A new hybrid method for mutual coupling minimization of an antenna array

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ABSTRACT

In this paper, a simultaneous application of geometric modification on patch elements and electromagnetic band gap (EBG) electromagnetic bandgap structures (hybrid method) has been suggested for 3.5 GHz wireless communication applications, to minimize the mutual coupling between radiating elements of microstrip array antennas. The suggested EBG slotted structure is composed of a one square ring and three squares placed on Rogers RO3010 having 10.2 and h=1.27 mm which presents respectively its dielectric constant and thickness. In this approach, the patch elements are geometrically modified, while also employing EBG structures, formed by four EBG cells, placed between the array elements at a near distance. The modification of the geometry of the antenna and the introduction of EBG reduces the mutual coupling of an array antenna with approximately 33 dB on the one hand and improves the antenna gain by approximately 0.43 dB on the other hand. Initially, slots are introduced in the patch geometry and then four EBG unit cells are inserted between two patches, operating at 3.5 GHz. The antenna array design parameters were optimized.

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1. INTRODUCTION

Microstrip antenna arrays are used extensively in many communication systems such as mobile telephony, multimedia wireless systems (Bluetooth, Wi-Fi), or radar applications, and because of their highly directional radiation patterns, antennas with high gain are popular for extended range communications, which include radar systems and satellite-to-land links. The use of high gain antennas is perhaps more conventional than using reflector and horn antennas, although they have bulky and unplanned configurations which makes them undesirable in applications with restricted space. Antenna arrays generally do not have similar bulk constraints; however, due to the wide separation between array elements, they can become laterally oversized to avoid mutual coupling. One of the most popular arrays is the microstrip antenna array because of its excellent performance, its simplicity of manufacture, and its low cost and weight [1]. They typically comprise several patch antennas with low gain arranged to constitute an array antenna. Various scientific investigations have been performed to enhance antenna array radiation performance. Developing methods to minimize the interaction of radiation sources is becoming a hot topic. However, the mutual coupling between the antennas resulting from surface waves becomes higher by reducing the spacing between the array elements. Therefore, high impedance surface electromagnetic bandgap (SHI) structures can be used as a solution.

The structure SHI is composed of four parts (a dielectric substrate, a ground plane, metal plates, and vias of connection) proposed by Sievenpiper *et al.* [2]. Various methods have been employed to analyze the characteristics of the SHI structure. They can be classified into three categories: a circuit equivalent model [3], [4], a model of transmission line [5]–[7], and a model based on periodic boundary conditions [8]. The equivalent circuit model is the simpler one in which SHI structure is described like a resonant circuit LC. The geometry of the SHI can establish its capacitance C and inductance L values, while its resonant properties are used to describe the SHI structure's bandgap characteristics. This is easy to interpret, however, due to the simplified expression of L and C, the results are not very accurate. This structure presents attractive microwave characteristics [2], [9], which are used to reject bands of frequencies [10] and stop electromagnetic waves from propagating [11]. The antenna efficiency improvement results in an increase of its gain and a reduction of the return radiation [12] caused by surface wave elimination, different SHI structures are investigated extensively in the last decade [13]–[15].

Other structure types may play the same role, for example in references [16], [17], The integration of slots on the ground plane defective ground structures (DGS), results in an attenuation of about 16 dB of the mutual coupling, the back lobe radiation is augmented by slots on the ground plane, therefore, radiating coupling between the array members is reduced with electromagnetic band gap (EBG) structures, so they are an appropriate choice to minimize the mutual coupling between the radiating components [18]–[21], that improves, in turn, the antenna performance. A new size-efficient design approach for reducing mutual coupling while maintaining the gain of the antenna is proposed in this paper. In this approach, EBG structures are used with modified patch geometry as a first step. The coupling between the elements is considerably minimized to 33 dB, with an increased gain of 0.43 dB achieving up to 4.61 dB using this new hybrid technique. The antenna size is 62.37×25.3 mm. the suggested structure is embedded on RO3010 Roger's substrate having 10.2 and h=1.27 mm which presents respectively its dielectric constant and thickness. In this document, simulation results are shown and discussed in section 3.

2. THE PROPOSED ANTENNA DESIGN

2.1. EBG unit cell design

Slot loading in EBG structures represents a new type of electromagnetic bandgap structure formed by adding slots in conventional mushroom-type EBG metal plates. In contrast, these slots influence the distribution of current upon the patches resulting in a longer distribution of current on the one hand and creating an additional capability that forms between the edges of the slots on the other hand. In the presented paper, a new slotted EBG structure was designed by inserting a square ring and three squares placed on Rogers RO3010 with 10.2 and h=1.27 mm which presents respectively its dielectric constant and thickness. The three squares have a width of 0.8 mm, while the ring width is 0.3 mm. Figure 1(a) shows the EBG unit cell, its dimensions are provided in Table 1. EBG structure could be represented by the equivalent circuit model to an LC resonant circuit. The presence of an electromagnetic wave striking the structure induces electric fields in the narrow spaces between the adjacent metal plates, resulting in the accumulation of charges at the metal plate ends, and this may be characterized by an effective capacity C. The charges circulation coming back, across the ground plane and the vias, defines an inductance L related to the conduction currents. The ensemble forms the circuit resonance which determines the EBG electromagnetic properties, see Figure 1(b). The initial inductance and capacitance of the conventional (mushroom-like EBG) structures are (1) and (2) [22].

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

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

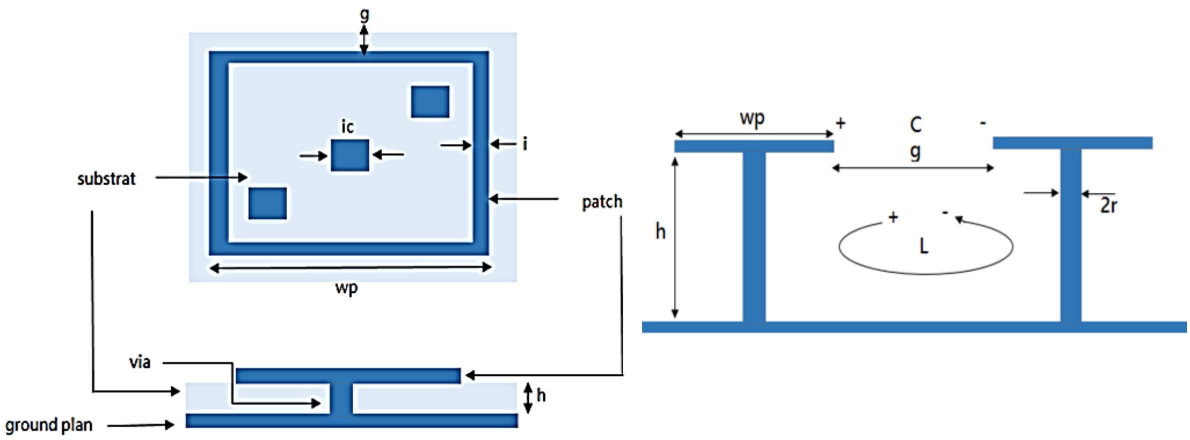
The free space permeability and permittivity are represented respectively by μ_0 and ε_0, where the parameter w represents the patch width, g is the space between EBG structure elements. The equivalents of inductance and capacitance are equal to those of the conventional mushroom-like structure, in addition to the new L and C that are made due to the slots. The initial value of L and C remains unchanged, by introducing the slots, while the equivalent value of L and C will increase and result in a decrease in frequency of resonance and consequently a compact structure. As shown in Figure 2, it is clear that the proposed EBG is obtained through four successive steps where three squares and one square ring are created in the metal plates of the conventional mushroom-like EBG. These slots are created to obtain better performance parameters for the antenna. The equivalent circuit resonance frequency is given by (3).

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

The band gap frequency bandwidth is expressed as (4),

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

with η is the free space impedance.



(a) (b)

Figure 1. The suggested EBG (a) EBG unit cell and (b) equivalent electric model

Table 1. Dimension of the EBG unit cell (in mm)

Parameters	ic	i	g	Wp	h	m	r
Valeurs (mm)	0.8	0.3	0.2	6.4	1.27	0.0175	0.5

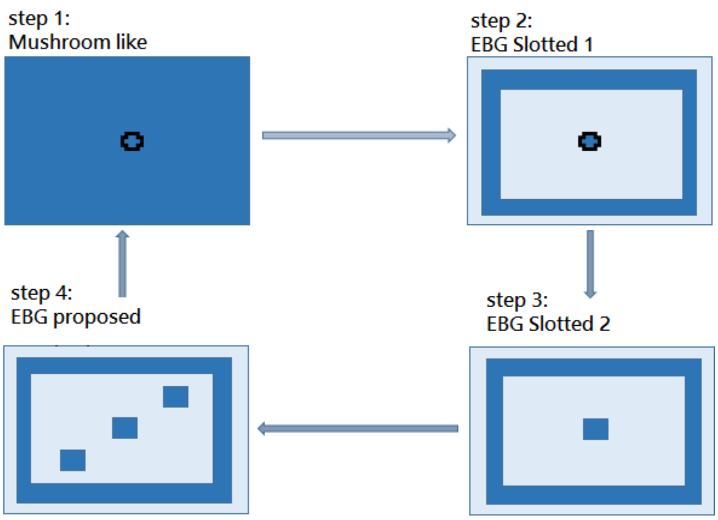


Figure 2. Design steps of the EBG unit cell

2.2. Patch antenna configuration

The proposed antenna was designed by modifying the geometry of the patch by adding slots in the patch, see Figure 3. The proposed antenna geometry was obtained through four successive steps, as shown in

Figure 3. It is clear that the proposed patch design consists of six square slots into the patch. This antenna is optimized to function at 3.5 GHz. These slots are created to achieve between the antenna's radiating elements a better reduction of the mutual coupling.

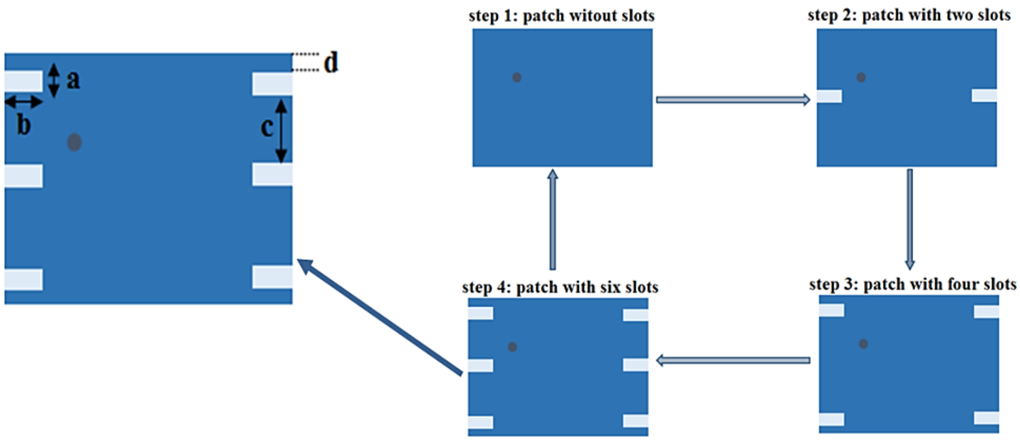


Figure 3. The proposed patch antenna design steps

To see the slots effect of a patch antenna on the coupling between the radiating elements, we propose to study the coupling between two printed antennas operating at 3.5 GHz. The antenna array parameters as well as geometry are presented in Figure 4. This array antenna is placed on a Rogers RO3010 substrate (because of many reasons including the weak noise and high frequency matching, commercial availability and excellent stability to temperature variations) [23] with 10.2 and h=1.27 mm which presents respectively its permittivity and thickness. The antenna resonant frequency is about 3.5 GHz, which is suitable for the WiMAX. Both antennas are excited via two coaxial probes. d=13.43 mm represents the separation between the two patch antennas (0.5*λ3.5 GHz), which is a shorter distance compared to the wavelength of the free space of 3.5 GHz. Table 2 showed the antenna parameters.

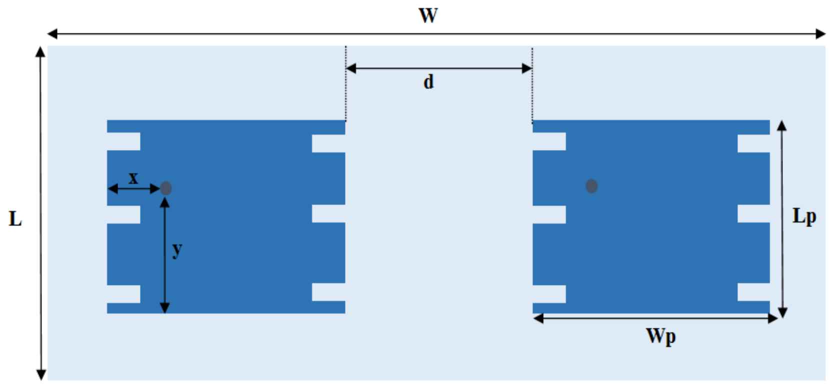


Figure 4. Two slotted patches microstrip array antenna

Table 2. Size patches

Parameters	W	L	Wp	Lp	d	a	b
Values (mm)	62.37	25.3	18.11	12.65	13.43	3.5	8

To study the effect of the slots added to the patch on the variation of the mutual coupling between two radiating elements, we must first study the coupling between two printed antennas resonating at 3.5 GHz, a high mutual coupling between the radiating components exists of about -20.21 dB, by inserting the slots into the patch antenna we observe a significant attenuation of the mutual coupling between the radiating components, see Figure 5. Therefore, as more slots are inserted into the patch, the mutual coupling decreases, hence the choice of a six-slot patch antenna for the rest of the design.

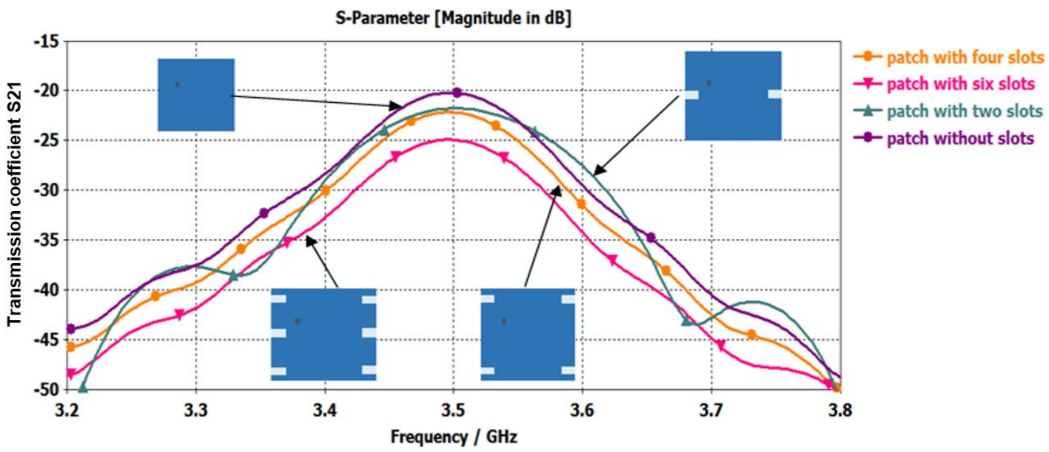


Figure 5. Mutual coupling variation as a function of patch antenna geometry

3. RESULTS AND DISCUSSION
3.1. Reduction of mutual coupling using cut side patches and EBG structures

In the previous section, we have seen that the modification of the patch geometry has a significant effect in reducing the mutual coupling, of which minimization of approximately 5 dB is obtained using a six-slot patch compared to a patch without slots. In this section we propose a simultaneous application of geometric modification on patch elements (as presented in the previous section) as well as the EBG introduction, to better minimize the mutual coupling between elements antenna of microstrip arrays. SHI structure is composed of three squares and one square ring, see Figure 1(a) placed over Rogers RO3010 material with 10.2 and h=1.27 mm which presents respectively its permittivity and thickness. In this approach, the patch elements are geometrically modified, while electromagnetic bandgap structures EBG, formed by 4 EBG unit cells, are situated between the array elements at an extremely narrow spacing. Figure 6 shows the array antenna with the hybrid method, the view from above of the antenna is shown in Figure 6(a), while Figure 6(b) presents the view from the side.

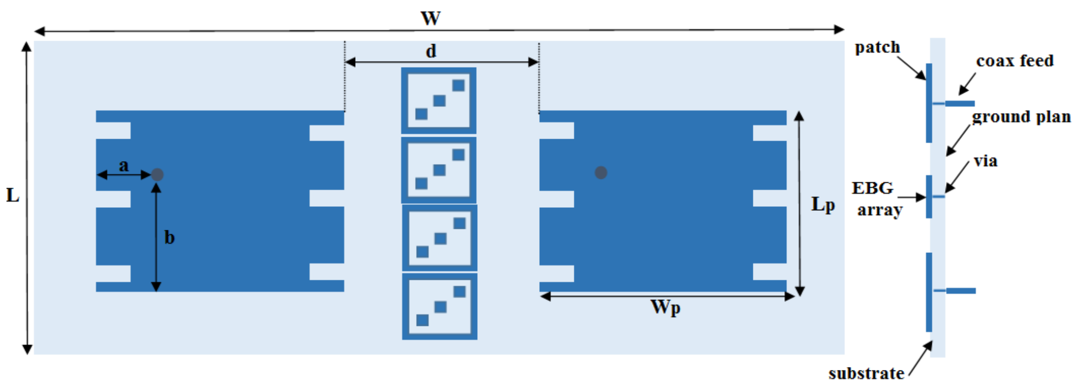


Figure 6. Array antenna with hybrid method (a) view from above and (b) view from the side

The spacing between the two patch antennas (0.5*λ3.5) is represented by d=13.43 mm, that is small compared to the wavelength of free space at 3.5 GHz. The surface waves generated impact significantly the mutual coupling between the radiating components. Especially when the array elements are placed on high permittivity substrates. The proposed hybrid method (EBG and modified patch) has demonstrated its capacity to eliminate surface waves and achieve a very significant mutual coupling attenuation at the frequency of resonance.

The mutual coupling of the system is analyzed separately to better understand the effects of each technique, the patch elements modified and also the EBG structures. As illustrated in Figure 7, it was clear that each technique individually was able to reduce the mutual coupling, reaching -28 and -24 dB, respectively, when using only the EBG structure and the modified patches, and -51 dB when both techniques are used at the same time, with the two patches separated by 0.5*λ0 (13.43 mm).

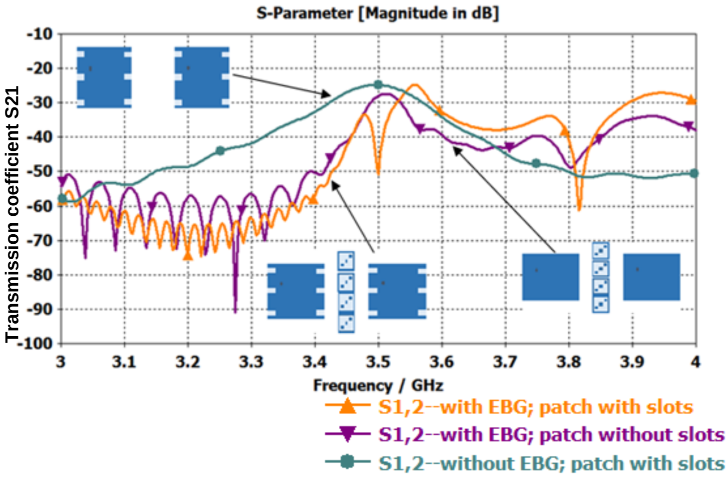


Figure 7. Antenna array mutual coupling with the hybrid method

Figure 8 illustrates the mutual coupling of the suggested structure (changed patches and EBG) and the conventional one, for a distance of 0.5*λ0 (13.43 mm) between the two patches. As shown in this figure, by employing a hybrid method, the mutual coupling between the patches was greatly decreased going over 18 dB to approximately 51 dB, so with this proposed structure, we have a 33 dB of mutual coupling reduction compared to a conventional configuration. We can also see in Figure 8 the reflection coefficient of the two-element array without and with the proposed hybrid method, in both cases the reflection coefficient is less than -10 dB around 3.5 GHz.

Figure 9 shows the horizontal and vertical section of the radiation pattern of the conventional and proposed two-element array antenna at 3.5 GHz, the radiation patterns of the antenna when phi=90 are shown in Figure 9(a) while Figure 9(b) when phi=0. This figure shows that the radiation patterns are unaffected by these EBG structures, on the contrary, they are slightly improved. Figure 10 illustrates the curve of gain and directivity in the Cartesian coordinate system, the directivity curve is shown in Figure 10(a), while Figure 10(b) present the curve of gain, where a slight increase can be observed in the direction of maximum gain and directivity.

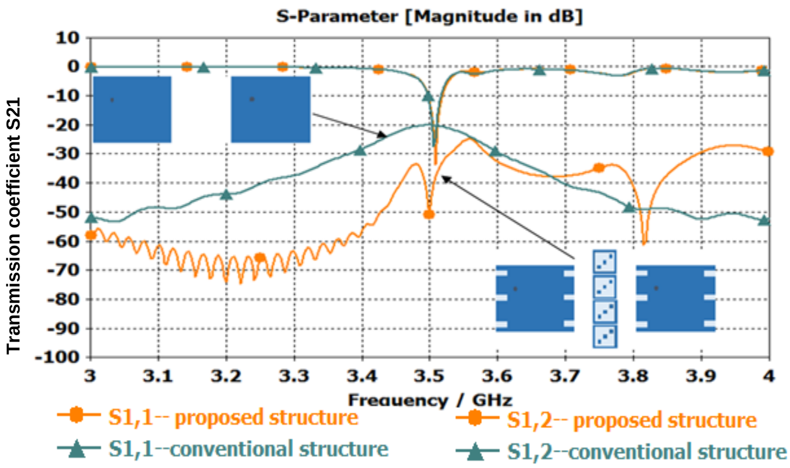
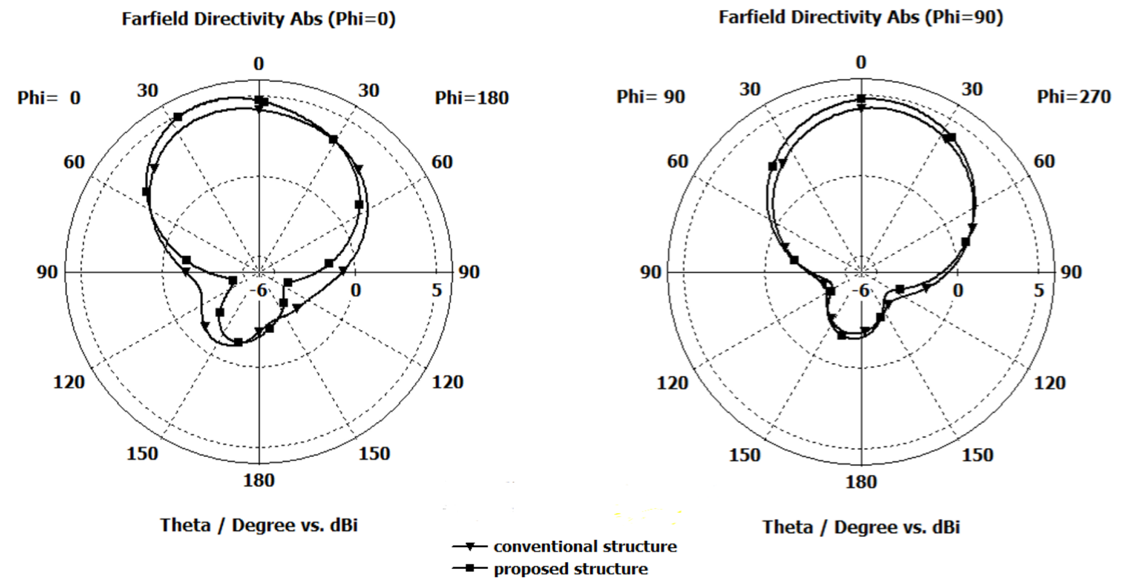
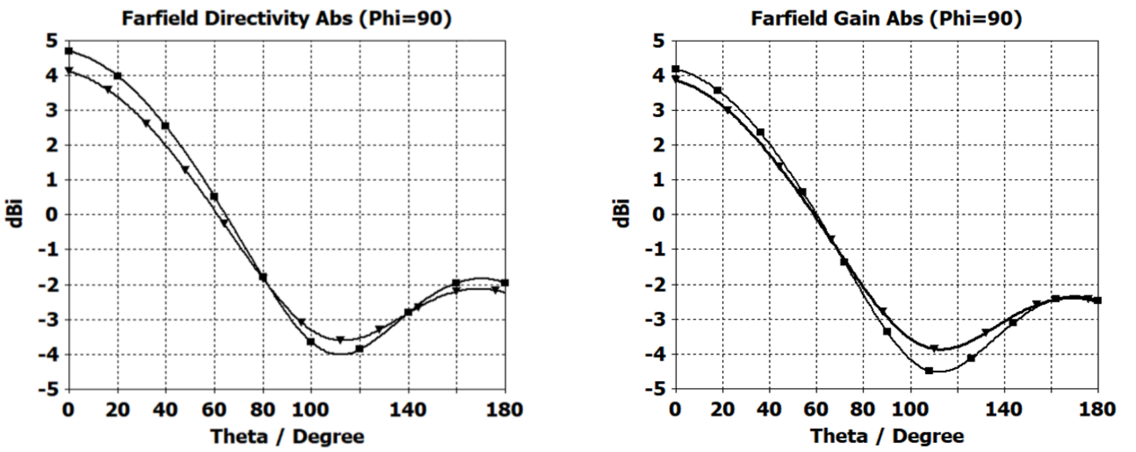


Figure 8. Parameter S of the conventional and proposed structure at d=0.5*λ0 (13.43 mm)



(a) (b)

Figure 9. Horizontal and vertical section of the radiation pattern of the conventional and proposed two-element array antenna at 3.5GHz (a) phi=90, (b) phi=0



(a) (b)

Figure 10. Curve of gain and directivity in Cartesian coordinate system (a) directivity and (b) gain

The comparison between the conventional and proposed array antenna is summarized in Table 3. In terms of antenna performance, it can be seen that when the patch geometry is modified and EBG structures are added to the antenna, the coupling between the radiating components decreases extensively as well as the antenna becomes more matched and more directive. To illustrate the benefits of our proposed structure in this document compared with other works, in Table 4 the characteristics of our proposed structure and certain previously published works are presented. As can be seen, our antenna provides a higher decrease of the mutual coupling and a slight gain increase in comparison to other works.

Table 3. Comparison between conventional and proposed antenna array

Array antenna	Conventional structure	Proposed structure
Resonance frequency (GHz)	3.5	3.5
return loss S11 (dB)	19.27	32.13
Directivity (dBi)	4.44	5.13
Parameters S12 (dB)	18	51

Table 4. Comparison between the proposed antenna and some literature antennas

Reference	Current work	2020 [24]	2020 [25]
Technique	Hybrid Technique	With EBG	Fractal structure
Centre frequency (GHz)	3.5	3.5	3.5
Volume W×L×h (mm^3)	62.37x25.3x1.27	62.37x25.3x1.27	36x22x20
Edge to edge distance	0.15 λ0 13.43 mm	0.22 λ0 19.33 mm	0.17 λ0 14.57 mm
Gain (dBi)	4.61	6.09	2.3
Gain improvement	0.43	1.57	---
Mutual coupling Reduction (dB)	33	8	8-32 dB (3.17- 4.15 GHz)

4. CONCLUSION

This document introduces an effective approach for minimizing mutual coupling for antenna arrays, combining two distinct approaches, to obtain a meaningful level of reduction of approximately 33 dB, for the first time, employing a mechanism that is efficient in terms of size and cost. Through this approach, a modification is implemented on the elements of the patch and, concurrently, EBG unit cells are inserted into close proximity to the elements of the array. Unlike the majority of mutual reduction methods, our suggested design does not just decrease the gain, it enhances the antenna gain by 0.43 dB.

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