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Research paper

Mutual Coupling Reduction in MIMO Microstrip Antenna by Designing a Novel EBG with a Genetic Algorithm

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Abstract

Background and Objectives: Multi-input multi-output (MIMO) antennas have been of interest in wireless communications in recent years. In these systems, many antennas are placed next to each other. The most important issue in the design of MIMO antennas is mutual coupling. Many methods have been proposed to reduce the mutual coupling of MIMO antennas. Many of these methods require an additional substrate on top or bottom of the antenna. In the reduction of mutual couplings electromagnetic band-gap (EBG) structures are preferred because they are coplanar with the antenna and can be compactly designed. In this paper, to reduce mutual coupling in MIMO antennas, a novel compact EBG structure based on the genetic algorithm optimization is proposed.

Methods: The method proposed in this paper to design an optimal EBG structure is to use a genetic algorithm (GA). In this method, an EBG unit cell is designed by a binary code, and then the 7×2 EBG structure of the unit cell is placed between two antenna elements with λ/2 distance. The optimization algorithm tries to find the best unit cell to reduce the mutual coupling between two elements. After 70 generations in the genetic algorithm, the GA determines a compact structure of EBG elements which reduces mutual coupling significantly.

Results: Two-element patch antennas with and without the proposed EBG structure are fabricated and the mutual couplings between array elements are measured at 5.68GHz in both cases. It is shown that the proposed compact EBG structure reduced the isolation of the two antennas by 27 dB. This decrease in mutual coupling is much higher than in the previous papers. The proposed EBG has little effect on other antenna radiation parameters such as S11 and radiation patterns.

Conclusion: In general, in this paper, a compact and coplanar EBG structure is proposed to significantly reduce the mutual coupling in MIMO antennas. The method presented in this paper can be used for other MIMO antenna configurations at other frequencies and the proposed method will create a completely optimal structure to reduce mutual coupling.

Introduction

One of the important methods in increasing the capacity of the telecommunication system in recent years has been the Multiple Input Output (MIMO) technology. Multiple-input-multiple-output (MIMO) technology not only provides high data transfer rates but also increases

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communication reliability and provides multiplexing gain. For these reasons, MIMO technology was used in the fourth generation of wireless communication and is being widely used in the 5G and beyond in the form of massive MIMOs [1]-[3].

In MIMO technology, antennas are designed with small interelement distances for wide-angle beamforming purposes. Due to the small space and a large number of elements, strong mutual coupling effects occur between antenna elements. Mutual coupling degrades the radiation performance [4], as well as the available throughput [5]. Therefore, in recent years, extensive research has been done on the methods of reducing mutual coupling in MIMO antennas in universities and industry [6]-[28].

In general, the methods of reducing mutual coupling can be divided into two categories of non-coplanar [6]-[10] and coplanar [11]-[25] methods. In coplanar methods, the antenna element and the decoupling structure are both located on the same layer. While in non-coplanar methods, the decoupling structure is placed higher or lower than the antenna element.

Among the non-coplanar methods, we can refer to the methods such as: using the near-field resonator [6], the array-antenna decoupling surface [7], the metasurface-based decoupling method [8], T-shaped decoupling network [9], and using of a transmission-line for decoupling [10]. Although these methods have had some success in reducing the mutual coupling of antennas, however, all these works lead to a high antenna profile and need an additional substrate layer. Therefore the non-coplanar methods are unattractive especially when low-profile performance is desired.

The coplanar methods do not require an additional substrate and provide a more compact antenna structure. Among the coplanar methods, we can refer to the methods such as: using different types of metamaterials [11]-[13], defect ground structures (DGS) [15], [16], and Electromagnetic band-gap (EBG) structures [17]-[26]. Among these methods, the advantage of EBGs is their simple construction compared to metamaterials, which is an important issue and shows the superiority of these structures.

EBG structures also increase the gain and reduce the back lobe in the antenna [19]. While the DGS for example reduces the antenna gain and increases the back radiations. In addition, EBG can help to reduce the dimensions of the designed antenna [21].

In massive MIMO applications where elements with small distances are used, EBG structures should also be designed with optimal and small dimensions. If the EBG gets too close to the antenna, antenna matching is affected negatively due to reactive coupling between the array elements and EBG [22]. Therefore, the miniaturization of EBG has been one of the issues of interest to researchers [23]-[25].

A compact EBG structure for low-profile applications is presented in [24]. However, the reported structure required a distance between the two antennas of more than 1λ and provided only a 6 dB improvement in isolation. In [25], the miniaturization of the EBG structure is done with the help of a fractal pattern and its combination with DGS. The final structure has provided a 16 dB improvement in isolation. But using the DGS structure degrades many advantages of EBG structures and increases the back radiation.

The EBG structures presented so far either have a specific design formulation or have introduced parameters that are changed by the designer to obtain the desired response [17]-[26]. All these methods require extensive trial and error simulation which is time-consuming in design. Also, all the proposed structures are presented for a specific antenna structure at a specific frequency.

In this paper, a novel EBG structure is generated by the genetic algorithm (GA) to reduce mutual coupling between array elements. In the proposed method a unit cell of the EBG structure is generated by the GA algorithm. This unit cell is then repeated with equal distances in length and width and the final EBG structure is created. The method proposed in this paper to generate an EBG structure with the genetic algorithm can be implemented in any desired antenna structure at any frequency.

Also, the electromagnetic simulations required to obtain the appropriate EBG have been performed automatically by linking MATLAB with the electromagnetic simulator.

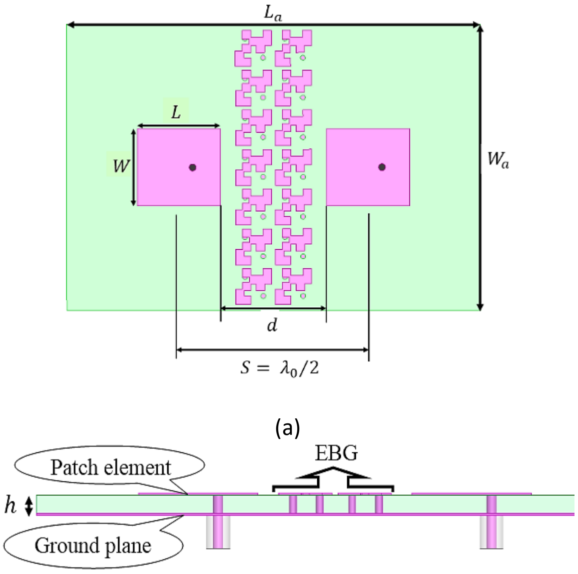
To demonstrate the proposed method two-element patch antennas with and without EBG are fabricated and measured. In the measurement results, a 27dB improvement in the array isolation can be seen, while the distance between the two elements of the antenna remains 0.5λ.

This paper is organized as follows. Section II describes how GA is employed to design the EBG structure. Section III presents simulation results and reports measurements on the constructed array including EBG. Finally, the conclusions of this study are reviewed in Section IV.

Design Procedure

As it is known, the EBG structures are periodic and consist of a large number of unit cells. In this paper, a unit cell of EBG is first designed by the genetic algorithm. Then, the unit cell is repeated along X and Y directions in a specific number and distances so that a novel EBG structure is created. The method for designing the novel EBG structure has already been used to design a wideband monopole antenna [27], [28], and microstrip filters [29], [30].

The reference antenna is a microstrip array including two patch elements designed at the 5.68 GHz frequency. This antenna is etched on an FR4 substrate with a 1.6 mm height and εr=4.4 and loss tangent of 0.03 as shown in Fig. 1. The distance between its elements is λ/2 and the periodic EBG structure is placed between the antenna elements. Other designed parameters of the microstrip array are: *L = 11.7 mm, W = 10.9 mm, d = 14.9 mm, L_a = 58.19 mm, W_a = 40.33 mm, S = 26.6 mm, h = 1.6 mm*.



(a)

(b)

Fig. 1: Geometry of the reference patch antenna array and the EBG structure. The distance between elements is $\lambda_0/2$. (a) Top view, (b) Side view.

To design the novel EBG with the GA, a unit cell of the EBG structure is decoded as a binary chromosome. This chromosome is mapped to a 5×5 square patch as shown in Fig. 2. As it can be seen, the GA chromosome has five genes with a five-bit binary sequence, therefore a 25-bit binary chromosome is used to define the EBG unit cell. These binary bits determine the presence or absence of 1 mm square patches. If the corresponding bit includes 1, the square is filled with a metal patch; when the corresponding bit is 0, the square is left free. These square patches also overlap so that when metal squares are connected only at one point, their electrical interconnection is assured.

Square patches employed in the EBG cell have 1mm edges and overlapping is considered to be 0.2mm; thus, each square has 1.2mm edges. In each unit cell, two connections to the ground (vias) are also considered. These vias are orthogonal to the structure of the planar section of the unit cell. The location of the vias is in the middle of each EBG cell and remains unchanged in the optimization process. As described in [22], the vias create inductive impedance in the EBG structure and block the surface wave propagation.

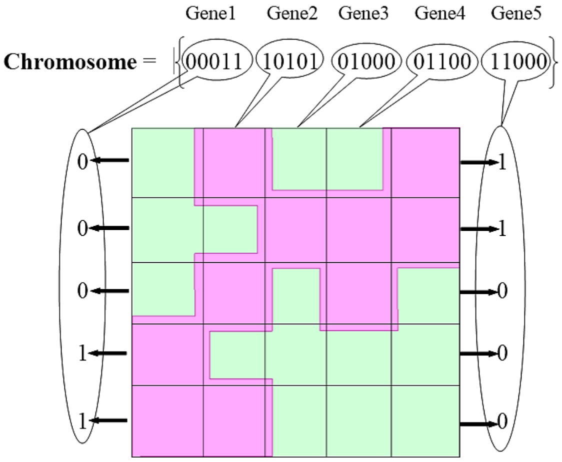
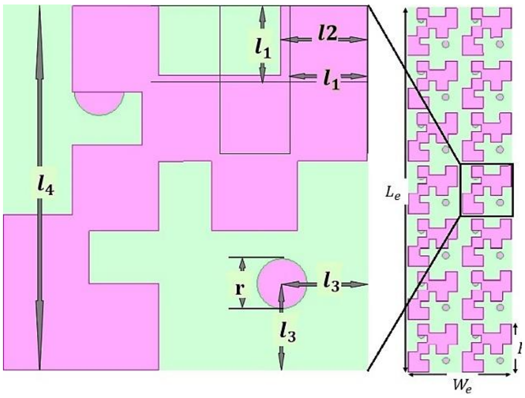


Fig. 2: GA chromosome implementation to the unit cell of the EBG.

Fig. 3 shows the complete dimensions of the proposed unit cell. The two vias with 0.72mm diameters are shown as a circle in this figure. The design EBG includes two columns and seven rows of the GA unit cells. The period of repeating unit cells is 5.7mm and therefore the gap between each unit cell is g=0.5mm.



(a) (b)

Fig. 3: The Proposed EBG structure using GA. (a) Top view of the EBG unit cell. (b) Top view of the EBG. The parameters are: $l_1 = 1mm,\ l_2 = 1.2mm,\ l_3 = 4mm,\ l_4 = 5.2mm,$ $r = 0.72mm,\ W_e = 1,\ L_e = 39.76mm, P = 5.7mm.$

GA is started by generating a forty randomly initial population. In each generation selection, cross-over, and mutation functions are used to create next-generation populations. The rates of selection, cross-over, and mutation functions are considered as 0.2, 0.7, and 0.1 respectively.

GA is employed using MATLAB software and the chromosome generated by GA is first transformed to a unit cell in HFSS software and then converted to the EBG structure by repeating along X and Y directions. The EBG evaluation in the HFSS is done after the implementation of the 7×2 EBG structure. It should be mentioned that each GA chromosome changes the EBG structures and the other parameters of the array antenna remain unchanged. The S-parameter obtained by HFSS simulation is exported to MATLAB and evaluated by the cost function. A lower value assigned to an EBG by cost function leads to a higher probability of using that EBG in subsequent generations.

The GA cost function has |S11| and |S21| parameters in the desired bandwidth and is evaluated as follows:

$$\mathrm{Cost1} = \sum_{i=1}^{N} w_i \left(\left| S_{12}(f_i) \right| \right) \tag{1}$$

$$\mathrm{Cost2} = \sum_{i=1}^{N} w_i \left(\left| S_{11}(f_i) \right| + \left| S_{12}(f_i) \right| \right) \tag{2}$$

in which N, is the number of sampling frequencies considered for the reduction of the mutual coupling, w_i represents the weighting value at the i-th sampling frequency, and f_i is the i-th sampling frequency.

In the decision-making process, the cost function is first considered to reduce mutual coupling in the intent frequency band by (1) and the matching definition is neglected. When the mutual coupling is reduced, a member of the generation is selected such that the matching condition and mutual coupling reduction are satisfied as defined in (2). In this step, weight coefficients for both conditions are considered to be the same. Weighting coefficients in (1) and (2) are chosen for better convergence of the genetic algorithm. For example, if the value of |S12| is better than -50 dB, the coefficient of that frequency becomes zero. Also, larger weighting coefficients are used at frequencies close to antenna resonance, where the importance of reducing mutual coupling is higher.

Table 1: Summary of the steps of designing the Proposed EBG structure

Step	Procedure
01	GA parameters and criteria are set in Matlab.
02	Matlab creates random 25-bit binary chromosomes.
03	The generated chromosomes are decoded as pixel EBG unit cells.
04	The generated unit cells send to HFSS by a Matlab link.
05	In HFSS the unit cells are repeated in the 7×2 array and create different GA-EBG structures.
06	HFSS simulates the GA-EBG structures between a predefined array of antennas.
07	The S11 and S12 results send back to Matlab.
08	GA evaluates the simulated GA-EBG structures with equations (1) and (2).
09	The next generation of GA chromosomes is created from the previous ones by mutation, selection, and cross overs over functions.
10	If there is no convergence, the algorithm continues from the third step.

Table 1 shows a summary of the design steps of the proposed GA EBG structure. The desired isolation between array elements is considered more than 45 dB and after 70 generations this isolation is obtained and the algorithm is terminated. The final microstrip array antenna with the obtained GA-EBG is shown in Fig. 1. The advantage of employing EBG using GA is that the designer can monitor all design steps accurately and obtain the desired response by changing parameters.

Results and Discussion

After designing GA-EBG, the simulation results of two microstrip elements with and without EBG are compared in Fig. 4. As can be seen, both antennas have resonance around 5.7 GHz frequency. The relative bandwidth of the antenna without GA-EBG is 4% from 5.54 to 5.78 GHz, while the antenna with GA-EBG has a bandwidth of about 3.5% from 5.6 to 5.8 GHz. In this figure, the designed EBG structure shifts the antenna resonance slightly. This issue can be solved by changing the dimensions of the microstrip antenna in the presence of the EBG structure.

The |S21|result of the microstrip arrays is also shown in Fig. 4. As can be seen, |S21| is -21dB if the array does not include EBG and is -50 dB if it includes EBG; therefore, the proposed EBG improves the mutual coupling by about 29dB in the simulation results.

The proposed two-element antennas with and without EBG are fabricated and their characteristics are measured as shown in Fig. 5. The printed circuit board technology is used for manufacturing these antennas.

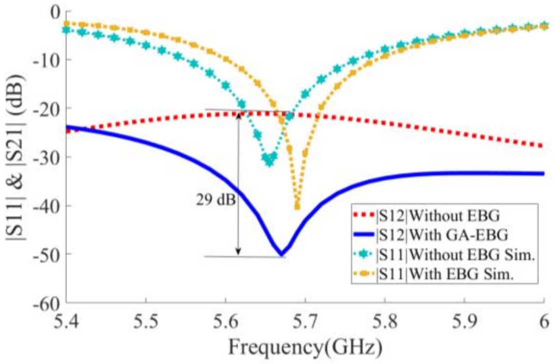
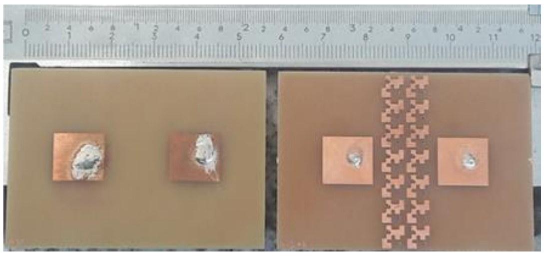


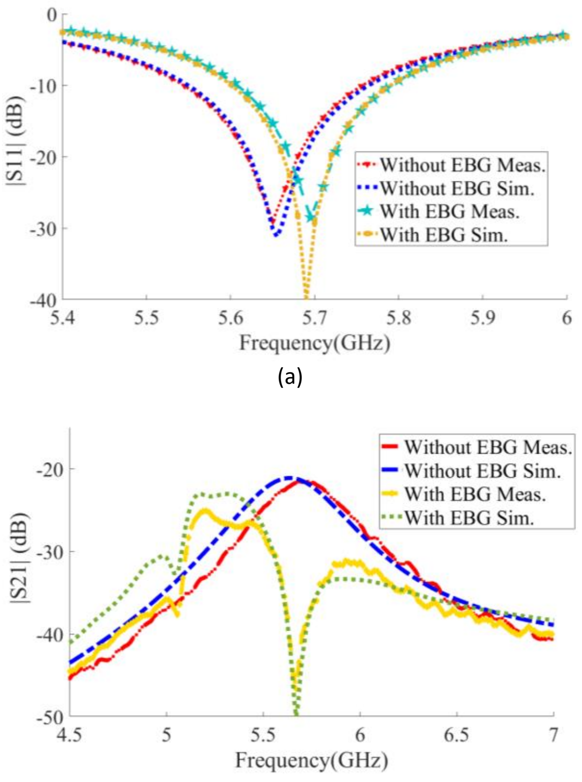
Fig. 4: Comparison of simulated scattering parameters for an E-plane coupled antenna pair (with GA-EBG and without EBG).



(a) (b)

Fig. 5: The fabricated prototype of the two-element patch antennas. (a) Without EBG, and (b) with the proposed GA-EBG.

The S-parameters of these microstrip arrays are measured using the vector network analyzer 3413E of Agilent and the results are shown in Fig. 6 (a) and (b). As can be seen in these figures, the measurement results are in very good agreement with the simulation results. In the measurement results at the frequency of 5.68GHz, |S21| is -21dB and by adding GA-EBG, it becomes -48 dB; thus, by adding EBG, the mutual coupling is improved by 27 dB. By comparing the measurement and simulation results in Fig. 4 and 6, it can be seen that the mutual coupling values in the measurement are about 2 dB higher than the simulation values. This issue could be due to the non-ideal nature of the antennas in the manufacturing conditions.

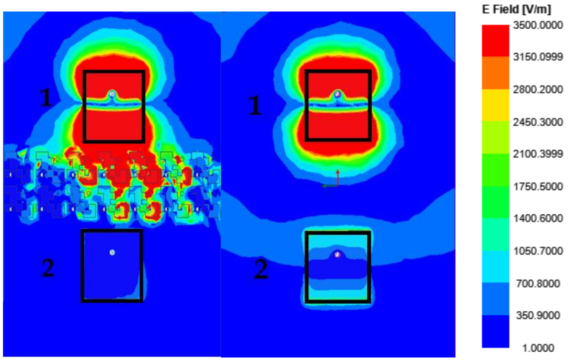


(a)

(b)

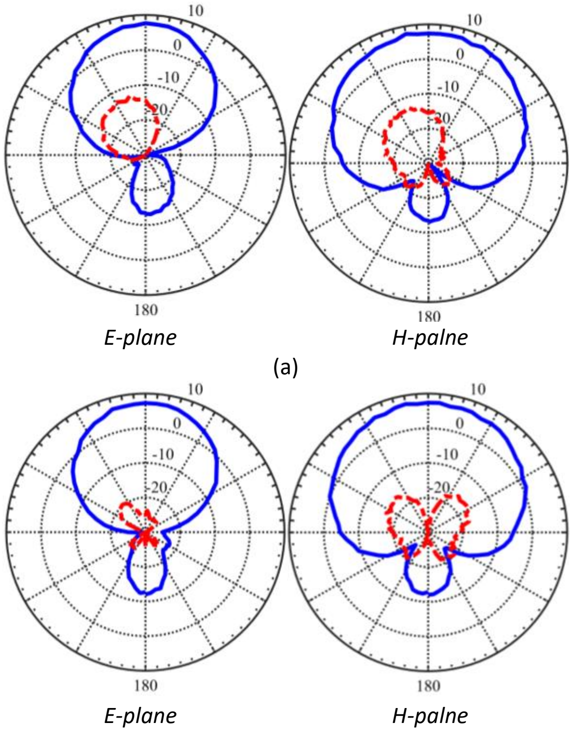
Fig. 6: Comparing the measurement and simulation results of the two-element antenna array with and without the presence of the proposed EBG. (a) S11 result, (b) S21 result.

Fig. 7 shows the amplitude of electric field distribution on the antennas, both in the presence and absence of EBG structure. In this figure, only one patch antenna (i.e. patch 1) is excited to observe the effects of isolation and mutual coupling on the side antenna (i.e patch 2). As can be seen, in the case where there is no EBG, the stimulated field has reached the second antenna from the first antenna. However, when the EBG is added to the structure it does not allow surface waves to propagate and there are very few fields around the second antenna. Therefore, in this condition, the mutual coupling is greatly reduced. To study the effects of adding EBG on the radiation of the antenna, the co and cross-polar radiation pattern of the antenna with and without EBG is measured and shown in Fig. 8. As can be the copolar radiation pattern of the antenna with the proposed EBG is almost match with the antenna without EBG. In this figure, it is also clear that, unlike previous works, the back radiation of the antenna has not changed much with the presence of EBG. However, the structure with the presence of EBG has slightly damaged the cross-polarization due to the creation of asymmetric currents. It should be noted that a slight increase in cross-polarization has been seen in most structures based on EBG.



(a) (b)

Fig. 7: The amplitude of electric field distribution on the antennas, (a) Without EBG, and (b) With GA-EBG, at 5.7 GHz frequency.



(a)

(b)

Fig. 8: Measured E- and H-plane radiation patterns of the proposed antenna with and without proposed EBG at 5.68GHz (a) the antenna with EBG, and (b) the antenna without GA-EBG. The solid line represents co-polarization, and the dashed line represents cross-polarization.

Finally, to compare the EBG designed in a paper with the previous paper, Table 2 is given. In this table, the structure presented in this paper is compared with six similar examples. As can be seen, the structure of this paper has made a significant improvement in the amount of mutual coupling, while the distance between two elements of the array remains λ/2.

In general, considering all the results presented in this paper, it can be concluded that a novel, compact, low-cost EBG structure has been presented to reduce the mutual coupling between MIMO antennas. The method presented in this paper can be used for other MIMO antenna configurations at other frequencies.

Table 2: Comparison of characteristics of various EBG Types with the proposed EBG structure

EBG Design Type	Freq. (GHz)	Mutual Coupling Reduction	Space Between Elements	Substrate (ε_r,height (mm))
SRR [11]	3.6	19dB	$0.5\lambda_0$	(4.4, 1)
CSRR [13]	5	10dB	$0.5\lambda_0$	(3.4, 1.27)
EBG+DGS [19]	5.8	22.3dB	$0.4\lambda_0$	(4.6, 1.6)
Uniplanar EBG [24]	5.6	13.5dB	$0.5\lambda_0$	(10.2, 2.54)
Fractal EBG [25]	5	16dB	$0.5\lambda_0$	(2.65, 1)
This Work	5.7	27dB	$0.5\lambda_0$	(4.4, 1.6)

Conclusion

In this paper, a novel compact EBG structure is proposed to reduce the mutual couplings between array elements. The proposed EBG is designed based on 7×2 unit cells of EBG created by the genetic algorithm. Two-element patch antennas with and without the proposed EBG are fabricated and the mutual couplings between array elements are measured in both cases. In the measurement and simulation results, the proposed EBG structure has improved the mutual coupling by more than 27 dB. In comparison to the previous paper, the proposed EBG has made a significant improvement in the amount of mutual coupling reduction, while the distance between two elements of the array and the height of the substrate remain as low as possible.

Author Contributions

R. shirmohamadi, M. Bod and G. Dadashzadeh developed the proposed antenna idea and performed the analytic simulations and measurements. M. Bod has written the manuscript. R.shirmohamadi and G. dadashzadeh edited/reviewed the paper.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

DGS	Defect ground structure
EBG	electromagnetic band-gap
GA	genetic algorithm
HFSS	High Frequency Simulation Software
f_i	the ith sampling frequency
MIMO	Multiple-input-multiple-output
SRR	Split ring resonator
CSRR	Complementary split ring resonator
w_i	the weighting value at the ith sample
λ_0	corresponding wavelength

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