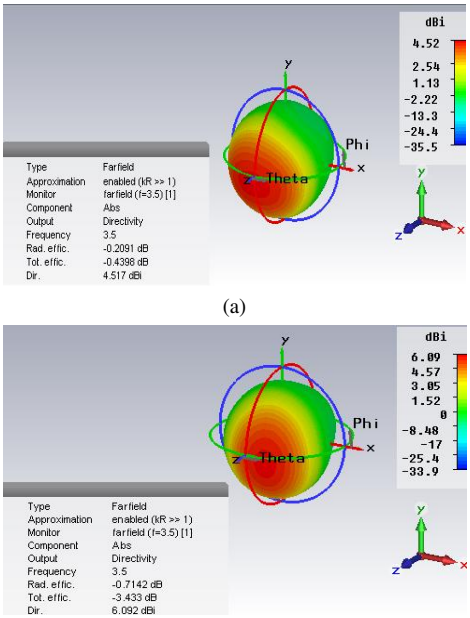


Fig. 11. Far-field radiation pattern of two-element array antenna 3.5 GHz: (a) without EBG and (b) with EBG

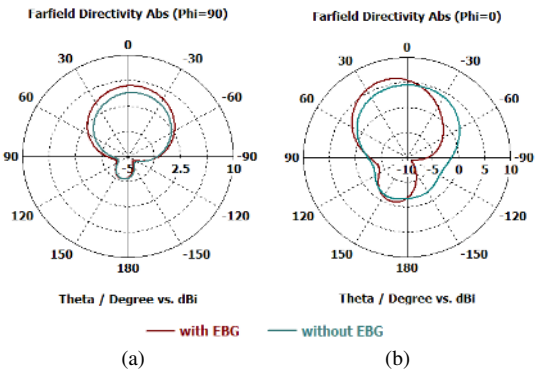


Fig. 12. Horizontal and vertical section of the radiation pattern of the two-element array antenna with and without EBG Structure at 3.5GHz (a) *phi*=90 and (b) *phi*=0.

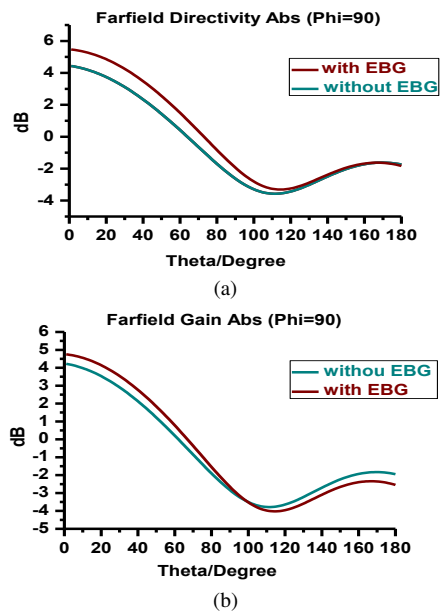


Fig. 13. The gain and directivity curve in Cartesian coordinate system (a) directivity, (b) gain.

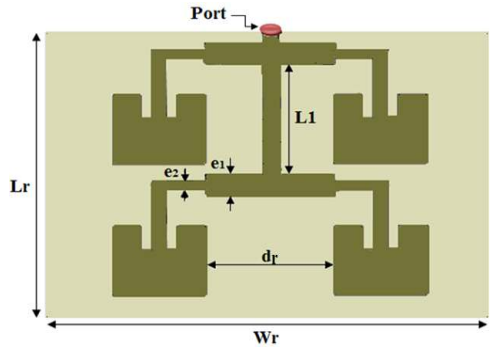


Fig. 14. Four patches resonating at 3.5GHz on a substrate of ε_r = 10.2.

TABLE II: DESCRIBES THE SUMMARY OF THE PARAMETRIC VALUES OF THE FOUR-ELEMENT DESIGNED NETWORK ANTENNA

Parameters	Values (mm)
L_r	50.6
W_r	76.4
d_r	20.12
$L1$	17.4
$e1$	5.5
$e2$	2

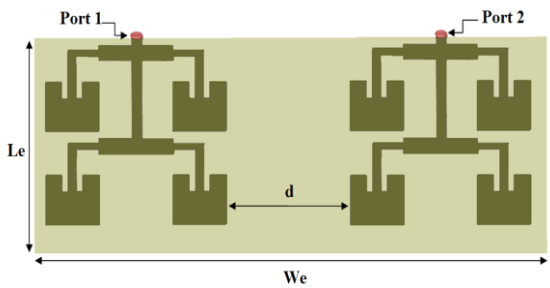


Fig. 15. Top view of the eight-patch antenna configuration L_e= 50.6mm, W_e = 152.8mm, d= 26.86mm

IV. EIGHT-ELEMENT ARRAY ANTENNA WITH AND WITHOUT EBG STRUCTURE

A. Eight-Element Array Antenna Design

In this section we present a patch antenna array consisting of four radiating elements with distances d_r = 20.12mm which are placed on the substrate (Rogers RO4350) which has a relative permittivity of 10.2 and a thickness of 1.27mm. The size of each patch is $w_p \times l_p$ mm^2. Fig. 14 shows the designed array antenna, and the summary of the parametric values of this design is presented in the Table II.

Next we will design an antenna composed of two arrays fed by a 50 ohm microstrip line, which are symmetrically positioned. Each array consists of four radiating elements separated by a distance d= 26.86mm (1.0 $\lambda_{3.5}$), on the Rogers RO4350 substrate. The physical dimension of the radiating array is 152.8mm × 50.6mm. Fig. 15 shows the proposed antenna without EBG structure.

B. Reduction of Mutual Coupling Using Slotted EBG

The EBG (electromagnetic band gap) structure are inserted between the antennas of the two array see Fig. 16 in order to reduce mutual coupling, first we make a study on the mutual coupling by changing the number and placement of positions of different EBG unit cells, we insert a matrix of 3×7 EBG unit cells in a first step then a matrix of 1×14, 2×14, 3×14 EBG unit cells. It can be seen from Fig. 17 that the insertion of the matrix 3×14 EBG unit cells gives a better reduction of the mutual coupling compared to the other matrix, this mean that the use of 42 pcs EBG unit cells for an array of eight elements depends on simulation results, same for an array of two elements we used 21 pcs EBG unit cells because they gives better reduction of mutual coupling.

The distance between the edges of the antennas is 19.33mm (0.72$\lambda_{3.5}$). In addition, the total size of the 14×3 EBG unit cells is 44.8mm × 9.6mm. From Fig. 16 we can see that the antenna dimension is reduced around 5%.

Fig. 18 shows the mutual coupling and the reflection coefficient of the array without and with EBG structures. We can observe that the two antennas (without and with EBG) are well matched to the input around 3.5 GHz with $S_{11} \leq -10$dB, and that the existence of the EBG structures have a weak effect on the return loss. The coupling coefficient shows that without EBG structure, the antenna shows a strong mutual coupling of −27dB, and in the presence of EBG we note that there is a significant improvement in terms of mutual coupling between the radiating elements with a reduction of about 12 dB obtained at the resonant frequency.

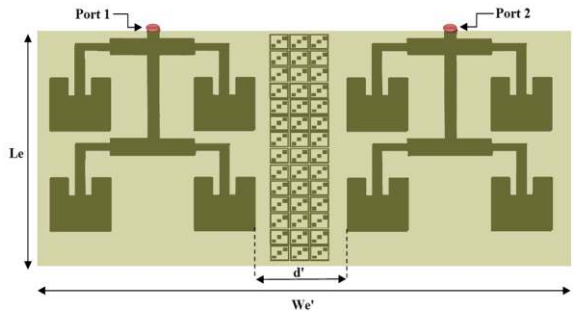


Fig. 16. Integration of the proposed EBG structure between the radiating elements of the array antenna, L_e= 50.6mm, $W_{e'}$= 145.27mm, and d'= 19.33 mm.

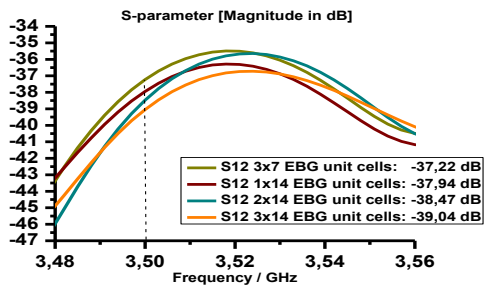


Fig. 17. Effect of number of EBG unit cell on the antenna array performance in term of S12 (mutual coupling).

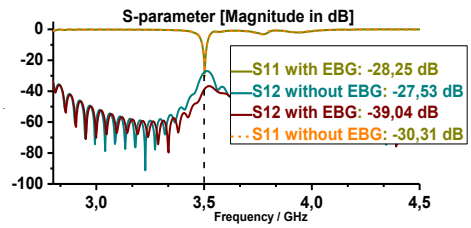
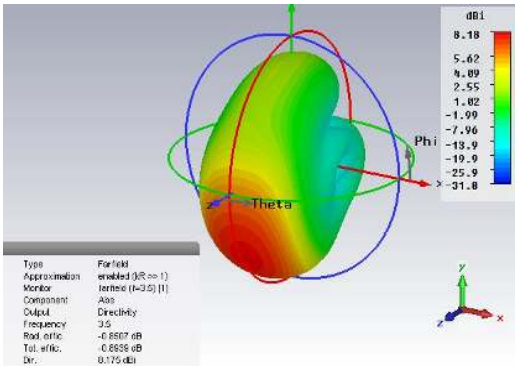
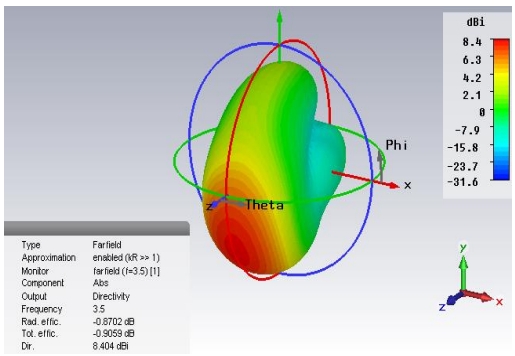


Fig. 18. Mutual coupling and reflection coefficient of array antenna with and without EBG structure.

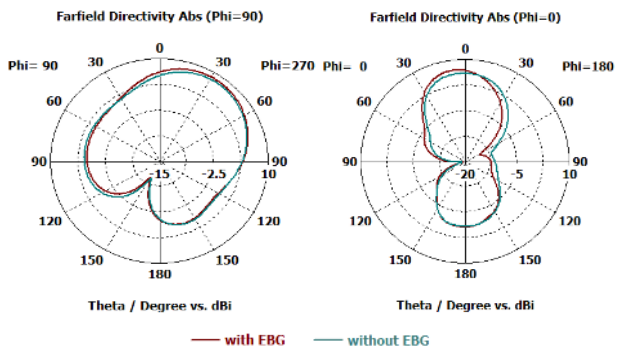


(a)



(b)

Fig. 19. Array antenna radiation pattern: (a) without EBG, (b) With EBG



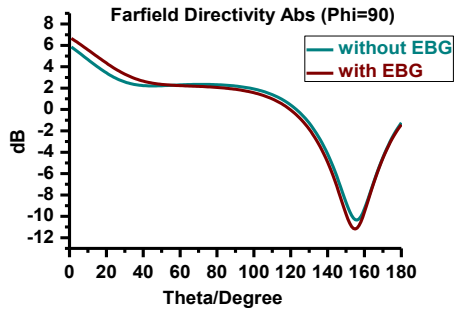
(a) (b)

Fig. 20. Horizontal and vertical section of the radiation pattern of the eight-element array antenna with and without EBG structure at 3.5GHz (a) *phi*=90 deg, (b) *phi*=0 deg

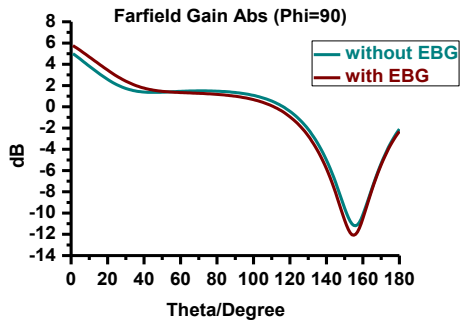
The radiation patterns for the two array configurations without and with EBG are shown in Fig. 19 and Fig. 20. These two figures show that the radiation patterns are not disturbed by the presence of EBG, on the contrary they are slightly improved. Fig. 21 shows the curve of gain and directivity in Cartesian coordinate system to better observe this slight increase obtained in the direction where the gain and directivity is maximum.

In Table III, we summarize the comparison between the array antenna with two and eight patches, in terms of antenna performance we note that when we add elements to the array (array antenna with eight patches) the antenna becomes more adaptive and directive.

In Table IV, we summarize the comparison between our work and some literature antennas. In the literature, all the proposed designs are composed with only two or four radiation elements, since they have not symmetrical configuration that prevent them to realize the arrays with more than two or four elements. However, in our work due to the symmetrical configuration of the structure we have increased the array elements to eight. Additionally, our proposed work provides better isolation enhancement compared to some recent references in Table IV.



(a)



(b)

Fig. 21. The gain and directivity curve in Cartesian coordinate system (a) directivity, (b) gain

TABLE III: COMPARISON BETWEEN TWO AND EIGHT ELEMENT ARRAY ANTENNA

Array antenna with EBG	Two patches	Eight patches
Resonance frequency (GHz)	3.5	3.5
return loss S11 (dB)	-26.08	-39.04
Reduction of Mutual coupling (dB)	8	12
Angular width (3dB) (deg)	113.9	44.1
Directivity (dBi)	6.09	8.40

TABLE IV: COMPARISON BETWEEN THE PROPOSED ANTENNA AND SOME LITERATURE ANTENNAS

Year / Ref.	Volume *W*×*L*×*h* (mm^3)	Mutual coupling (dB)	Resonance frequency (GHz)	Element number	Edge to edge distance mm
[23]	76.4×91×1.43	6	3.5	2	0.1λ
[24]	140×100×1.52	6.19	3.3	2	----
[25]	50×100×1.6	6	3.65	2	----
[26]	60 × 60 ×1.6	17	4.6	2	0.5λ
[27]	44 × 37	9	5.8	2	0.13λ
[28]	18.5×55.5×3.2	12	2.5	2	36.5
[29]	48×38×1.6	10	2.4	2	0.2λ
[30]	90×90×1.58	10	8-10	2	0.1λ
[31]	120.8×57.5.6×1.6	10	4.2-6.5	2	0.42λ
[32]	65×50×1.6	12	3.5	2	0.07λ
This work	145.27×50.6×1.27	12	3.5	8	0.72λ

V. Conclusion

In this paper we have shown a very effective aspect of EBG (Electromagnetic band gap) slotted electromagnetic band gap structures. These structures play a very important role, they reduce the coefficient of mutual coupling between the radiating sources on the one hand, and on the other hand, they allow to design very low profile antennas. The insertion of slotted EBG structures between the radiating elements leads to a reduction in mutual coupling of around 10 dB compared to the array antenna without EBG structure, in addition the gain and directivity are slightly improved. We present here only the results obtained for d=0.72$\lambda_{3.5}$ to 3.5GHz. In perspective, the proposed antenna will be manufactured and the simulation results will be validated by the experimental results.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Author's contribution to this work: Sara Said and Abdenacer Es-salhi conducted the research and analyzed the data; Mohammed Elhitmy corrected the paper (linguistic correction); all authors had approved the final version.

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