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A novel microstrip patch antenna design enhanced by mushroom like electromagnetic band gap structures with different via configurations

Farklı pin konfigürasyonlarina sahip mantar benzeri elektromanyetik bant aralığı yapıları ile geliştirilmiş yeni bir mikroşerit yama anten tasarımı

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Abstract

In this study, the designs with suitable combinations of a microstrip patch antenna and mushroom like EBG structures having different via locations are presented. The performance of the reference antenna is improved with the designs having removed and/or offset via configuration. It has been experienced with different designs that the vias removed and/or shifted from the first row of EBG structures, which are closest to the radiating patch of the antenna, have a significant effect on antenna performance. With the proposed designs, up to 32% bandwidth enhancement and up to 2.9 dBi gain increment are achieved according to the reference antenna. Moreover, the front to back ratio (F/B) of the reference antenna is enhanced to values between 26 and 29 dB from the 16.9 dB by the presented designs. In addition, while the simple single layer designs of the presented antennas facilitate their manufacturing, they also achieve a good thin profile merit (h/λ_0, λ_0 is the free-space wavelength at the centre frequency) with a value of 0.05.

Keywords: Microstrip patch antenna, Electromagnetic band gap structures, Via locations, Bandwidth, Gain.

Öz

Bu çalışmada, bir mikroşerit yama anten ve farklı pin konumlarına sahip mantar benzeri EBG yapıların uygun kombinasyonlarıyla tasarımlar sunulmuştur. Referans antenin performansı kaldırılan ve/veya merkezden kaydırılan pin konfigürasyonarına sahip tasarımlarla geliştirilmiştir. Özelikle antenin yayın yapan yamasına en yakın olan EBG yapıların birinci sırasından kaldırılan ve/veya kaydırılan pinlerin anten performansı üzerindeki etkisinin daha belirgin olduğu farklı tasarımlarla gözlenmiştir. Önerilen tasarımlarla, referans antene göre %32'ye kadar bant genişliği iyileştirmesi ve 2.9 dBi'ye kadar kazanç arttırımı sağlanmıştır. Referans antenin 16.9 dB olan ön/arka (F/B) oranı sunulan tasarımlarla 26 ile 29 dB arasındaki değerlere iyileştirilmiştir. Ayrıca, sunulan antenlerin tek katmanlı basit tasarımları üretimlerini kolaylaştırırken, 0.05 ile iyi bir ince profil değeri (h/λ_0, λ_0 merkez frekanstaki boş uzay dalga boyudur) de sağlar.

Anahtar kelimeler: Mikroşerit yama anten, Elektromanyetik bant araliği yapılar, Pin konumları, Bant genişliği, Kazanç.

1 Introduction

The rapid advancing of the wireless communication technologies brings together the need and usage of more compact and smaller antennas. Although microstrip patch antennas (MPA) have some certain drawbacks like surface wave excitation, low gain and narrow bandwidth, the lots of advantages that they have make them still one of the widely used type of printed antennas [1].

Improving the antenna characteristics as broader bandwidth, higher gain, better performance, lighter weight and low-profile design is still a hard-to-reach goal for scientists and researchers. During the last few decades to overcome these problems and improve antenna performance metamaterials are widely used with MPAs by utilizing their engineered material properties. The electromagnetic band gap (EBG) structures, a kind of metamaterial, act as a high impedance surfaces because of their capability to forbid the propagation of surface waves in the specified frequency band [2]-[5]. The EBG structure has to design as the center frequency of antenna being in the band gap of this structure. There are two types of EBG structure according to the existence of vias. The EBG structures which have a via between the metallic patch and ground plane known as mushroom like EBG structures because of the shape similarity and was introduced by Sievenpieper [6].

In this study, MPA and mushroom like EBG structure collocations in a favourable design with enhanced performance are presented. The performance improvement is achieved by proper via locations in the proposed designs. The IEEE gain and bandwidth values obtained by simulations are compared and the radiation patterns are analysed. The structure designs and the simulations were all carried out with CST-MW [7] in this study and the simulations have been performed with the Transient Solver in order to check antenna properties.

2 The reference antenna and EBG design

In this study, a traditional MPA is used as reference antenna to provide a basis for different designs. The geometric specifications of the antenna and used EBG structure are given in Table 1 and Table 2, respectively. Rogers Ultralam 2000 is

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used as dielectric substrate for all antennas in the study. The microstrip antenna is excited by a coaxial probe due to the ease to fabricate, provide high gain [8] and simple impedance matching properties of the feeding technique.

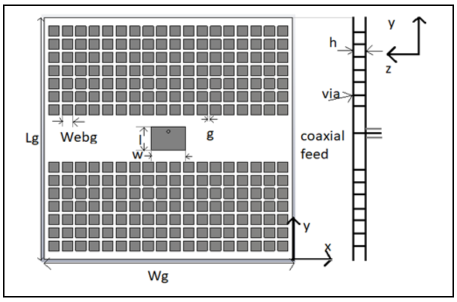
Table 1. Microstrip patch antenna specifications.

	Parameter	Value
Patch	Length (l)	8.16 mm
	Width (w)	11.33 mm
Ground	Length (Lg)	83 mm
	Width (Wg)	83 mm
Substrate	Dielectric Constant, ε_r	2.5
	Height (h)	1.524 mm

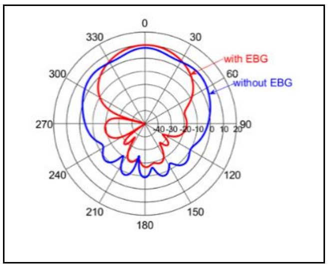
Table 2. EBG unit cell specifications.

Parameter	Value
Width (Webg)	3.5 mm
Gap Width (g)	1 mm
Radius of via (r)	0.12 mm
Periodicity (p)	4.5 mm

The first design proposed in this paper includes a MPA working at 10 GHz and a conventional mushroom like EBG structure laid in E plane with 7 rows and 18 columns. EBG structures improve the antenna performance by wasting less power in backward direction and reducing surface waves [9],[10]. However, generally the area for more EBG patches on the substrate are limited. The distance between the EBG structure and the antenna is determined as 4 mm in the presented study. This distance is nearly equal to the periodicity of the EBG structure and is one of the closest spacing presented in literature. Generally, the EBG structures are placed just about the half wavelength far from the radiating edges of the MPAs, here the mentioned wavelength is the free space wavelength at the operation frequency. It was reported that by laying the first row of the EBG to a place nearly equal to the period of the unit cell enhanced antenna properties can be achieved besides the size reduction [11],[12]. The initial design with 4 mm separation between antenna and EBG structure and the 2D polar radiation patterns for the antenna with and without EBG are shown in Figure 1(a) and (b), respectively.



(a)



(b)

Figure 1(a): Initial design (Front view and Side view). (b): Gain patterns in yz-plane of the reference antenna and ID.

When the gain patterns of the antenna without EBG and the EBG structure integrated antenna named as initial design (ID) are compared the positive effect of the EBG structure is obvious. The EBG structure prevents the propagation of unwanted surface waves consequently reduces side-lobe levels and increases antenna performance. The gain value for the reference antenna is 7.9 dB whereas 10.1dB for the proposed ID. Nevertheless, the bandwidth value is decreased to 0.37GHz from 0.72GHz by the ID. This can be attributed to the increase in the coupling between the antenna patch and the EBG structure. Even so, the increase in gain and reduction in side lobe levels are worth to evaluate.

3 Bandwidth and Gain Enhancement Studies Due to the Modifications on Via Configurations of the EBG Structure

The simulations are continued with the bandwidth and gain enhancement studies that are carried out in three steps. These steps include modifications of the mushroom like EBG structure not depend on the shape of the patches but the via configurations.

In the first step some of the vertical vias that are connecting the metallic patches to the ground of the EBG structure are removed. It is known that the vias are necessary to suppress surface waves within the substrate [13]. The EBG surfaces need vias for well-defined bandgaps [14]. When the vias are removed, the surface wave bandgap could narrow or disappear in the related frequency band. Therefore, the surface waves can exist over the interested frequency band. Although the removal of the vias has significant effect on the surface wave bandgap properties of the EBG, the in-phase reflection features of the EBG structure for normally incident plane wave can be similar in both situations [15]. Therefore, it was important to enhance the bandwidth by removing as few vias as possible. By this purpose the vias of the EBG patches at the middlemost of the first row away from the antenna's radiating edge removed starting from six patches and increased two by two. The results are shown in Figure 2.

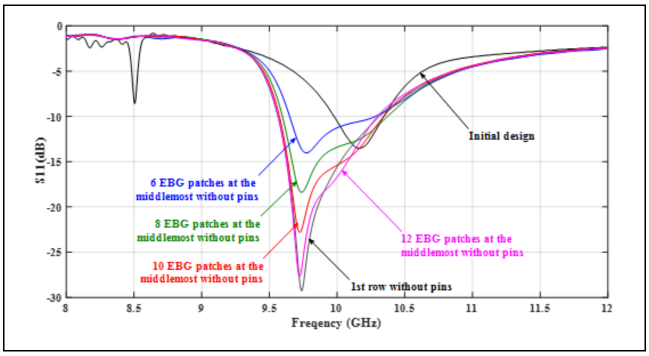


Figure 2. The simulated S11 results for different designs with different number of removed vias.

The simulated bandwidth and gain values obtained in this part of the study are given in Table 3. The results show that the bandwidth values are enhanced approximately 97% with reasonable gain values according to ID. However, when the number of removed vias are increased similar results are obtained with the EBG structure is placed to a location nearly twice of the EBG period. Because the patches without vias losses their ability to suppress surface wave propagation.

Table 3. The bandwidth and gain results for designs with different number of removed vias.

The number of EBG patches at the middlemost without vias	Bandwidth (GHz)	Gain (dBi)
0 (ID)	0.37	10.1
6	0.63	8.15
8	0.78	8.93
10	0.77	9.63
12	0.73	10.0
18 (first row without vias)	0.75	8.42

Consequently, the second step of the simulations are performed by the designs with offset vias. The conventional mushroom like EBG structures have centred vias. The vias are crucial components of the mushroom like EBG structures. There are some studies related with the effect of the via locations on EBG characteristics in the literature [16]-[18]. Changing the locations of the vias are both effects the reflection phase characteristics [19]-[21] and the operation frequency bandgap [22],[23] of the EBG structure. For examining the aforementioned effects and the contributions to the bandwidth improvement studies of the proposed designs the vias are offset stepwise by the value of 0.2 mm only in x, only in y and both in x and y directions, respectively. The effects of the via locations to the frequency bandgap characteristics of the EBG structures are investigated with the suspended microstrip line method by using 4×4 EBG arrays. Suspended microstrip line method is a common technique for bandgap prediction of an EBG structure. For the consideration an array of EBG unit cells is prepared and used as the ground of another substrate with a transmission line printed on it's top. Than two ports are connected to both ends of the line. As the EBG structure limits the transmission of the wave a significant reduction in S21 is occurred at a certain frequency band and the frequency region that provides S21<-10 dB designates the bandgap of the EBG structure. Some of the selected transmission characteristic results obtained by simulations that informs the effect of offset vias to the bandwidth enhancement studies of the proposed design are given in Figure 3. The S21 results presented in Figure 3 are due to offsetting the vias by the value of one fourth of the EBG patch width in x, in y and both in x and y directions, respectively. The S21 values obtained at the 10 GHz frequency region, which is the operation frequency of the used MPA, is important. When the vias are offset both in x and y directions a significant reduction in S21 value is observed. This situation can contribute to the better improvement of the antenna performance by limiting the surface waves.

In the view of the results obtained by transmission characteristic studies the ID is modified with different offset via models. After lots of trial modifications, 4 modified designs (MD) are selected with enhanced bandwidth and also improved gain values with reduced side lobe levels. The gain values are approximately 10.38 dBi at 10 GHz for all of the 4 MDs, whereas the best value is 10.8 dBi and obtained for MD-3. Furthermore, the bandwidth is enhanced up to 0.62 GHz with these designs. The schematic illustrations of these MDs and the S11 results belongs to them are given in Figure 4 and Figure 5, respectively. The marked vias of the MDs that are shown in Figure 4 are all offset by the value of one fourth of the EBG patch width in the given directions, though the unmarked ones are centered. Considering the S11 analysis, the modified designs with all vias are offset (MD-2 and MD-4) are gave better results than the ones with offset vias only in the first rows. Figure 6(a) and (b), illustrates the gain patterns of MD-1, MD-2 and MD-3, MD-4 in comparison with reference antenna, respectively. The gain pattern of the designs indicates the success of the designs with reduced side lobe levels and improved directivity.

When the results of the first two steps were reviewed it can be seen that the bandwidths are enhanced with better values by the designs constituted with removed vias whereas the designs with offset vias gave better improvements in gain values with approximately 50% bandwidth advancements with respect to ID. Accordingly, all the studies are combined, and hybrid designs are developed with EBG patches both containing removed and offset vias. In respect to the results given in Table 3 the model that is formed with 10 removed vias at the middlemost and gave optimum results is chosen. Starting with this model the hybrid designs are formed. Two hybrid designs (HD) that are depicted in Figure 7 are selected after many trial simulations. The first-row patches of both HDs are arranged in the same manner, the vias of the 10 patches at the middlemost are removed, the rest 4 vias at the left side and 4 vias at the right side are offset to right by the value of one fourth of the EBG patch width. All the vias of the other rows in HD-1 are offset to left by the value of one fourth of the EBG patch width. But in HD-2 the side of the offsetting vias in the rows are changed alternatively left to right.

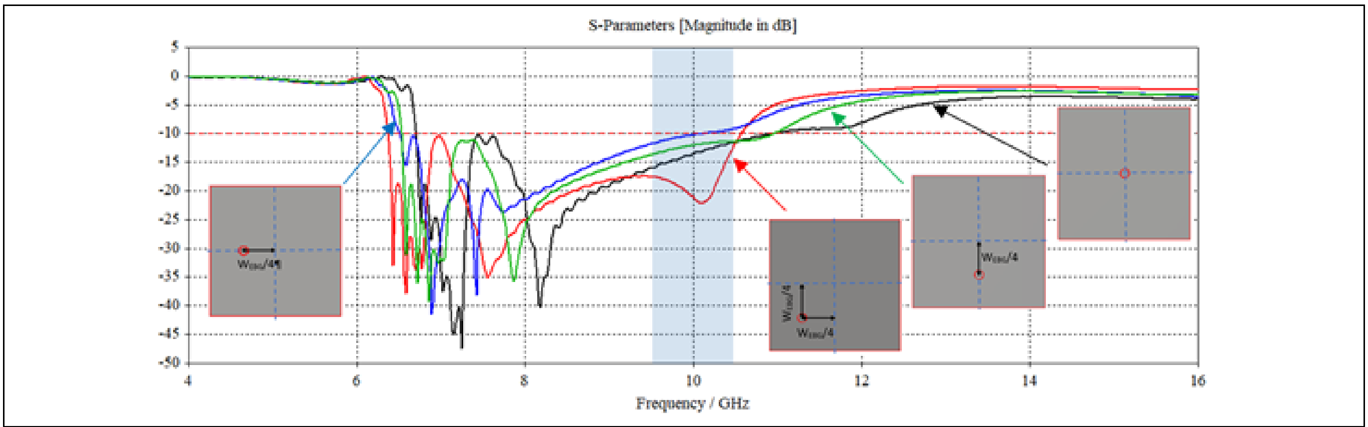


Figure 3. The simulated S21 (transmission coefficient) results for offset vias in only x, only y and both x and y directions for 4x4 arrays.

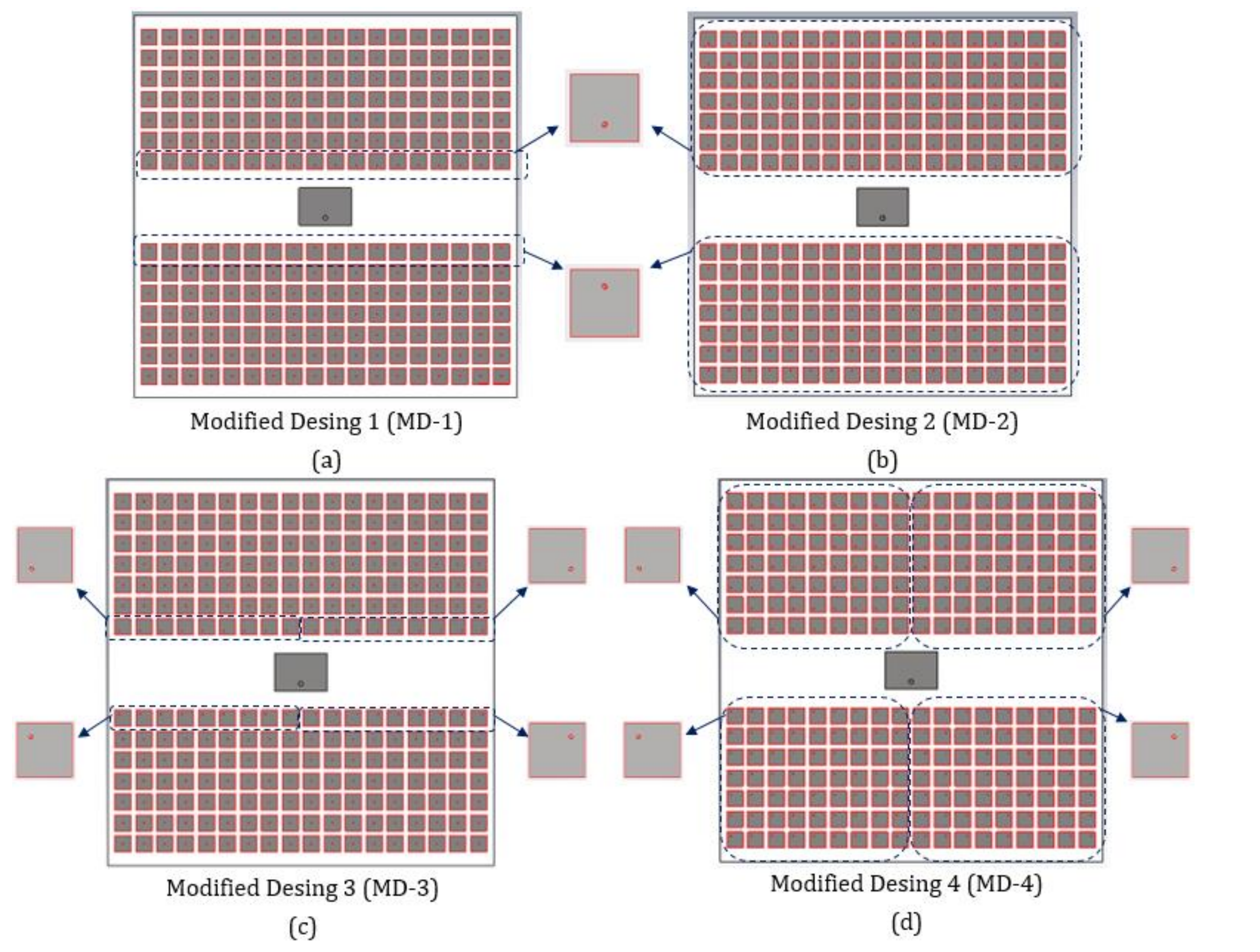


Figure 4. The illustrations of the modified designs.

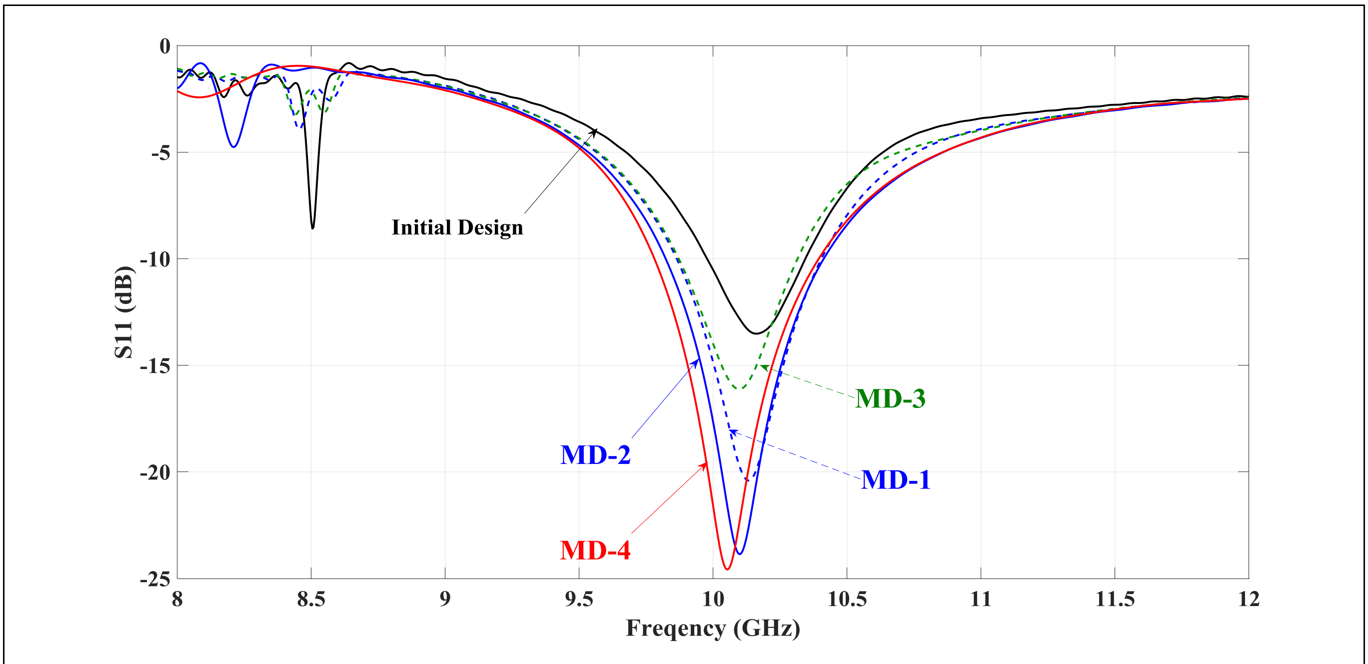
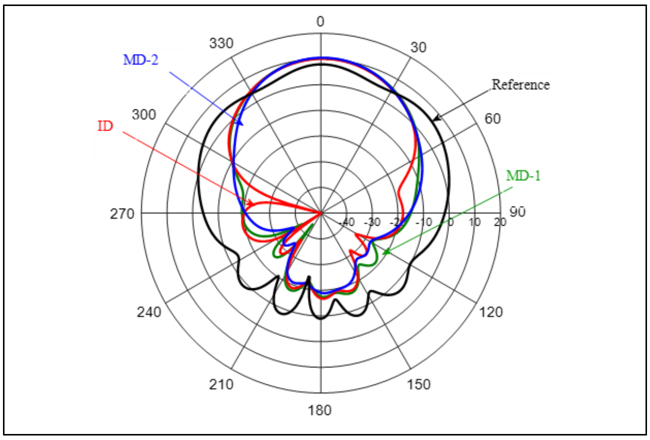
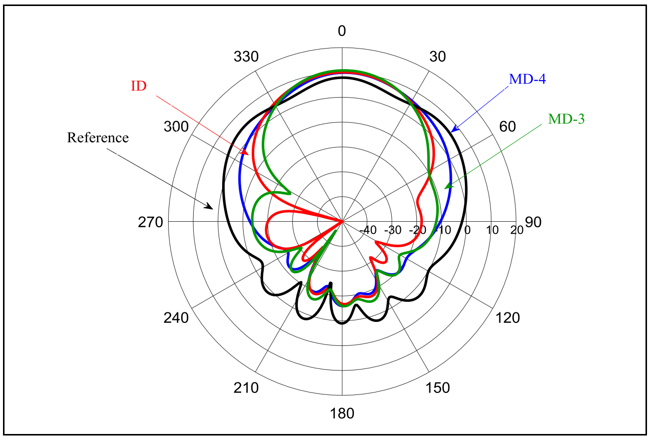


Figure 5. The simulated S11 (reflection coefficient) results for different designs with offset vias.



(a): MD-1, MD-2.



(b): MD-3, MD-4.

Figure 6. Gain patterns of MD-1, MD-2 and MD-3, MD-4 in yz-plane, in comparison with ID and reference antenna.

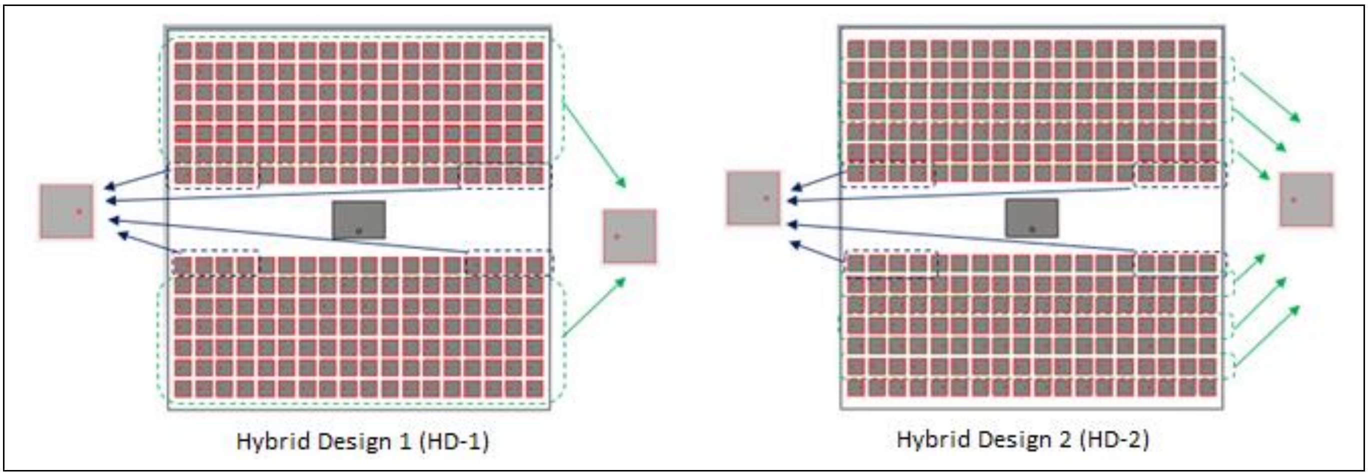


Figure7. The illustrations of the hybrid designs.

The bandwidth values obtained by the HDs are 0.94 and 0.95 GHz, respectively. These results clearly show that the bandwidth of the ID is enhanced 575 MHz in average (increased about 2.5 times) with hybrid designs as seen in Figure 8. The simulated gain values are 9.09 dBi for HD-1 and 9.56 dBi for HD-2 at 10 GHz.

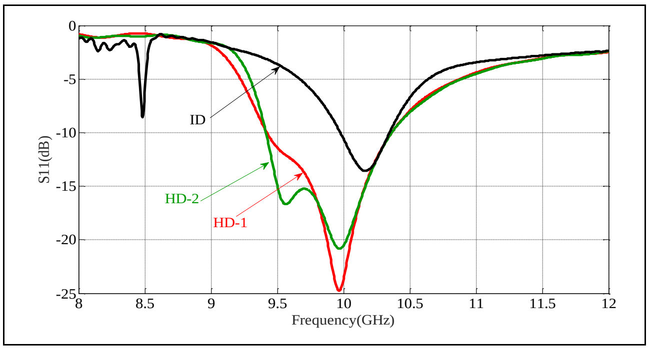


Figure 8. The simulated S11 (reflection coefficient) results for HD-1 and HD-2.

Figure 9 illustrates the gain patterns of HD-1 and HD-2 in comparison with the reference antenna and ID. Due to these results, it can be concluded that significant improvements are achieved with HDs.

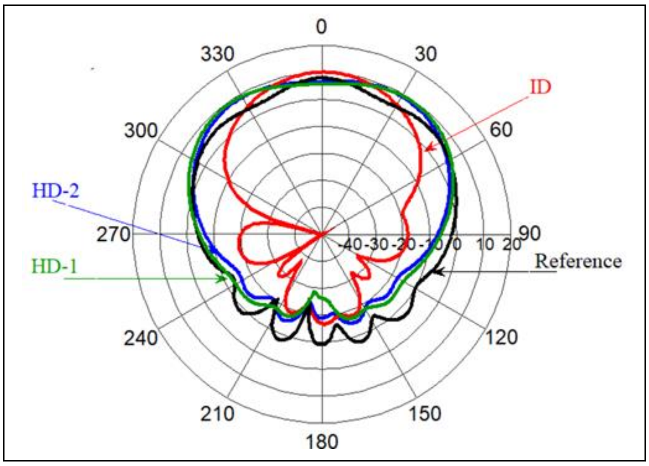


Figure 9. Gain patterns of the HD-1 and HD-2 in comparison with the reference antenna and ID.

The gain vs. frequency results of the proposed designs (MD-2 and HD-2) selected from the presented ones are shown in Figure 10. As seen, the gain is successfully advanced around the operation frequency region with the MD-2 and HD-2. The obtained peak gain values are 7.92dBi, 10.45 dBi and 10.34 dBi for the reference antenna, MD-2 and HD-2, respectively.

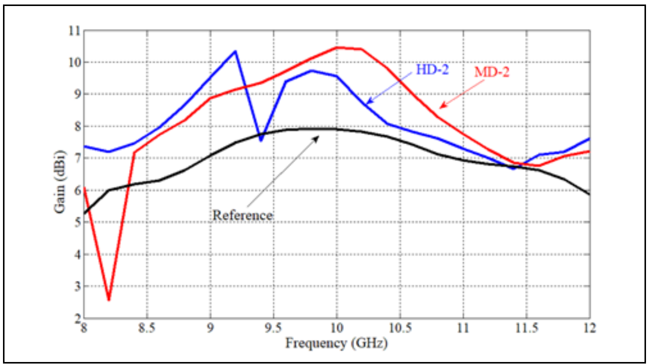


Figure 10. Comparison of the gain frequency graphs of the proposed antennas MD-2 and HD-2 with the reference antenna.

Finally, the proposed designs are compared with recently reported similar structures in Table 4. As seen from the comparison the designs proposed in this study achieves good gain enhancement results, besides providing comparable bandwidth enhancements. Moreover, the presented antennas are away from having a complex geometry with their single layered design. On the other hand, the antenna performance improvement studies with vialess periodic structures can give more satisfactory results, when compared to the ones designed with mushroom like EBG structures. But unfortunately, there are fewer studies designed with mushroom like EBG structures relative to vialess EBG structures in the literature. Therefore, further researches are still needed on designs containing mushroom like EBG structures.

4 Conclusions

High gain, wideband and low profile MPAs are the need of many communication applications. However, surface wave propagation that ends up with reduction in antenna gain and maximized side lobe levels is a serious problem in MPA design procedures. Additionally, it limits bandwidth. EBG structures can successfully use in bandwidth improvement by effectively reducing surface waves excitation in MPAs. Some designs by the combinations of a MPA and several mushroom like EBG structures with different via options are proposed in this study. All the antenna structure designs and the analyses were carried out with CST MW simulations. The EBG structure is modified with different via configurations by removing or offsetting the vias of the EBG patches. The presented designs with removed and offset via positions succeed in improving the overall antenna performance. The bandwidth value can broaden up to 0.95 GHz. The proposed MDs and HDs are increased the gain values up to 10.45 dBi which is 7.9 dBi for the reference antenna at 10 GHz. Furthermore, the F/B of the reference antenna is enhanced approximately 12.1 dB by the proposed designs.

5 Author contribution statements

Cemile TANGEL designed the models, carried out the simulations and analysed the data. Nigar Berna TEŞNELİ designed and supervised the study. Nigar Berna TEŞNELİ and Ahmet Yahya TEŞNELİ contributed to the evaluation and interpretation of the results. All authors contributed to paper organization and writing the final manuscript.

6 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person / institution in the article prepared”.

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Table 4. Comparison with previously reported similar structures.

Reference	Size Lenght×width×height	BW	Peak Gain Enhancement (first →proposed)	Layer
[20]	$1.5\lambda_0\times1.5\lambda_0\times0.06\lambda_0$	1.3 GHz (7.6-8.9 GHz)	13.1 dBi →14.1 dBi	2
[22]	$1.23\lambda_0\times1.23\lambda_0\times0.053\lambda_0$	1 GHz (7.2 - 8.2 GHz)	10.14 dBi → 12.9 dBi	2
MD-2 (This study)	$2.76\lambda_0\times2.76\lambda_0\times0.05\lambda_0$	0.6 GHz (9.8 - 10.4 GHz)	7.92 dBi→ 10.45 dBi	1
HD-2 (This study)	$2.76\lambda_0\times2.76\lambda_0\times0.05\lambda_0$	0.95 GHz (9.41-10.36 GHz)	7.92 dBi → 10.34 dBi	1

λ_0 is the free space wavelength at the operation frequency.

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