TELKOMNIKA, Vol.16, No.1, February 2018, pp. 151~158
ISSN: 1693-6930, accredited **A** by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v16i1.7017

Reduction of Mutual Coupling between Closely Spaced Microstrip Antennas Arrays Using Electromagnetic Band-gap (2D-EBG) Structures

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Abstract

Reducing mutual coupling is a key research area in design of compact microstrip antennas arrays. To minimize the overall size of the antennas arrays, the distance between them must be very small, as a result a strong mutual coupling is appears. Periodic structures can help to design a low profile of antennas arrays and enable to improve their performances by the suppression of surface waves propagation in a given frequency range. This paper proposes a novel configuration of mushroom-like electromagnetic band-gap (2D-EBG) structure created by microstrip technology placed between two antennas arrays to reduce the mutual coupling more than -33.24dB. When 13×2 EBG structures are used, the mutual coupling reduces to -59.36dB at the operation frequency 5.8GHz of the antennas arrays. A 26.12dB mutual coupling reduction is achieved, which proves that the surface wave is suppressed. The proposed configuration is designed, optimized, and miniaturized by using electromagnetic software CST Microwave Studio. The measured results show that there is a good agreement with the computed results.

***Keywords**: mutual coupling, microstrip antennas arrays, mushroom-like electromagnetic band -gap Structure (EBGs), surface wave, ISM band.*

1. Introduction

There is always demand on high-performance electronic components to support the rapid growth in the telecommunications field, among them we find the antennas. The development of the antennas with new performances become mandatory for the modern wireless communication [1]. Recently, the scientific community is devoted to improve the performance of antennas [2]. The use of the printed antenna array in telecommunication systems allows us to improve various antenna characteristics, for example, increasing gain, directivity -to meet the demands of long distance communication- and other functions that are hard to do with only one element. Thereafter, one of the basic characteristics of an antenna array appears when two or more elements are located near to each other and effect each other is the mutual coupling [3-4]. In addition, if several antennas share the same ground plane, surface currents can cause also unwanted mutual coupling. The mutual coupling is adversely affects the input impedance of the radiating elements, gain, side lobe level, and radiation pattern shape [5]. In a practical way, the coupling mechanisms depend on numerous factors such as the permittivity and thickness of substrate used, type of excited modes, ground plane size and do not forget the distance between radiating elements [6].

To solve the problem of mutual coupling, several techniques have been proposed in the literature to reduce the mutual coupling while keeping the antennas arrays elements as they are. Among the most famous methods proposed to reduce the MC for printed microstrip antennas arrays are using electromagnetic band-gap (EBG) structures such as uniplanar compact electromagnetic band-gap (UC-EBG) [7-9], as EBG design using butterfly radial stubs [10], as mushroom-like EBG structure [11-13]. Parasitic elements between the antennas [14], defected wall structure [15] and defected ground structures (DGS) [16-18]. A simple UC-EBG structures presented in [5], are printed on a superstrate layer to miniaturize the distance between the elements of antennas arrays and reduce the mutual coupling. Also, these periodic

Received November 12, 2017; Revised January 17, 2018; Accepted January 30, 2018

structures have a very narrow EBG bandwidth. Insertion of a meander DGS slots was suggested in [19], with significant reduction in mutual coupling by 29dB at the operation frequency of the array.

The only way to miniaturize the space in array configurations is to bring closer the antennas between them, consequently a strong mutual coupling appears. To reduce total size and improve gain, radiation efficiency or reducing the mutual coupling in printed antennas arrays, we can use electromagnetic band-gap (EBG) structures that suppress the propagation of electromagnetic waves at certain band of frequency. Electromagnetic bandgap (EBG) structures appear to be periodic structures by many columns or lines or both. These structures are known through a set of names such as Frequency Selective Surfaces (FSS), Photonic Crystals and Photonic Band Gaps (PBG). The different nomenclature share certain basic characteristics such as reflects the waves which propagate in the forbidden band and at other frequencies it will act as transparent medium, also suppress the surface wave propagation on the ground plane of the antennas [6] and therefrom can be grouped under the broad category of EBG [10].

In order to obtain a weaker mutual coupling between the printed antennas or rather between antennas arrays integrated in a small area, multifarious research efforts have been undertaken. Many reports have studied the effects of one-dimensional transmission line, two dimensional planar surfaces and three-dimensional volumetric EBG structures on microstrip elements, and have shown the ability to suppress or reduce the mutual coupling in printed antennas arrays structures. The purpose of this work is to decrease both the distance between two neighbor arrays as well as the mutual coupling in array structures. To achieve this, two columns of the novel mushroom-like EBG structure are inserted between two antennas arrays each contains four microstrip patch antennas.

2. Antenna Array Design

Four-elements array are designed using FR-4 epoxy substrate with relative permittivity of 4.4, and loss tangent of 0.025. The substrate thickness is 1.6mm, and the elements is be fed by multiple lines called corporate-feed network, indeed the radiating elements are linked each other by using the quarter wavelength impedance transformer method. The patch size is Lpx Wp=11.18x15.74mm^2, and the edge-to-edge distance between the antennas is d2=12.12mm. The center-to-center separation between the printed antennas is selected to be d1=27.86mm (0.539$\lambda_{5.8GHz}$), where $\lambda_{5.8GHz}$ is the wavelength in free space. The microstrip antenna array are fed with 50-Ω coaxial probes, and the elements share a common ground plane of size Lg×Wg=63×60mm^2. After many series of optimization and miniaturization by using CST MW solver, the final optimized geometric parameters of the proposed microstrip antenna array are: L1=7mm, L2=1.4mm, L3=8.33mm, L4=6mm, L5=10.7mm, L6=10.7mm, W1=1mm, W2=0.8mm, W3=0.8mm, W4=0.6mm and W5=2.55mm. Accordingly the antenna array operates in (5.6586GHz-5.9365GHz) which covers the Industrial Scientific Medical (ISM) band. Figure 1(a) shows the layout schematic of the planar four-elements antenna array under consideration.

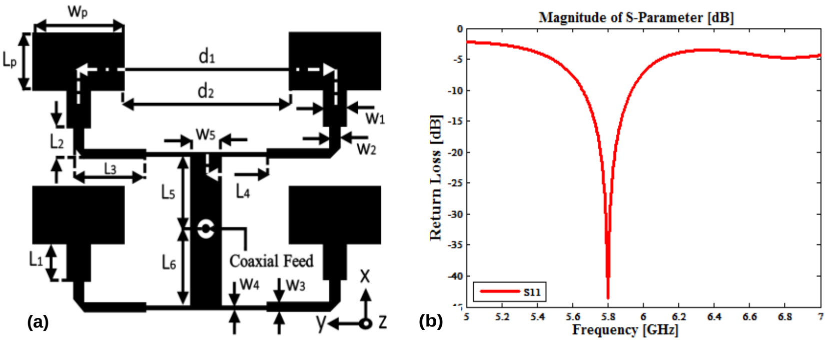


Figure 1. The proposed microstrip antenna array (2x2): (a) Geometry, (b) Return loss (S11)

3. Mutual Coupling between Two Antennas Arrays

The mutual coupling between two antennas arrays depends upon the distance between them. The mutual coupling between two antennas arrays for four different separations are shown in Figure 2(b). At first, the initial separation between the two antennas arrays is selected to be d1=51.72mm ($1\lambda_{5.8GHz}$) and d1=41.38mm ($0.8\lambda_{5.8GHz}$), a low mutual coupling usually exists between radiating elements. Secondly, for d1=27.86mm ($0.539\lambda_{5.8GHz}$) and d1=20.69mm ($0.4\lambda_{5.8GHz}$) the both of antennas arrays are close to each other the mutual coupling will be greater. It can be clearly observed that the coupling coefficient reduces linearly as the distance between the arrays is increased. Substantially, the strength of mutual coupling between elements is inversely proportional to the distance between them. Then the easiest solution to reduce the mutual coupling is to widen the distance between antennas arrays, but unfortunately the volumetric size of the structure is going to be bigger. To solve this problem-decrease simultaneously the distance between the radiating elements as well as the mutual coupling in array structure-a new configuration of mushroom-like EBG structures are inserted between the both antennas arrays.

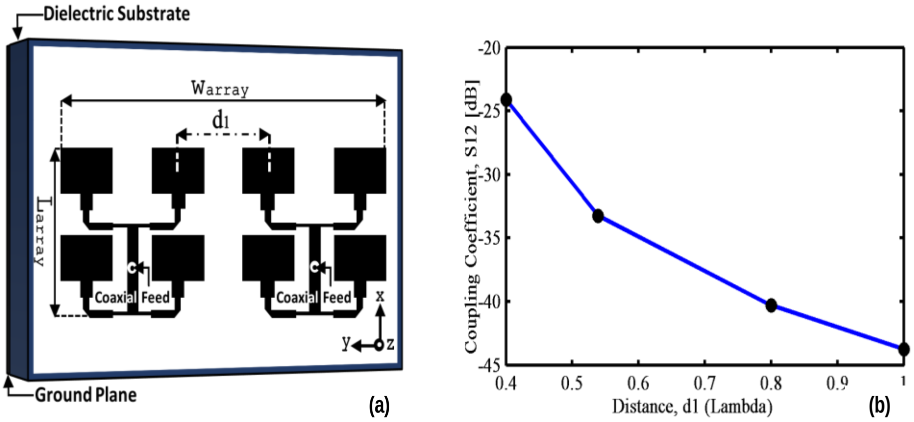


Figure 2. (a) Perspective view of the both printed antennas arrays configurations: Larray =41.58mm, Warray=99.32mm and (b) Coupling coefficient for different separations distance (d1) between the both antennas arrays

4. Novel Design of Mushroom-Like EBG Structure

4.1. Mushroom like-Electromagnetic Band-gap (2D-EBG)

The mushroom-like electromagnetic band-gap (EBG) structure is one of the basic and most common EBG structures, is arranged in a two-dimensional lattice, this structure is composed as follows: a ground plane, a dielectric substrate, a square metal patches and a connecting vias [6]. For the simple square lattice mushroom-like electromagnetic band-gap (EBG) structure, the inductance depends mainly of the dielectric substrate and the capacitance is due to proximity of the top metal patches [20]. The surface impedance of the mushroom-like EBG structure can be represented by a parallel resonant LC circuit and is given as [6]:

$$Z_{Surface} = \frac{j\omega L}{1-\omega^2 LC} \tag{1}$$

Where ω=2πf and f define the angular frequency and frequency of the wave respectively. The equivalent sheet capacitance C and the equivalent sheet inductance L, are given as follows [21]:

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

$$L = \mu_0 \mu_r h \tag{3}$$

The constants ε$_0$ and μ$_0$ are the permittivity of free space and the permeability of free space, respectively. The variable μ$_r$ is the relative permeability of the substrate and g is the gap between elements in EBG structures. The bandwidth of the band gap frequency can be determined by using formula (5) [11]:

$$\omega = \frac{1}{\sqrt{LC}} \tag{4}$$

$$BW = \frac{\Delta\omega}{\omega} = \frac{Z_0}{\eta_0} \tag{5}$$

Where $Z_0 = \sqrt{L/C}$ and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$ is the free space impedance which is 377Ω.

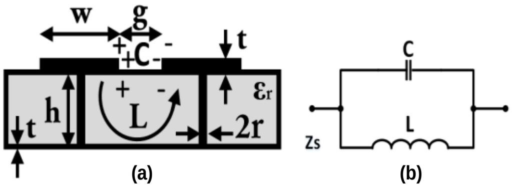


Figure 3. (a) Origin of the capacitance and inductance in the effective LC model, (b) Effective circuit used to model the surface impedance

4.2. Two Slots Loaded (2D-EBG)

Unlike the conventional mushroom-like EBG, we have designed a novel slot loaded EBG structure by cutting two slots, y-oriented slots into the patch of a mushroom-like EBG cell. The geometrical dimensions of the novel unit cell of mushroom-like EBG structure used in the proposed configuration are shown in Figure 4. The overall size of elementary cell is 4.25mmx4.25mm with 4mmx4mm of patch. The metallic via connecting patch and ground plane has a 0.56mm diameter. The other parameters of the EBG unit cell are as follows: r= 0.28mm, g=0.5mm and w=4mm. Widths and lengths of slots are optimized to obtain the most compact structure. Finally, dimensions of slots are designed as: m=1.5mm, n=0.6mm.

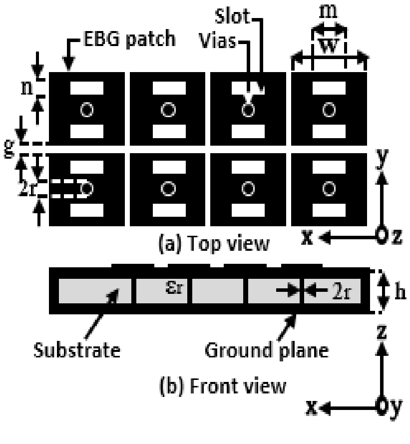


Figure 4. Configuration and details of eight units of the novel mushroom-like EBG structure (a) Top view, (b) front view

5. Mutual Coupling Reduction in Closely Spaced Antennas Arrays

Two columns of proposed mushroom-like EBG structure is placed between the coupled antennas arrays to reduce the mutual coupling as shown in Figure 5(a). The distance between the antennas edges is 12.12mm ($0.234\lambda_{5.8GHz}$), and the gap between the edge of antenna and EBG is 1.81mm ($0.035\lambda_{5.8GHz}$). Additionally, the overall size of 13x2 EBG unit cells is $58x8.5mm^2$.

5.1. Simulation of Antennas Arrays Integrated With EBG Structures

The model is simulated in CST Microwave Studio electromagnetic solver (CST-MWS). The Simulated S-parameters of the proposed antennas arrays with and without the EBG structures are shown in Figure 5(b). It is observed that both antennas arrays resonate at 5.8 GHz with return loss better than -10dB. For the antennas arrays with the EBG structures, the mutual coupling is adjusted to -59.36dB. An approximately 26.12dB reduction of mutual coupling is achieved. To visualize the band-gap feature of surface-wave suppression. The electric filed distribution at the frequency 5.8GHz of both of the two cases -antennas arrays with and without EBG structures- are simulated and graphically presented as shown in Figure 6. It is observed at the left antenna array, the intensity of the electronic field decreases obviously when we add two columns of EBGs.

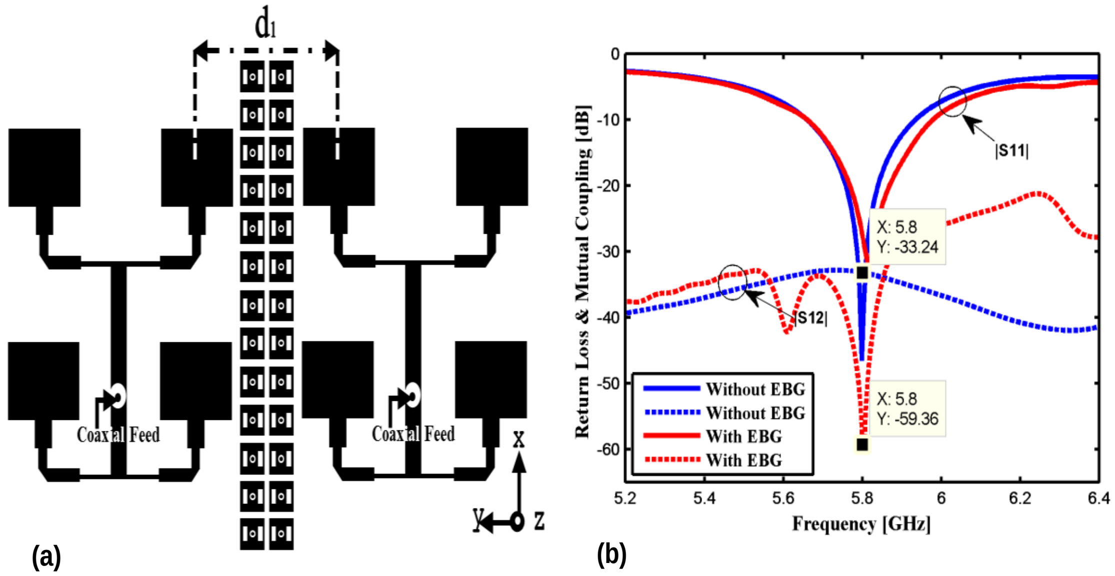


Figure 5. (a) Configuration of the designed antennas arrays with the proposed EBG structure, (b) Simulated scattering parameters for the proposed antennas arrays with and without EBGs

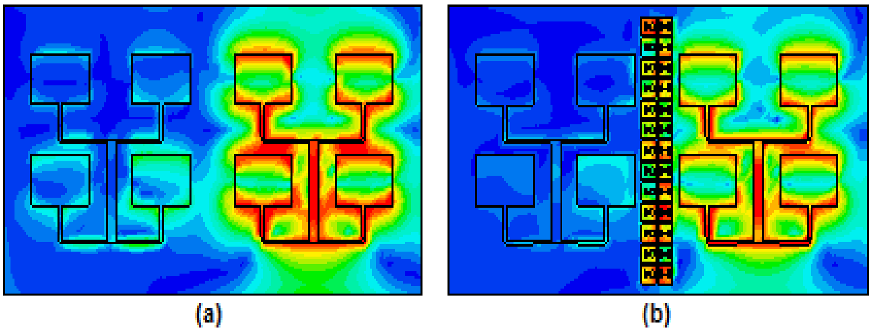
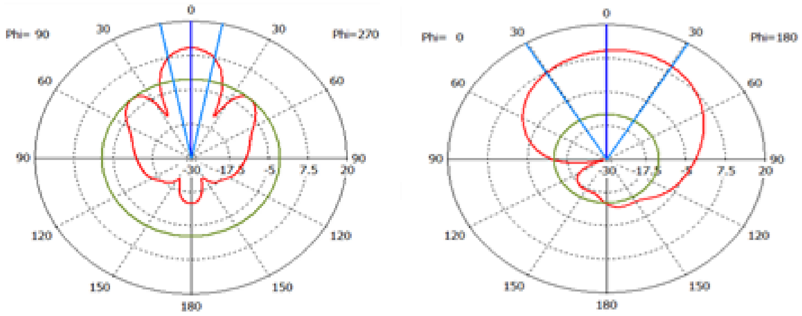


Figure 6. Electric-field distribution of antennas arrays, (a) without mushroom-like EBGs, (b) with mushroom-like EBGs observed at resonant frequency 5.8GHz

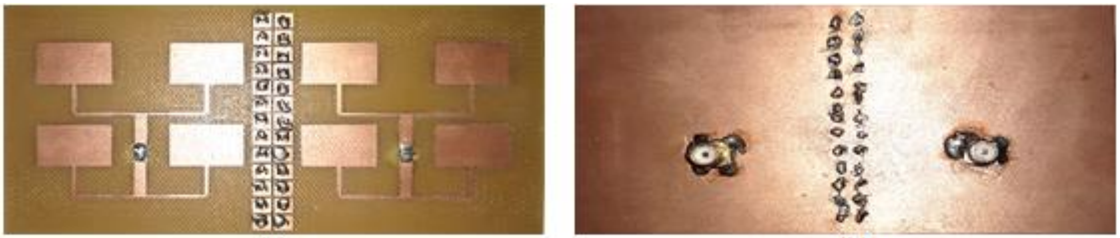


(a) (b)

Figure 7. Simulated radiation patterns at 5.8GHz (a) E-plane (b) H-plane

5.2. Experimental Results and Discussion

In order to validate the mutual coupling reduction performance of the proposed approach, a prototype antennas arrays with 13x2 EBG unit cells, as shown in Figure 8, was fabricated and measured to confirm the validity of the proposed design. The proposed circuit is manufactured by using LPKF machine and it is printed on the top layer of a substrate FR-4 epoxy with thickness equals to 1.6mm and relative dielectric permittivity of 4.4. The measurement is performed by using the Vector Network Analyzer (VNA) from Rohde & Schwarz. The measured S-parameters are shown in Figure 9 where they are compared with the simulation results. The measured results indicate that the arrays operates at (5.462GHz-6.635GHz), 0.85GHz higher than the simulated one. It can be indicated that the resonant frequency has a little shift due to the fabrication constraints, such as welding the coaxial ports as well as the vias of EBG structures. At the operation frequency 5.8GHz, the mutual coupling is -59.36 dB and the measured one is -54.35dB, which means the mutual coupling has been reduced by 26.12dB and 21.11dB, respectively.



(a) (b)

Figure 8. Photographs of the manufactured prototype, (a) Front view, (b) Back view

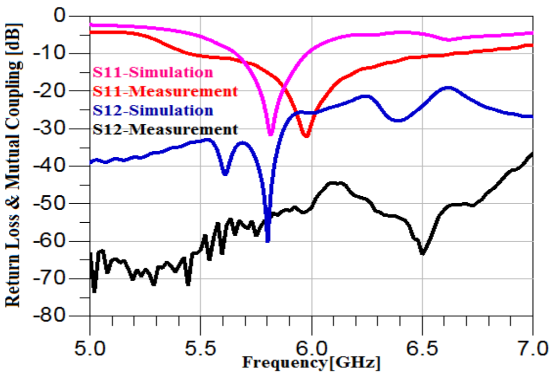


Figure 9. Simulated and measured S-parameters of the fabricated prototype

Table 1. Performance Comparison of the Different Results Obtained by Simulation and Measurement

Parameters	Simulated Results by CST-MWS		Measured Performance
	Without EBG	With EBG	With EBG
BW [MHz]	277.2	321.4	1173.2
S11, S12 [dB]	-44.5,-33.24	-27.8,-59.36	-15.3,-54.35
Gain [dB]	10.81	10.63	-

Table 2 compares the performance of the various designs that were adopted for miniaturization and mutual coupling reduction. It can be summarized that each design has its own characteristics. As a result, the proposed EBG has better mutual coupling reduction performance than those reported in [22], [23] and [24]. The antennas arrays with proposed decoupling structure has been designed, optimized, and tested for minimum spacing and found suitable for different applications. The novel EBGs in between the elements of the antennas arrays has a little influence on the radiation characteristics in terms of gain and directivity. The latter two factors have decreased their values about 0.18dB and 0.13dBi compared with the antennas structures without EBGs.

Table 2. Performance of the Proposed Structure Compared with Previous Reported Designs

Ref. No.	[22]	[23]	[24]	Proposed
Approach	SMLR	CSRR	DGS	EBG
Center. Freq (f_0) in GHz	4.8	5.0	9.2	5.8
Edge to Edge Spacing	$0.11\lambda_0$	$0.25\lambda_0$	$<0.33\lambda_0$	$0.234\lambda_{5.8GHz}$
Center to Center Spacing	$0.38\lambda_0$	$0.50\lambda_0$	$0.70\lambda_0$	$0.539\lambda_{5.8GHz}$
Improvement in S12 (dB)	6 to 16	10	16.50	26.12

6. Conclusion

In this work, a new configuration of mushroom-like EBG structure has been proposed to enhance the isolation between two antennas arrays. By using this structure, a high isolation of better than 26.12dB is obtained. A prototype has been fabricated and measured to confirm the validity of the proposed structure; this prototype achieved the high isolation of about 21.11dB at the operating frequency 5.8GHz with edge-to-edge distance of $0.234\lambda_{5.8GHz}$. Good consistency between the simulated results and experimental results was also achieved. The proposed structure is more compact and does not require an intricate design to obtain these results. The proposed mutual coupling reduction structure can be used in MIMO systems or rectenna application for reducing size and enhancing isolation performance.

Acknowledgment

We thank Mr. Mohamed Latrach Professor in ESEO, engineering institute in Angers, France, for allowing us to use all the equipments and solvers available in his laboratory.

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