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A wideband, thin profile and enhanced gain microstrip patch antenna modified by novel mushroom-like EBG and periodic defected ground structures

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ABSTRACT
This paper presents a wideband, thin-profile and enhanced-gain microstrip patch antenna improved by using a novel mushroom-like Electromagnetic Band Gap (EBG) structure and forming periodic Defected Ground Structures (DGS) on the ground plane. The proposed antenna operates between 9.56 and 14 GHz and has 4.44 GHz–10 dB impedance bandwidth. With A4, the gain of the reference antenna is increased by 64.4%, while a 38% bandwidth is also achieved. The parametric analyses carried out on the metallic part area of the novel EBG patch indicated that when the area of the used EBG patches are approximately three quarters or less of the conventional ones, greater gain values for the designed antenna are obtained. This relation between the EBG patches and the antenna gain can be pointed out as the novelty of the study. The results were analysed by the simulations carried out with CST Microwave Studio and were verified by measurements from manufactured prototypes.

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KEYWORDS
Wideband; thin-profile; gain enhancement; microstrip antenna; EBG; DGS

1. Introduction

In recent years as a result of developing technology, the microwave and RF circuits have inevitably reduced in size and also the dimensions of the antennas which are the basic elements of these circuits have became smaller. Besides the reduction in size, the multi-functionality is another challenging issue. The antenna performance has to be adaptable to the new applications. The antennas providing wide impedance bandwidth (IBW) are also significant. Although the microstrip patch antennas are preferred because of their easy fabricatable, conformable, and inexpensive features they have some usage limitations such as low gain ($\sim$6 dBi), low efficiency and narrow bandwidth ($<$ 5%). In the literature, there are many studies to overcome these undesired properties. Despite using a substrate with a low dielectric coefficient in the microstrip antenna design, the surface wave excitation that naturally exists and decrease the antenna gain and efficiency are the outcomes of these kind of antennas. Conversely, a substrate with a high dielectric coefficient could be chosen

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in the design, but this advances the unwanted surface wave excitation and narrow bandwidth [1,2]. To enhance the antenna performance by limiting the surface waves the usage of the microstrip antennas in conjunction with EBG structures is one of the methods that frequently came across [3–6]. EBG structures are designed by the alignment of conductors and/or insulators in a periodic arrangement and joining the repeating unit cells in the period with the ground by a conductor via. This type of EBG structure is known as mushroom-like EBG structure. These structures prevent or support the propagation of electromagnetic waves in a particular frequency band gap for the structure. For eliminating the surface waves the antenna's operation frequency should be in the band gap of the EBG structure. Therefore, the design parameters of the EBG structure need to be in certain ranges. So, the antenna and the EBG structure have to be designed so they can work in accordance with each other.

There are some different integrations of antennas with EBG structures in the literature. In some studies, an EBG structure can be replaced by the ground of the antenna [3,7–10] and both the gain and impedance bandwidth of the antenna can be enhanced with EBG-backed designs. An alternative usage of the EBG structure is an EBG superstrate. In this type of configuration, the EBG structure is placed at a certain distance above the radiation source of the antenna and usually, the uniplanar EBG is used [11,12]. Unfortunately, the thickness of the antenna is increased with both of these implementations. Another usage of the EBG structures in antenna designs is that the patches of the mushroom-like EBG structures and the radiating patch of the antenna share the same substrate and ground [13–15]. In these designs generally, the gain can be improved more than the designs with EBG-backed ones besides the thickness is kept the same [16].

The mushroom-like EBG patches designed differently from the conventional square-shaped patches can improve the antenna gain more than the conventional ones and lighter antennas can be designed [17–19]. In this paper, a novel mushroom-like EBG structure is used for improving the performance of a microstrip antenna. Afterwards for improving impedance match and broadening the impedance bandwidth the design is supported with periodic slots etched on the ground [20–22]. The slots formed on the ground plane are introduced as defects and these kinds of ground planes are identified as defected ground structures (DGS). This method can be applied easily to the designs and the antenna gain can be increased by improving impedance match and bandwidth besides reducing the antenna weight. Moreover, the defected ground structures can be used to reduce the antenna size [23].

The paper has the following sections: In Section 2 the design processes of the proposed antennas are explained in detail and the simulation results are presented. An investigation of the effect of the metallic part area of the EBG patch on the antenna gain takes place in Section 3. Section 4 compares the proposed antennas with recently published similar designs. Section 5 presents the validation of simulations with measurement results of the proposed A3 and A4. Finally, Section 6 presents the summary of the results and conclusion of this study.

2. The design procedure and simulation result

The study is initiated with a coaxial-fed rectangular microstrip patch antenna design. An FR4 substrate with a 4.3 dielectric coefficient, a tangent loss of 0.025 and a thickness of

1.6 mm thickness is used. A $9.2 \times 6.1\,\text{mm}^2$ antenna patch is placed on it and fed at a point with $x_f = 0$ mm and $y_f = 5$ mm coordinates with respect to the middle of the bottom edge of the patch. The ground plane and substrate sizes are adjusted as $65 \times 65\,\text{mm}^2$. This antenna operates at 9.95 GHz with 0.94 GHz bandwidth and is named as a reference antenna. In line with the aim of the study, a conventional EBG structure is designed and implemented to the reference antenna in the first step of the evolution process. For this purpose, the characteristic EBG parameters as dimensions of the EBG patches, the distances between the patches and the number of EBG rows on the substrate are obtained by calculations and simulations. The surface wave bandgap of the EBG structure is arranged as the operation frequency of the antenna will be in the bandgap. This is controlled due to transmission characteristics acquired by the suspended transmission line method. The conventional-type EBG patches have a $3.1 \times 3.1\,\text{mm}^2$ patch area, 0.5 mm via diameter and 0.9 mm distance between each patch. The second antenna referred to as A1 is designed as the conventional EBG patches and the reference antenna patch shares the same substrate and ground, as shown in Figure 1. The distance between the EBG patches and the antenna patch on the EBG substrate is adjusted to a value equal to the sum of the one EBG patch and the distance between patches, which is equal to the periodicity of the EBG structure [14].

The gain of A1 is obtained as 7.93 dBi whereas the reference antenna has 4.86 dBi gain value. Furthermore, the main lobe in the radiation pattern is narrowed, but the bandwidth is also reduced with A1. The DGSs designed by repeating a slot shape periodically, like an EBG structure applied on the ground, improve the bandwidth of the patch antennas [24,25]. To tolerate the narrow bandwidth drawback of the A1 design, periodic square slots

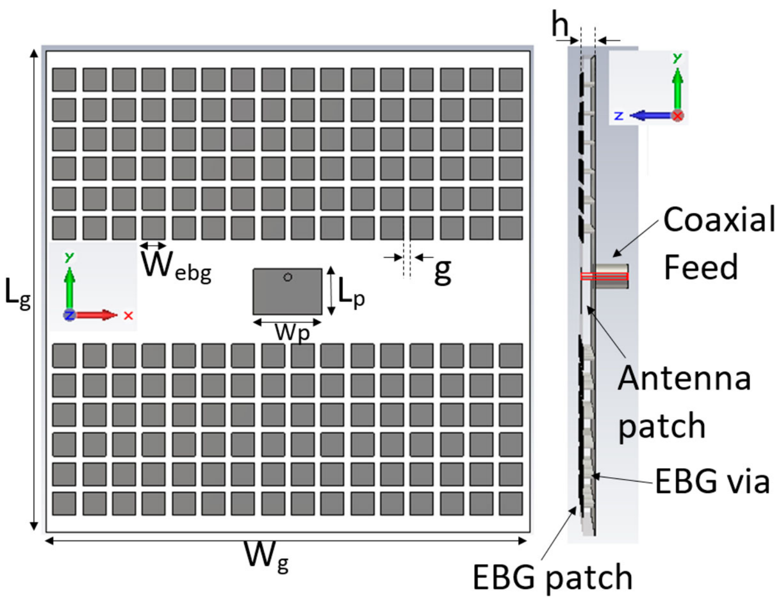


Figure 1. Front and side view of the A1 ($W_{ebg} = 3.1$ mm, $g = 0.9$ mm, $L_g = W_g = 65$ mm, $h = 1.6$ mm, $W_p = 9.2$ mm, $L_p = 6.1$ mm).

Table 1. Effects of different-sized square holes on antenna performance.

$W_{dgs} \times L_{dgs}$ (mm)^2	S11 (dB)	f (GHz)	G (dBi)	IBW (GHz)
Without-slots	−16.5	10.2	7.93	0.6
1.0 × 1.0	−16.9	10.25	7.76	0.61
1.5 × 1.5	−17	10.24	7.86	0.64
2.0 × 2.0	−17.3	10.20	7.95	0.69
2.5 × 2.5	−20	10.16	7.96	0.82
3.0 × 3.0	−27	10.13	7.57	0.98
3.5 × 3.5	−26	9.9	6.41	1.34

Table 2. The effect of the slot length on antenna performance parameters.

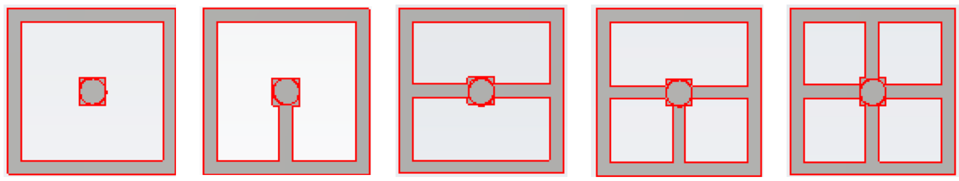
$W_{dgs} \times L_{dgs}$ (mm)^2	S11 (dB)	f (GHz)	G (dBi)	BW (GHz)
3.0×3.1	−24.7	10.1	7.56	1.03
3.0×3.2	−25.5	10.12	7.51	1.08
3.0×3.3	−26	10.14	7.41	1.13
3.0×3.4	−26	10.14	7.27	1.2
3.0×3.5	−27	10.18	7.27	3.8
3.0×3.6	−28.8	10.2	7.14	3.5
3.0×3.7	−38	10.3	6.98	3.06

are etched on the ground plane of A1. The effects of different-sized square holes on antenna performance are investigated and the results are listed in Table 1.

As per Table 1 the antenna IBW increases as the dimensions of the DGS square hole increase. However, the DGS hole width has to be limited to 3 mm as the EBG patch pins should not overlap the etched slots. On the other hand, the ground size is also another limitation. Therefore, the width of the slots is fixed to 3 mm and only DGS hole lengths (y-axis) are gradually increased. The increase in the length of the slots continued until they became strips and its effects on antenna parameters are investigated. The simulation results are depicted in Table 2.

The evolution process is continued by changing the conventional EBG patches with a novel one for more performance enhancement on the reference antenna and the effect of this change on the antenna performance is investigated. The electromagnetic properties of the EBG structures are determined by the physical properties and dimensions of the EBG structure, so the new models are designed with considering this fact and the EBG patch width, the distances between patches, dielectric coefficient of the substrate and substrate thickness values are kept the same. EBG patch models were studied by only conductor area reduction from the 3.1 × 3.1 mm^2 EBG patches of the A2. Nevertheless, the new EBG patches have to produce an EBG structure with a band gap involving the operation frequency of the reference antenna. The EBG model was created with an outer square ring and an inner square patch, connected by strips. The new EBG unit cell was specified after the transmission characteristics analysis, and then the parametric studies were carried out on this EBG patch model for acquiring the optimum results. The studied EBG unit cell structure with different strip numbers is shown in Figure 2.

The surface wave bandgaps of the studied EBG structures without strips and with one, two, three and four strips are acquired by the suspended transmission line method for 4 × 4 arrays of the novel EBG patch and the results are given in Figure 3. When the strips connecting the outer square ring and the inner square patch are removed the first band gap region is disappeared and only one band gap region in the higher frequencies due to



(a) EBG without stripes (b) EBG with 1 stripe (c) EBG with 2 stripes (d) EBG with 3 stripes (e) EBG with 4 stripes

Figure 2. Top view of new mushroom-like EBG unit cells without stripes (a) and with one, two, three and four stripes, respectively (b, c, d, e).

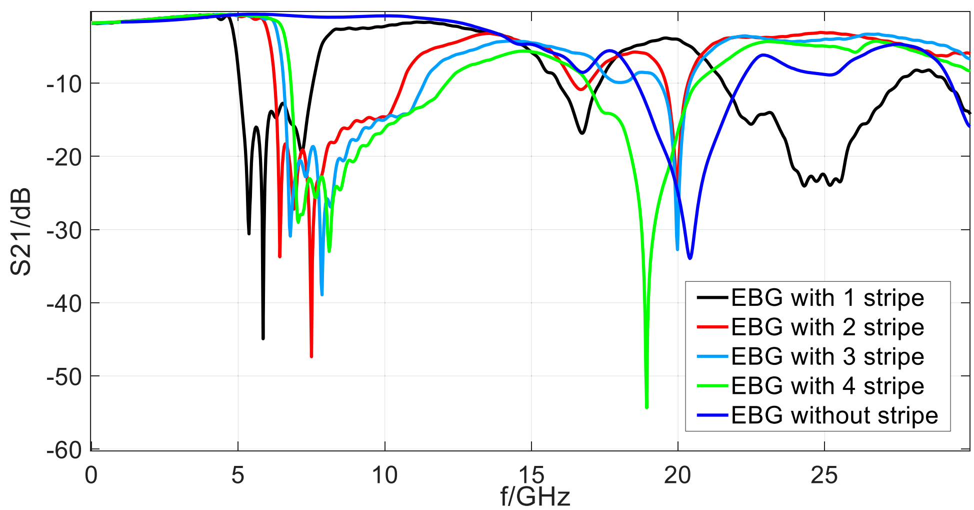


Figure 3. The simulated S21 results for 4 × 4 arrays of the novel EBG patch (with one, two, three, four and without strips).

the inner patch is observed. The strips on the model provide the current flow between the unit cells by combining the square part in the middle, the other square metal ring, via, and the conductor ground plane. As known, the current flowing through the paths behaves like an inductor and the gap effect between the adjacent patch parts acts as a capacitor so the designed EBG structure can be modelled as an LC filter and the surface currents of the antenna being limited due to the high impedance surfaces caused by the EBG structure [26]. In conclusion, the strips have an important role in the construction of the aforementioned high impedance surface so elimination of the surface waves.

It can easily be seen from Figure 3 that the first surface wave bandgaps of the EBG structures broaden and shift to the higher frequencies due to the increasing number of stripes. The surface wave band gaps occurred in the range 5–7.5 GHz, 6.25–10.6 GHz, 6.55–11.34 GHz and 6.8–12 GHz for single, two, three and four strips, respectively. Since the operating frequency of the reference antenna is in the band gap of the all-new EBG structures with different stripe numbers, the choice of the most advantageous EBG unit cell structure was made by examining the gain results of the antennas in the related frequency region.

As mentioned before the reference antenna operates around 10 GHz. When the gain vs. frequency values of the antennas designed with one, two, three and four striped EBG structures are examined in Figure 4, the highest gain values in the related frequency region are obtained using a three-striped EBG unit cell. Moreover, the gain enhancement is almost symmetrical at the 8.5–11 GHz region. Therefore, studies were continued with the three-striped EBG unit cell. The used novel EBG unit cell and equivalent circuit model are shown in Figure 5.

In the equivalent circuit model of the unit cell, the via was modelled as the inductor L and the dielectric between the centre patch and the ground is named capacitor C. While the L1 and L2 inductors represent the microstrip lines aligned through the centre patch, the capacitances C1 and C2 are due to the dielectric between the microstrip lines and ground.

As a result, Antenna 3 (A3) is designed by only changing the conventional EBG patches with the proposed novel three striped EBG unit cells and all the dimensions of A2 are kept the same. A3 is illustrated with its front and back sides in Figure 6.

A3 provides a wide IBW like A2 design. −10 dB impedance bandwidth of A3 is 3.76 GHz (9.54–13.3 GHz) and the reflection zeros are located at 10.13, 11.5 and 12.8 GHz, respectively. With A3, the gain value is increased by 54.7% compared to the reference antenna, while it is also improved compared to A2. Since the EBG unit cell of A3 was obtained by removing a part of the metal parts of the EBG unit cell patch of A2, approximately 60% weight alleviation was obtained in A3 compared to A2. The metal part area of each EBG unit cell patch used in A3 design is 3.89 mm^2.

Finally, A3 is modified by partial cutting to give rise the size reduction of the design. The E-field plots of the reference antenna show that the surface waves propagating along the E-plane is significant according to the H-plane propagation. Moreover, in some studies it has been stated that to locate the EBG unit cells in the E-plane is sufficient for surface waves reduction [1,27]. Thus, the antennas proposed in this study were designed with EBG

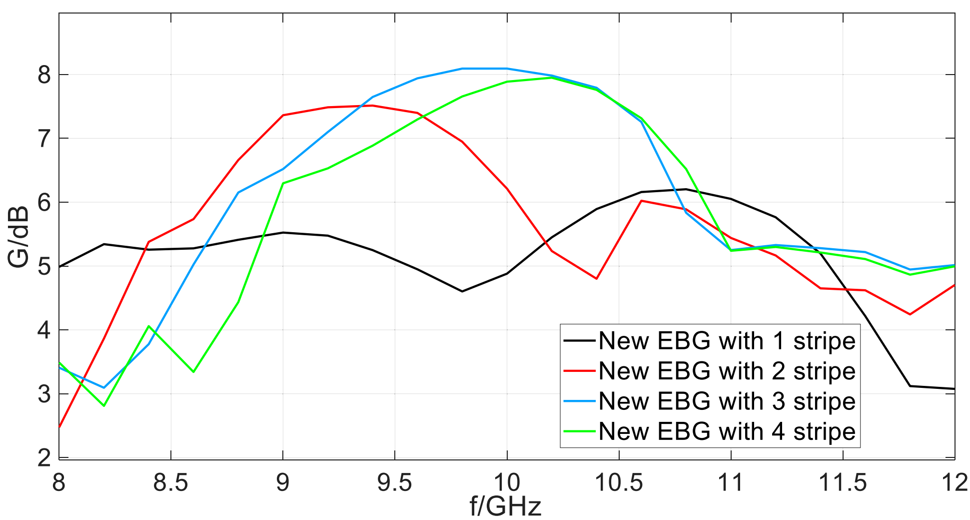


Figure 4. Gain of the antennas designed with one, two, three and four-striped EBG structures.

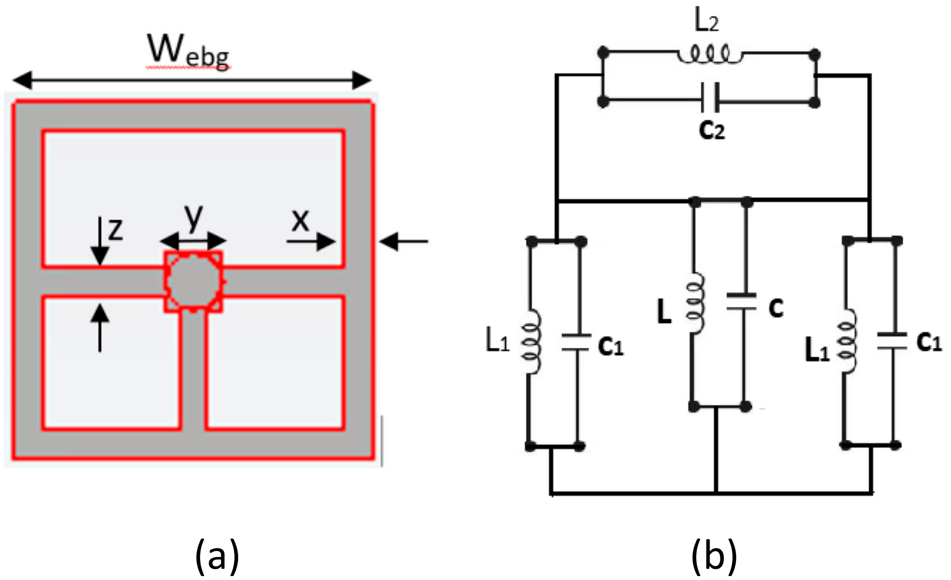


Figure 5. Top view of mushroom-like novel EBG unit cell. Parameters: Webg = 3.1 mm, $x = 0.25$ mm, $y = 0.5$ mm, $z = 0.25$ mm (a) and the equivalent circuit model of EBG unit cell (b).

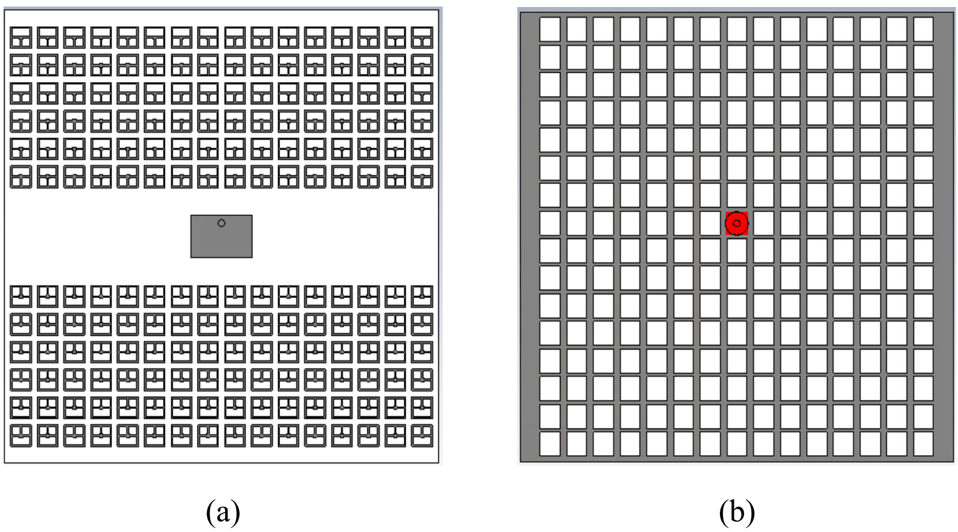


Figure 6. Front view (a) and back view (b) of the A3.

unit cells placed only in the E-plane. These types of designs are especially useful for suppressing the surface waves between two adjacent antenna patches. Reducing the mutual coupling between adjacent antenna patches in systems with more than one patch such as multiple-input and multiple-output (MIMO) antennas or antenna arrays is a challenging task. On the other hand, the compact size is an inevitable feature of modern communication systems. Decreasing the distance between the adjacent patches increases the near-field electromagnetic coupling. At this point, the designs using EBG structures between the

Table 3. Gain and bandwidth values and comparisons for all the presented antennas.

Antennas	Gain (dBi) (at 10 GHz)	Enhancement according to reference antenna	IBW(GHz)	Enhancement according to reference antenna
Reference Antenna	4.86	–	0.94	
A1	7.93	3.07 dBi (63.17%)	0.60	−0.34 GHz (−36%)
A2	7.27	2.41 dBi (49.6%)	3.80	2.86 GHz (304%)
A3	7.52	2.66 dBi (54.7%)	3.76	2.82 GHz (300%)
A4	7.99	3.13 dBi (64.4%)	4.44	3.5 GHz (372%)

neighbouring patches to improve the performance of the antenna structure are widely come across. The antenna patch and EBG structure layout presented here can be a suitable choice for such an application. During the design procedure, the number of rows of the EBG cells was determined with step-by-step studies. So, the partial cutting process was done only from the left and right sides of the antenna. Four EBG unit cell columns from both the left and right sides of the antenna were removed. The final size of the antenna became $38 \times 65\,\text{mm}^2$ as a result of the 27 mm reduction from the width of the antenna. This antenna is introduced as A4, and it has the same design properties with A3 but is 41.5% reduced in size. For A4, the gain value around 10 GHz is 7.99 dBi whereas the peak gain is 8.3dBi. The simulated IBW of A4 for < -10 dB limit is 4.44 GHz and it has three reflection zeros at 10.1, 11.7 and 13.46 GHz. These features make the A4 a suitable antenna for the 9.56–14 GHz frequency region, coinciding with the X and Ku bands, commonly used for radar and satellite applications.

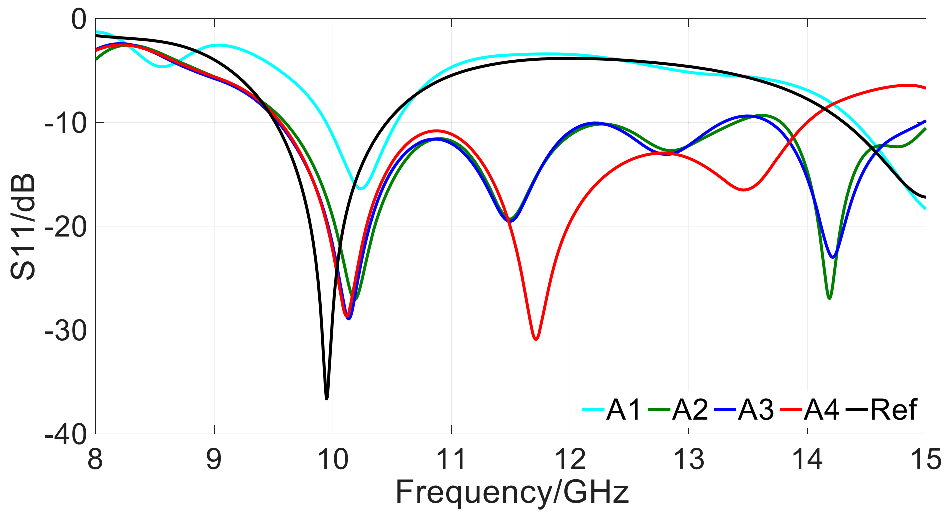
The gain and the bandwidth results of the antennas (A1, A2, A3 and A4) introduced so far are given in Table 3 in comparison with the reference antenna. The simulated $|S_{11}|$ and gain-frequency characteristics are also illustrated in Figure 7(a,b), respectively.

According to these results, it can be seen that 4.7 times wider bandwidth and 1.64 times better gain values are obtained with the A4 design compared to the reference antenna. These improvements in antenna performance have been achieved by the appropriate use of a novel EBG structure in the antenna design and periodic DGS in the ground plane. Furthermore, A4 is 41.5% smaller with respect to the reference antenna.

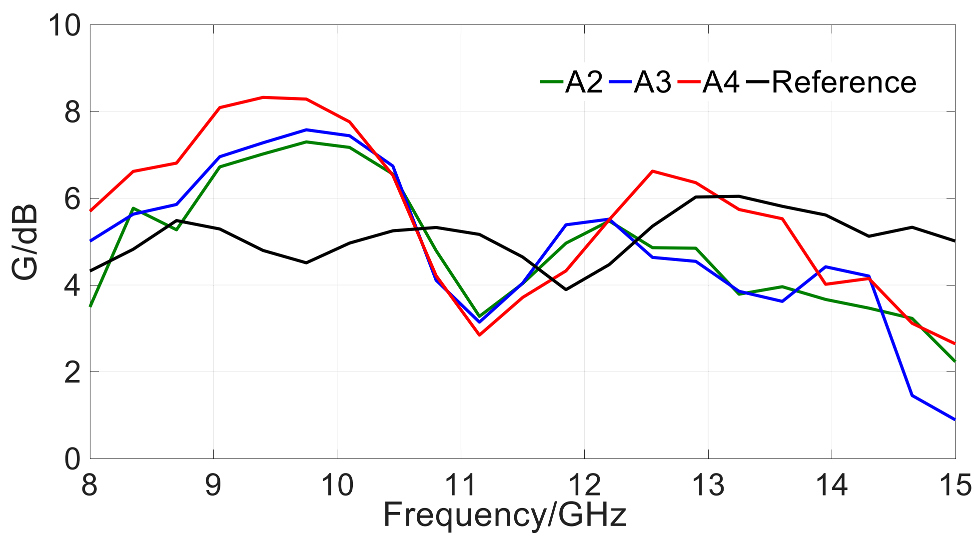
The 2D radiation patterns of the antennas are given in Figure 8. The reference antenna has a dispersed radiation pattern. However, the explicit reduction of the main lobe beam width with the presented designs is clearly distinguished from Figure 8. A3 and A4 have similar and well-directed radiation patterns. Thus, much better-directed antennas are proposed with 76% radiation efficiency. So, the proposed antenna offers a useful design with its wideband, enhanced gain, thin profile and lightweight features for relating the frequency region.

3. Investigations on the effect of the metallic part area of the EBG patch on the antenna gain

The proposed antennas in this study are advanced by a novel mushroom-like EBG structure supported with DGS. When the presented results are examined, it is understood that the gain increments are achieved by the EBG structure, while the IBW improvements are enabled by DGS. So, additional studies are carried out on the patch of the novel EBG unit cell. This investigation examines the effect of the reduction in the metallic part area of the



(a)



(b)

Figure 7. Simulated $|S_{11}|$ (a) and gain (b) vs. frequency of the presented antennas.

EBG patch on the antenna gain, provided that the EBG patch boundaries remain the same. The parametric studies on the novel EBG patches are performed due to the design parameter named as x as shown in Figure 5(a). In the analysis y and z are kept at 0.5 and 0.25 mm, respectively and x is changed with 0.05 mm increments in the 0.05–1.3 mm range. It can be easily seen from Figure 5(a) that the increase in the x value, which denotes the outer square frame thickness of the novel EBG patch, increases the metallic part area of the novel EBG patch. So, the antenna gains and bandwidth results were followed when the novel EBG unit

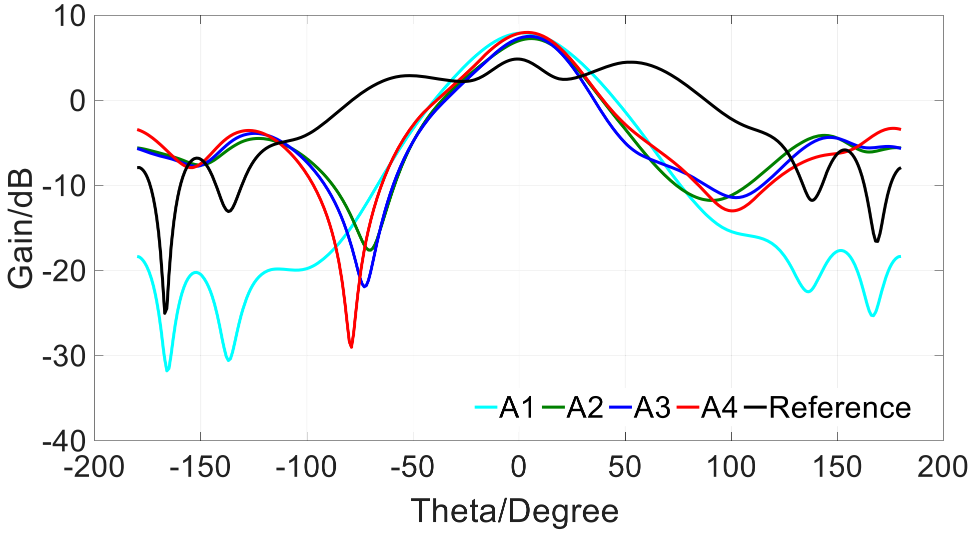


Figure 8. The 2D radiation patterns of the presented antennas.

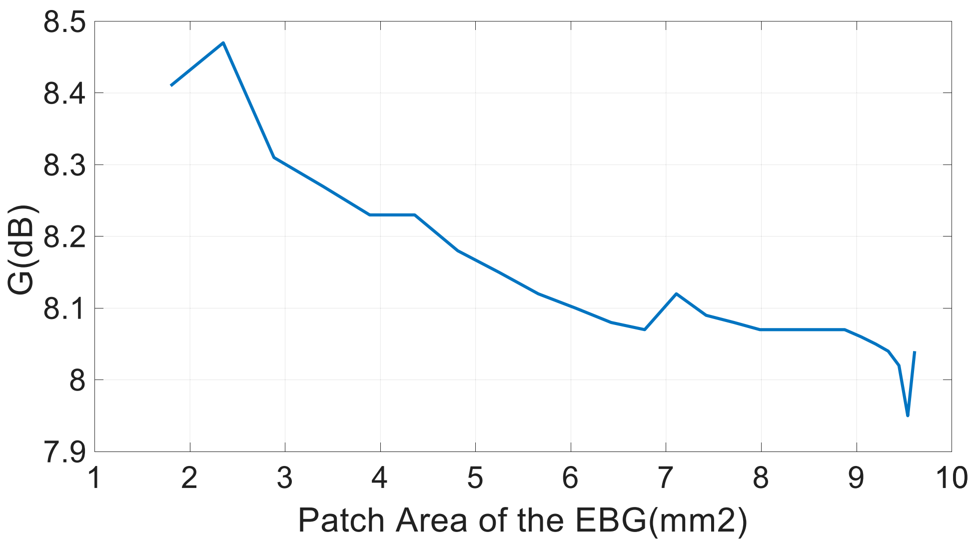


Figure 9. The variations of the gain values depending on the increment of the novel EBG patch metallic part area due to the increments on the *x* parameters for A4-a.

cell is evaluated to the conventional one step-by-step. The simulations are repeated for all EBG structures with the *x* value under investigation and the gain and bandwidth results are obtained verses to the metallic part area of the EBG patch. This investigation is done for the A4-a (A4-a has the same geometric features as A4 except for the DGS application in the ground). The results show that the gain is enhanced although there are no prominent changes in the bandwidth values. The obtained gain results versus the metallic area of the EBG patch are given in Figure 9. The gain values generally decrease due to the increase in the metallic area of the EBG patch.

Table 4. Comparison of previously reported metamaterial-based designs with the proposed antenna.

Ref	Size Length × width	IBW (%)	Peak Gain (dBi)	h/λ_0	Layers
[8]	$1.5\ \lambda_0 \times 1.5\ \lambda_0$	15.8	13.1 14.1	0.057	2
[9]	$1.63\ \lambda_0 \times 1.63\ \lambda_0$	38.42	$8.88 \rightarrow 10.05$	0.15	2
[10]	$1.24\ \lambda_0 \times 1.24\ \lambda_0$	18.2	$10.66 \rightarrow 12.48$	0.051	2
[11]	$1.55\ \lambda_0 \times 1.55\ \lambda_0 \rightarrow$	24.3	$12.1 \rightarrow 12.5$	0.11	4
[15]	$1.07\ \lambda_0 \times 1.15\ \lambda_0$	26.56	$8.17 \rightarrow 8.97$	0.058	1
[22]	$1.66\ \lambda_0 \times 1.66\ \lambda_0$	58.6	$-- \rightarrow 12.52$	0.054	3
[28]	$0.86\ \lambda_0 \times 0.86\ \lambda_0$	5.33	$-- \rightarrow 2.64$	0.058	2
This study	$1.36\ \lambda_0 \times 2.16\ \lambda_0$	38	$6 \rightarrow 8.3$	0.053	1

Note: λ_0 is the free-space wavelength at the centre frequency.

From Figure 9 it is obvious that the gain is increasing with decreasing the metallic part area of the patch. Better gain values begin to be obtained when the metallic part area of the new EBG patch is reduced by approximately 3% compared to the traditional EBG patch area. The gain increases almost steadily when the new EBG patch metallic part area is in the range of 24% to 75% of the traditional EBG patch area. To examine the effect of the reduction in the metallic part area of the EBG patch, the metallic area changes were done by varying the width of the inner square of the novel EBG (y parameter) and similar results were acquired with the previous ones. Furthermore, parallel results were also obtained by performing similar studies with a different dielectric material. In both situations, almost linear gain increment was observed as the metal portion of the EBG patch decreased.

4. Comparison with the proposed similar designs

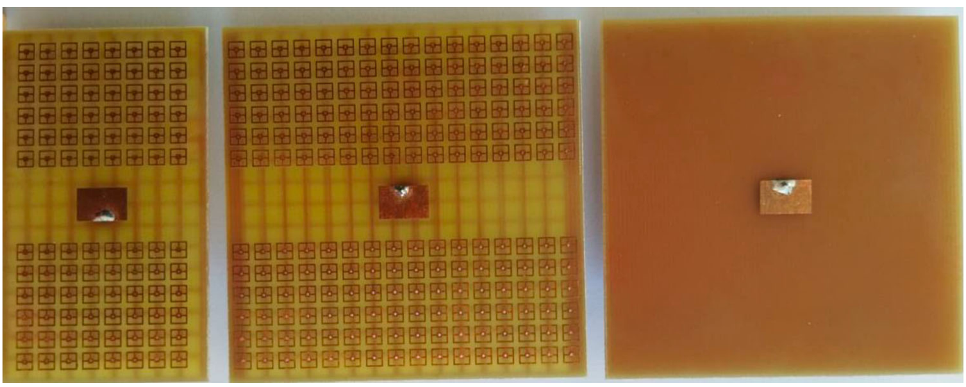
Although narrow bandwidth and low gain are disadvantages for microstrip patch antennas, they are widely used in many applications due to their advantages. For this reason, studies on improving the gain and bandwidth of microstrip antennas are still of great interest. The success of metamaterials in controlling the propagation of electromagnetic waves makes them attractive to overcome the disadvantages of microstrip antennas and causes periodic structures such as artificial magnetic conductors (AMCs) and EBGs to be frequently used in artificial ground plane designs. In Table 4, recently published designs using metamaterials for gain and bandwidth enhancement of antennas are given in comparison with the results presented in this study.

As seen in Table 4, the proposed antenna has 38% IBW and 8.3 dBi peak gain. In the design of an antenna, its physical features are also important in addition to its performance parameters such as IBW and gain. The thin profile merit ($h/\lambda_0 \sim 0.05$) is a significant indicator at this point. Although the IBW values of [9,22] are as good as or better than the presented antenna, antennas proposed in [9] have a high profile and large size with their 2-layered structure. The antenna of [22] has shown thin profile merit despite its 3 layers but it has a complex structure emerged by the multi-layered design. In the presented designs, the EBG patches are located in the same layer as the radiating patch of the antenna, and the design includes only a single dielectric layer. Therefore, the proposed designs achieve a thin profile, easy manufacturability and mechanical strength besides the wideband feature, compared to EBG-backed and AMC-grounded antennas. On the other hand, the peak gain values of the listed works are given compared with their initial peak gain values. The peak gain of 8.3 dBi of the proposed antenna, even though not the highest gain, provides the best-enhanced gain value with a 38.3% improvement. The improvement rate does not exceed 20% in other studies given in Table 4.

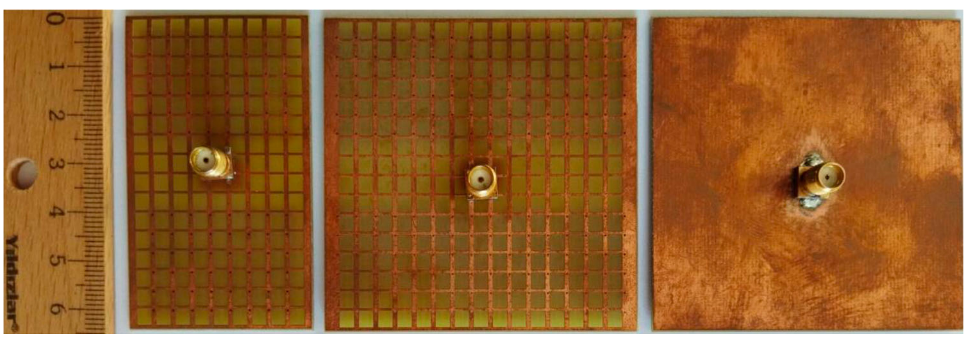
5. Measurement results

The reference antenna, A3 and A4 are fabricated to verify the simulation results and the photographs of the prototypes are given in Figure 10.

The measurements were performed with a Rohde and Schwarz ZVB 20 vector network analyser. The simulated and measured reflection coefficient ($|S_{11}|$) results are illustrated in Figure 11(a). The measured |S11| results of the fabricated antennas confirm the simulated results with satisfactory agreement. The measured bandwidths of the A3 and A4 are 34.6% and 37.86%, whereas the simulated ones are 33% and 38%, respectively. The small deviations observed at the lower and higher frequency values might be attributed to fabrication and measurement errors. Figure 11(b) compares the simulated and measured radiation patterns in the yz – planes at 10 GHz for A3 and A4. The simulated and measured radiation patterns are well agreed. The small variations may be due to the noises in the anechoic chamber.

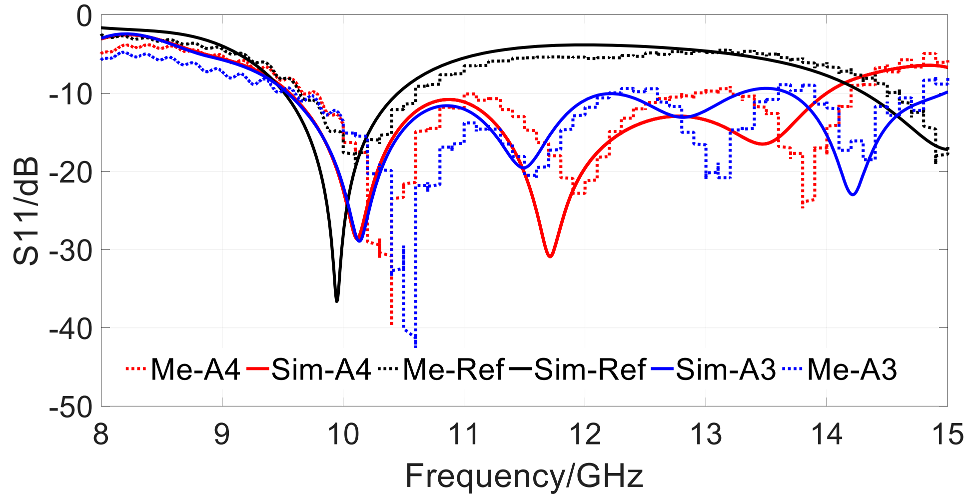


(a)

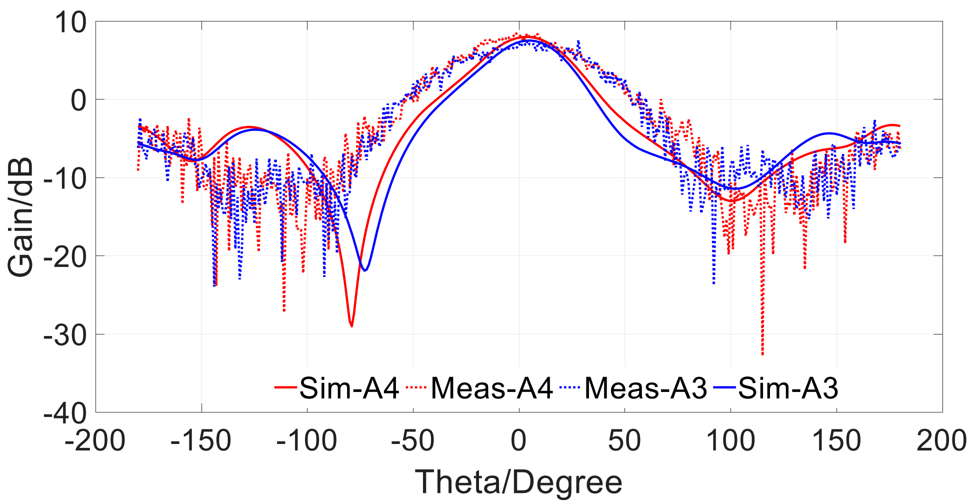


(b)

Figure 10. Prototypes of the manufactured antennas, A4, A3, Reference (from left to right), the front view (a), and back view (b).



(a)



(b)

Figure 11. Simulated and measured |S11| results (a) and radiation patterns (b) of the proposed antennas.

6. Conclusions

In this study antennas designed with mushroom-like EBG structures, two with a novel EBG unit cell and two with a conventional unit cell, are analysed and compared. Three of the proposed antennas have defects with periodically etched slots on the ground. In the designs, the EBG structures provide gain enhancement, whereas the DGS improve the bandwidths of the antennas. The novel EBG structure used in the designs of the A3 is 60% lighter than the conventional EBG. Furthermore, the periodic defective ground used in the proposed designs is 59.4% lighter than the whole conductor ground. Therefore, the structures with reduced metal parts used in the designs of the presented antennas make significant contributions to the overall weight of the reference antenna. In addition, a 41.5% size reduction is achieved with A4. Moreover, the gain and bandwidth values are increased. In fact, the significant contribution of the novel EBG unit cell is in the gain enhancement of the antenna. The parametric analysis carried out on the novel EBG unit cell demonstrates that better gain values can be obtained when the EBG patch's metal parts area is approximately 24% or smaller than the conventional square patch area with the same patch width. This result can be concluded as the prominent novelty of the presented study. Although there are some studies reporting gain enhancement with different EBG patches in the literature, the relationship between the used EBG patches and gain enhancement has not been introduced. On the other hand, the rate of the antenna performance improvement studies with mushroom-like EBG structures relative to the works performed with via-less periodic structures is notably less in the literature. The results reported in this study are remarkable also in this respect. Finally, two thin-profile, wideband and enhanced gain microstrip antennas are proposed. The large main lobe of the reference antenna is reduced with A3 and A4 designs. Thus, much better-directed antennas are obtained with 76% radiation efficiency. As a result, the proposed antennas are light, small, suitable to handle easily and applicable to X and Ku bands with their improved features.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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