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INVESTIGATED NEW EMBEDDED SHAPES OF ELECTROMAGNETIC BANDGAP STRUCTURES AND VIA EFFECT FOR IMPROVED MICROSTRIP PATCH ANTENNA PERFORMANCE

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Abstract—Three novel shapes of mushroom-like electromagnetic band-gap (EBG) structures are presented in this paper. The three shapes are based on rectangular metal strip with different combinations. The performances of the three-shape structures are studied by using both incident plane wave method and transmission coefficient approach. The effect of height and via location are also studied to achieve multi or wide band gap. These shapes are embedded in microstrip patch antenna substrate. The performance of the MPA is improved as increasing the antenna gain by 5 dBi, decreasing the surface current so improving the antenna radiation pattern as well as reducing the antenna size by more than 70% compared to the original size. The new shapes of EBG structure are integrated with MPA as a ground plane, where the conducting ground plane is replaced by a high impedance surface EBG layer. Parametric studies are conducted to maximize their impedance bandwidth and gain. It is found that the antenna bandwidth increased by about four times than original band and its gain is similarly increased. Sample of these antennas are fabricated and tested, to verify the designs.

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1. INTRODUCTION

In recent years, unique properties of electromagnetic band-gap (EBG) structures have made them applicable in many antenna and microwave applications. Various kinds of EBG structures have been suggested at microwave frequencies for applications in the electromagnetic and antenna community [1, 2]. EBG structures are periodic structures which can suppress the propagation of electromagnetic waves in particular frequency bands. The mushroom-like EBG structure with square patches connected to a dielectric substrate ground by vertical posts or metal-plated via was first developed by Sievenpiper et al. in 1999 [1].

The physical mechanism of the mushroom-like EBG structure can be simply explained from the viewpoint of an LC parallel resonant circuit. Then some new techniques, which were mostly used to increase the inductance or capacitance, were utilized to improve the characteristics of EBG structures [2, 3]. With the growing interest in designing multi-band antennas in wireless communications systems, the investigations on compact and multi-band EBG structure has been attractive to many researchers [4–6]. In this paper, three novel shapes of EBG structures are investigated and by cascading two columns of these shapes a novel dual-band structure is formed. The effects of the via position and height are discussed with the method of suspended microstrip line [7, 8].

The study reveals that: first, the resonant frequency is decreased as via height increased and bandwidth of the bandgap is increased. Second, the resonant frequency is decreased when the position of via is moved from the patch center and the bandwidth of the bandgap is decreased. Curve fitting was used to obtain an approximate equations of the via effect on both bandgap resonance frequency and bandwidth. The new shapes parameters are compared with conventional square EBG mushroom shape.

A unique feature of the proposed structure is the realization of tuned two stop-band positions without changing the size of the structure. By adjusting the position of via simultaneously, the frequency of the stop-band can be tuned easily over a wide frequency range and the antenna can be wideband by using tuning of the via position to produce staggered modes. The metal patch area used in these shapes is less than that used in the conventional square patch at the same periodicity and same resonance of the bandgap. Therefore, the performance of the structure is maximized by occupying the spacing area between patches by embedding another structure with smaller dimension to get another bandgap. Two main interesting features associated with this EBG structures which are suppression of surface waves and increased in-phase refection coefficient bandwidth [8–15]. Suppression of surface waves results in higher efficiency, smoother radiation pattern, and less back lobe and side lobe levels in antenna applications [16]. On the other hand, these structures are used in design of low profile antennas because the radiating current lies directly adjacent to the ground plane without being shorted. Then embedding these shapes of EBG structure on the MPA substrate improves the performance compared with conventional square shape. As well as integrating these structures as a ground plane of MPA increases the antenna bandwidth and reduces the antenna size.

2. DESIGN THE MODEL OF A UNIT CELL AND EQUIVALENT CIRCUIT

The three new shapes of EBG structure are investigated and compared with conventional square shape of EBG. Both incident plane wave

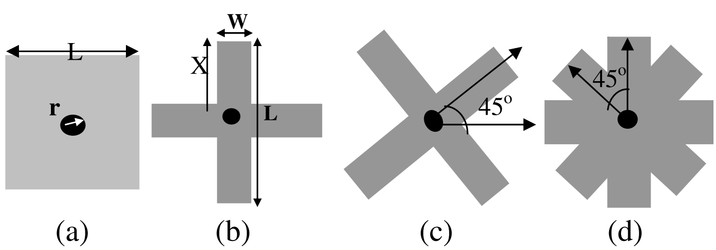


Figure 1. Geometry of the four suspended patches EBG unit. (a) Square shape, (b) plus shape, (c) cross shape and (d) compound plus-cross shape.

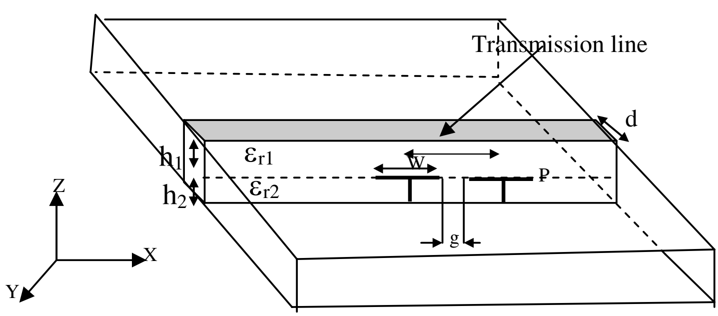


Figure 2. 3D of microstrip transmission line approach.

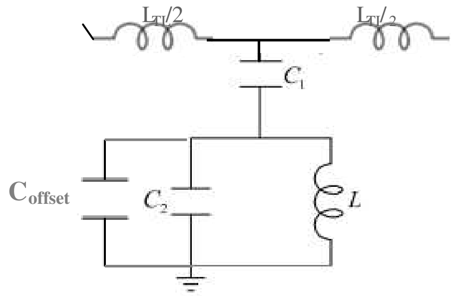


Figure 3. The electrical equivalent circuit.

method and suspended microstrip line approach are utilized to investigate the performance of these shapes. Geometries of the suspended microstrip line over the four shapes of EBG cell are shown in Figure 1. The EBG structure is designed on a substrate with relative permittivity $\varepsilon_{r2} = 10.2$ and height $h_2 = 1.25$ mm. The side length of the square patch is $L = 5$ mm. The center of the pad is connected to the ground plane by a thin metal via with a radius $r = 0.25$ mm. The dimensions of the three new shapes consist of metal strip with length $L = 5$ mm and width $W = 1$ mm for fist shape like add sign (**plus shape**), second shapes is obtained by rotating the plus sign with 45 degree (**cross shape**) and the final shape is composed of the two previous shapes (**compound shape**). All structures have the same periodicity $P = 5.5$ mm and h_2 varies between 0 to 2.45 mm. The relative permittivity of the supporting material is $\varepsilon_{r1} = 10.2$ and the width of $50\,\Omega$ microstrip line is $d = 2.1$ mm as shown in Figure 2. Figure 3 shows the electrical equivalent circuit of this structure [17]. The coupling between the microstrip line and the patch generates a capacitance C_1, the coupling between the embedded EBG and the ground plane creates a capacitance C_2, and the metal via yields an inductance L, C_{offset} is an additional capacitance due to displacement of via hole from the center of the patch. The following Eqs. (1)–(12) give the resonant frequency and bandwidth in terms of the equivalent circuit elements [17].

$$F_{res} = \frac{1}{2\pi\sqrt{L(C_1 + C_2)}} \tag{1}$$

$$C_1 = \frac{\varepsilon_0 \varepsilon_{r1} A}{h_1}$$

$$\text{(where } A \text{ is the cell patch area, for a square shape } L^2\ \text{mm}^2\text{)} \tag{2}$$

$$C_2 = \frac{\varepsilon_o \varepsilon_2 L}{\pi} \cosh^{-1}\left(\frac{L+g}{g}\right) \tag{3}$$

at small g, $C_1 = C_2$

$$|Z_s| = \left|\frac{j\omega L}{1-\omega^2 LC}\right| = \eta = 377\,\Omega \tag{4}$$

$$\eta^2 = \frac{\omega^2 L^2}{1 - 2\omega^2 LC + \omega^4 L^2 C^2} \tag{5}$$

$$\omega^2 = \frac{1}{LC} + \frac{1}{2\eta^2 C^2} \pm \frac{1}{\eta C}\sqrt{\frac{1}{LC} + \frac{1}{4\eta^2 C^2}} \tag{6}$$

where $C = C_1 + C_2$

$$L = \mu_o \frac{h_2}{2\pi}\left[\ln\left(\frac{2h_2}{r} + \sqrt{1+\left(\frac{2h_2}{r}\right)^2}\right) - \sqrt{1+\left(\frac{r}{2h_2}\right)^2} + 1/4 + \frac{r}{2h_2}\right] \quad h \gg r \tag{7}$$

$$L = \mu_o \frac{h_2}{2\pi}\left[\ln\left(\frac{2h_2}{r}\right) + 1\right] \tag{8}$$

$$\omega^2 \approx \frac{1}{LC} \pm \frac{1}{\eta C}\sqrt{\frac{1}{LC}} \tag{9}$$

$$\omega = \frac{1}{\sqrt{LC}}\sqrt{1 \pm \frac{1}{\eta}\sqrt{\frac{L}{C}}} \tag{10}$$

$$BW = \frac{\Delta\omega}{\omega} = \sqrt{1 + \frac{1}{\eta}\sqrt{\frac{L}{C}}} - \sqrt{1 - \frac{1}{\eta}\sqrt{\frac{L}{C}}} \tag{11}$$

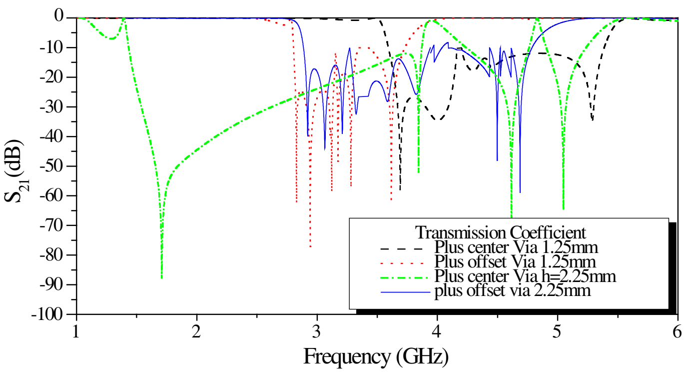


Figure 4. The transmission coefficient of plus shaped EEBG.

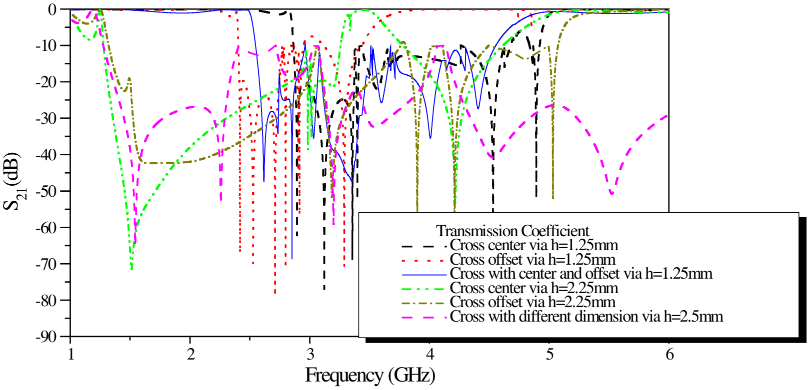


Figure 5. The transmission coefficient of cross shaped EEBG.

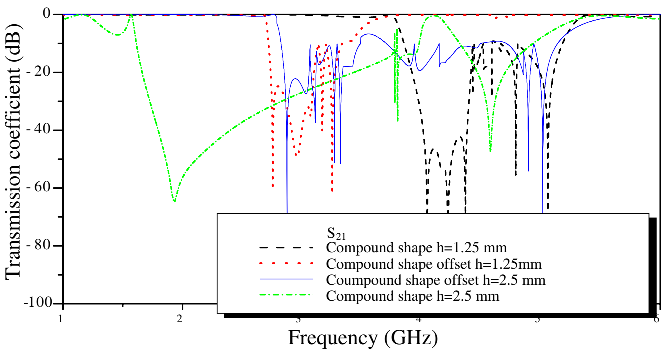


Figure 6. The transmission coefficient of compound shaped EEBG.

The effect of via can be represented by an additional capacitor due to increasing the area of the patches

$$C_T = C + C_{offset} \tag{12}$$

C, depends on the patch area from the center patch edge and C_{offset} depends on the area from the patch center to via position. Variation of the via height effect for the four shapes on bandgap resonance and bandwidth are studied. Figures 4–6 are calculate using the ready-made simulator HFSS version 11. In order to obtain the formulas of Table 1 and Table 2, are calculated S_{11} for different values of h_2 and X and then obtained the behavior of the resonant frequency and bandwidth. The formulas obtained give errors that do not exceed 4%. These formulas are then compared with what obtained from Eqs. (10) and (11) and they were found to be satisfactory. A curve fitting approach is used to generate an approximate equation for each shape as given in Table 1.

Table 1. The bandwidth and resonance frequency of embedded EBG patches as function of h_2 (mm).

Shapes / Parameters	Square shape	Plus shape	Cross shape	Compound shape
Bandwidth	$\frac{1}{0.94 - 0.211 h_2}$	$\frac{1}{0.946 - 0.2411 h_2}$	$\frac{1}{1.386 - 0.416 h_2}$	$\frac{1}{2.2 - 0.712 h_2}$
Resonance frequency	$4.13\cos(0.43h_2)$	$4.38\cos(0.44h_2)$	$4.852\cos(0.45h_2)$	$5.25\cos(0.477h_2)$

Table 2. The bandwidth and resonance frequency of embedded EBG patches as function of via position X (mm).

Shapes / Parameters	Square shape	Plus shape	Cross shape	Compound shape
Bandwidth	$-0.388X+1.5$	$-0.1657X+1.7$	$-0.1X+2$	$-0.286X+2.16$
Resonance	$-0.88X+7.483$	$-1.083X+7.433$	$-0.988X+6.729$	$-0.86X+6.58$

These formulas are obtained by substituting the values of C_1, C_2, L (Eqs. (2), (3), (8) into Eqs. (1) and (11). Note that as the height h_2 increases, the inductance increases and capacitor keeps nearly fixed so the resonance frequency decreases and the bandwidth of the bandgap increases as obtained from the fitting equations given in Table 1. The effect of via position is also studied as given in Table 2, where X is the distance between the center of the via hole and the center of the patch.

These formulas are obtained by substituting C_T (Eq. (12)) instead of C in the aforementioned equations. Note that as position of the via is changed, the distance between via and the center of the metal patch X decreases. The distribution of electric field on the patch will change as well. By adjusting the position of the via, the center frequency can vary in a certain range. From above equations, the inductor is nearly fixed and the capacitor increases so resonance frequency decreases as well as bandwidth of the bandgap as given in Table 2.

The transmission response of the new shapes namely ***plus***, ***cross*** and ***compound*** shape are presented in Figures 4, 5 and 6, respectively. It can be noticed that the bandwidth of the new shapes are larger than conventional square shape at the same resonance frequency and the same periodicity. Moreover, metal area used for these three shapes is less than used in square from L^2 to $2W_L$, $2W_L$ and $4W_L$, respectively. From this concept, we can use two columns with center via followed by two columns with offset via so the bandwidth can be increased to achieve broadband of EBG band gap. Dual band gap can be achieved by tuning the via poison as shown in Figures 4, 5 and 6.

On the basis of the fact that the EBG structure behaves like a stop band filter which can be seen from Eq. (6), it is expected that a broadband EBG can be achieved when two different kinds of EBG unit are cascaded. As mentioned earlier when position of the vias is moved off the center of the metal, the bandwidth of the stop-band is decreased as well as decreasing the resonant frequency of the band. So, we use two columns when vias are at the center followed by two columns with offset vias. The four columns units which have the same patches and radius of via are arranged along the Y-direction to form a cascaded structure, as shown in Figures 4, 5 and 6.

The reflection angle is also studied by using plane wave incident on a single unit cell [5] for these shapes and compared with conventional square shape, then the effect of via position is studied as shown in Figures 7 and 8. Figure 7 shows that the reflection phase bandwidth of the three new shapes extend from 1 to 5 GHz and from 7 to 8 GHz. However, the conventional shape is extended from 1 GHz to 3.5 GHz and from 5 to 7 GHz as shown in Figure 8. In addition, the resonance frequency of the compound shape is smaller than conventional shape by about 1.5 GHz. On the basis of the fact that the EBG structure behaves like a stop band filter which can be seen from Eq. (6), it is expected that a broadband EBG can be achieved when two different kinds of EBG unit are cascaded. As mentioned earlier when position of the vias is moved off the center of the metal, the bandwidth of the stop-band is decreased as well as decreasing the resonant frequency of the band. So, we use two columns when vias are at the center followed by two columns with offset vias. The four columns units which have the same patches and radius of via are arranged along the Y-direction to form a cascaded structure, as shown in Figures 4, 5 and 6.

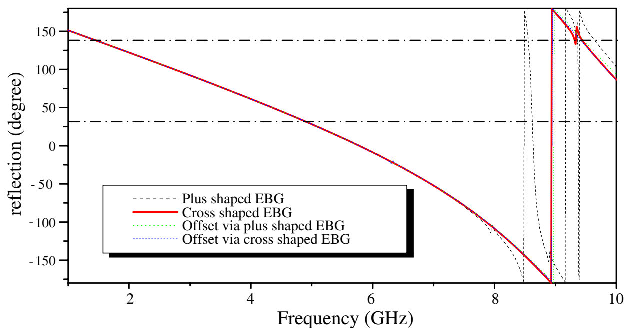


Figure 7. Phase reflection of plus and cross centered and offset via.

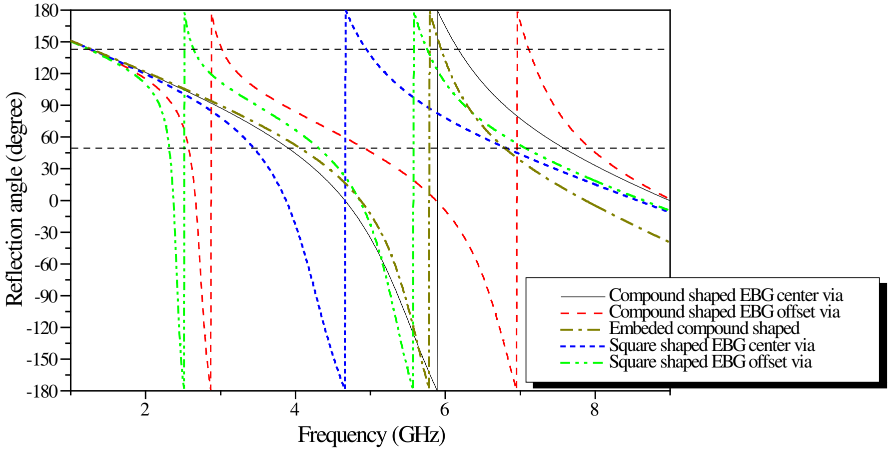


Figure 8. Phase reflection of square and compound centered and offset via.

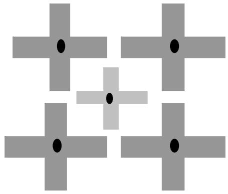


Figure 9. The geometry of two different shapes.

As mention before, the metal patch area used in these three shapes is smaller than that used in square at same periodicity. So, dual band-gap structure are provided by occupying the space area between these patch cells and printing another patch with different dimension as shown in Figure 9. The transmission coefficient response for this structure is shown in Figure 10. The two structures are fabricated and their photos are shown in Figure 11.

3. MICROSTRIP ANTENNA PERFORMANCE

The MPA [18, 19] is applied at the surface of the structure instead of the transmission line with dimension W_p and L_p equal to 12 mm and 11 mm, respectively. The substrate dimension $W_g \times L_g = 30 \times 30\,\text{mm}^2$ with height 2.5 mm and $W_f = 2.1$ mm as shown in Figure 12. The antenna resonates without embedded EBG at 3.8 GHz. The three new shapes are embedded in the MPA substrate as well as the conventional square shape, then the antenna performance is simulated and the

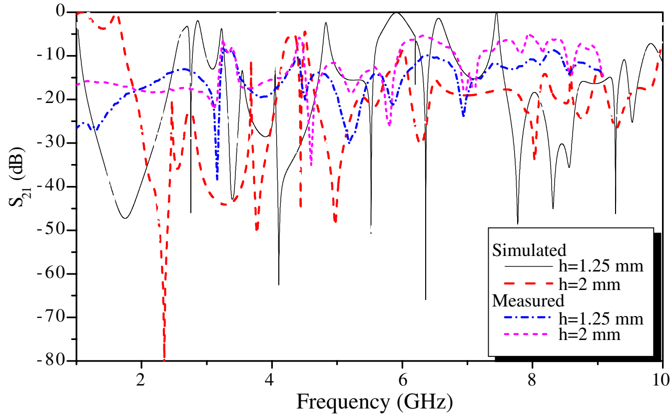
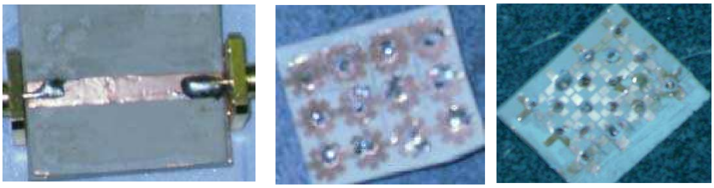


Figure 10. The transmission response for the structure shown in Figure 9.



(a) (b) (c)

Figure 11. The fabricated structures. (a) Transmission line, (b) wide band gap structure, and (c) dual band gap structure.

Table 3. The antenna performance with different embedded EBG shapes.

Types / Antenna parameters	Patch without EBG	Patch with embedded square	Patch with embedded plus	Patch with embedded cross	Patch with embedded compound
Frequency (GHz)	3.8	3.4	3	2.9	2.65
Gain (dBi)	2.5	3.5	4.75	5.5	7
Fractional bandwidth	5%	2.9%	3%	3.1%	3.5%

results are given in Table 3.

It was found that for an EBG patch antenna operating at the fundamental mode, the embedded EBG patch size is significantly smaller than the size of the radiator patch of microstrip antenna.

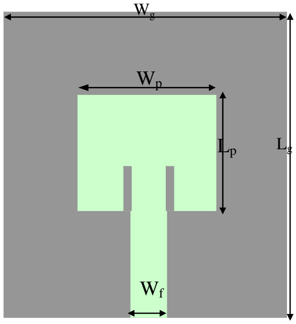


Figure 12. The geometry of microstrip patch antenna.

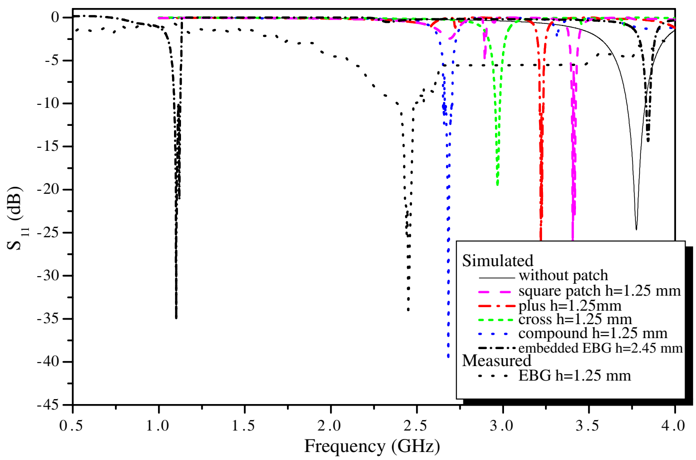
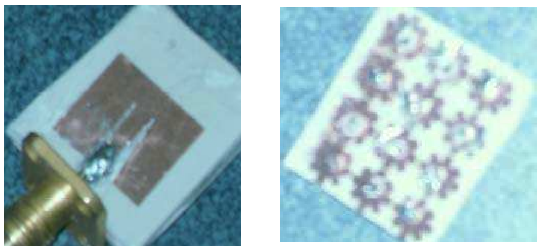


Figure 13. Comparison of reflection coefficient of antenna with the new EBG structures.

This property is useful for antenna miniaturization. The antenna reflection coefficient is shown in Figure 13, without and with embedded EBG at different embedded heights. From this figure, it is noted that the compound shape reduces the antenna size by 25% at height = 1.25 mm and by increasing the via height to 2.45 mm, the resonance frequency reaches 1.1 GHz which indicates 70% size reduction from the original size. In addition to increase the antenna gain by 4.5 dBi than that of the conventional MPA. The antenna with compound shape of embedded EBG at height = 1.25 mm is fabricated as shown in Figure 14.

The reflection phase without and with embedded shapes is shown in Figure 15, from which it is clear that the number of zero slot reflection phase is increased from antenna with embedded patches and the bandwidth of reflection phase $\pm$ ($45°$ to $135°$) is increased for the new shapes especially the compound EEBG shape and gives bandwidth better than square EEBG.

The surface current distribution on the antenna ground plane of the MPA is also studied using HFSS simulator, as shown in Figure 16. This figure indicates that the antenna without embedded



(a) (b)

Figure 14. The fabricated antenna with compound shape of embedded EBG. (a) Radiator and (b) embedded EBG structure.

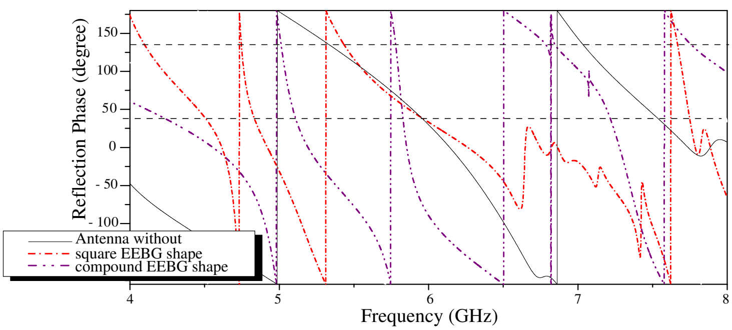
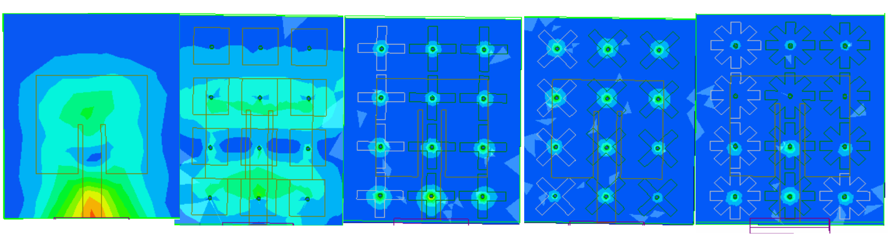
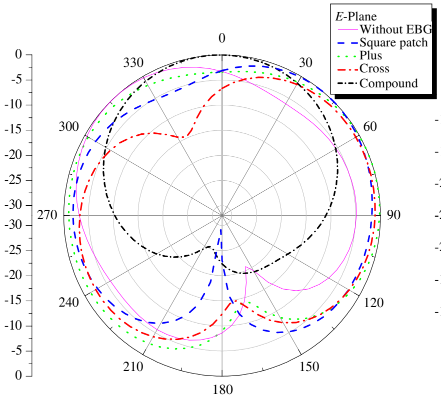


Figure 15. Comparison of reflection phase between antennas with and without embedded EBG structures.



(a) (b) (c) (d) (e)

Figure 16. The surface current distribution on the ground plane.



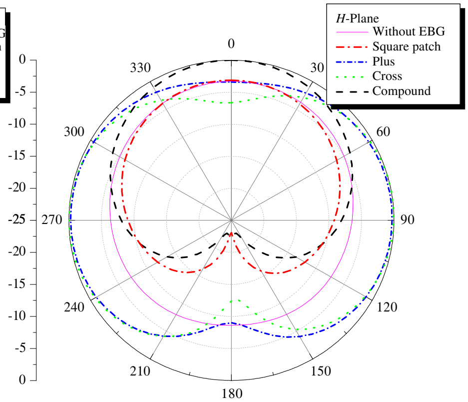


Figure 17. The *E*-plane and *H*-plane radiation pattern for microstrip antenna without and with embedded EBG.

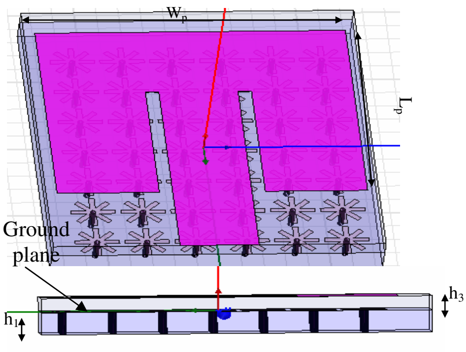


Figure 18. The antenna geometry with EBG ground plane.

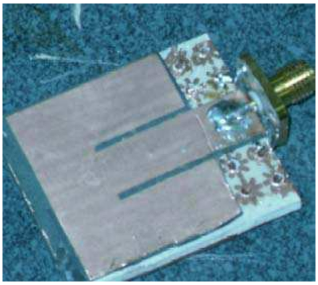


Figure 19. The fabricated patch antenna with EBG ground plane.

EBG have higher surface current which causes poor antenna gain and radiation pattern. The three new shapes of EEBG give better surface current distribution than conventional square patch and the embedded compound EBG shape gives the best current distribution.

The radiation patterns of the antennas without and with embedded compound shape EBG patches are shown in Figure 17. Figure 17 shows that the antenna with embedded compound shape gives better *E*- and *H*-radiation patterns than others. Compound EBG as a ground plane is used to increase antenna bandwidth and improve antenna reflection coefficient. The EBG ground plane was

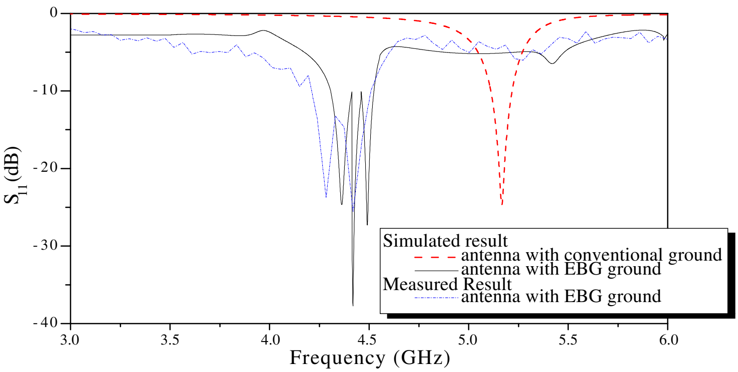


Figure 20. Comparison between reflection coefficient with conventional ground plane and EBG ground plane.

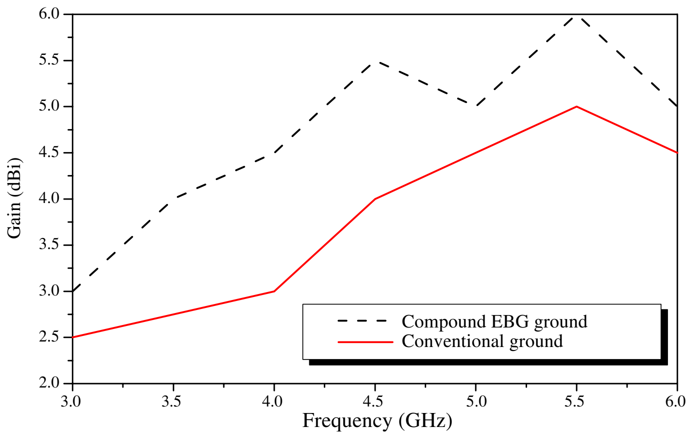


Figure 21. Comparison of gain between the patch antenna with and without EBG ground plane.

built on RTD6010 substrate with dielectric constant 10.2 and thickness $h_1 = 2.5$ mm, then the radiator of microstrip patch antenna was built on foam substrate with dielectric constant 1.7 and far from ground plane by $h_3 = 2.5$ mm. The prototype geometry is shown in Figure 18 and the fabricated antenna is shown in Figure 19. The comparison between reflection coefficient with and without ground plane is shown in Figure 20. Figure 20 shows that the bandwidth is increased by about four times than the original bandwidth with 18% reduction in antenna size. It gives better reflection coefficient by -10 dB than using conventional ground. Figure 21 shows comparison of gain the patch antenna with and without EBG ground plane.

4. CONCLUSION

This paper presented three new shapes of unit cell patches used as EBG structure. These shapes give performance better than conventional square EBG. The effect of via height and position were studied and new equations that describe the relation between bandgap resonance and bandwidth with height and position of via were derived. A multi-band and broad-band were achieved by using two ways, first by cascaded two columns with different via positions and second by occupying the space area between unit cells with another type of EBG structures. The compound shape is used as embedded EBG and integrated with microstrip patch antenna. It was found that for an EBG patch antenna operated at the fundamental mode, the patch size is significantly smaller than the size of a conventional microstrip patch. This property is useful for antenna miniaturization. For the MPA with the EEBG substrate, and operating inside its bandgap, antenna area is reduced by 70% compared to original size, increasing the antenna gain by 4.5 dBi. Detailed parametric studies were conducted for patch antennas with an embedded EBG substrate. Then the compound EBG shape was integrated as a ground plane of microstrip patch antenna. The patch antenna was designed to work within its bandgap. Bandwidth is increased by about four times than the original bandwidth with 18% reduction in antenna size. It gives better reflection coefficient by −10 dB than that using conventional ground.

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