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AN UWB FRACTAL ANTENNA WITH DEFECTED GROUND STRUCTURE AND SWASTIKA SHAPE ELECTROMAGNETIC BAND GAP

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Abstract—In this paper, an ultra wideband antenna employing a defected ground structure is presented. The radiating element is a circular patch on which a fractal based geometry is inscribed in the form of slots and excited by a tapered feed-line for impedance matching. The antenna has an impedance bandwidth of 8.2 GHz (117% at centre frequency of 7 GHz) and a peak gain around 6 dB. To improve the impedance bandwidth and gain, a Swastika shape Electromagnetic band gap (EBG) structure is proposed. The unit cell of the proposed EBG has a compact size of 3 mm × 3 mm and is obtained by introducing discontinuities in the outer ring of the Cross-Hair type EBG. The stop band (−20 dB) achieved with this EBG is 3.6 GHz (7.5 GHz–11.1 GHz) which is 1.6 GHz more than that achieved by a standard mushroom-type EBG of the same size and same number of elements. After application of the proposed EBG, there is an improvement of 12% in the impedance bandwidth while the peak gain increases by about 2–3 dB. The radiation of the antenna shows a dumb-bell shaped pattern in the E-plane and Omni-directional pattern in the H-plane. All the measured results are in good agreement with simulated results.

1. INTRODUCTION

Nowadays, printed ultra wideband (UWB) antennas have attracted much attention among researchers due to their small size, low cost and high data rate features. The Federal Communications Commission has allotted 3.1 GHz to 10.6 GHz for unlicensed ultra wideband applications. Most of the ultra wideband antennas are either microstrip fed or coplanar waveguide fed monopoles or slots. By using

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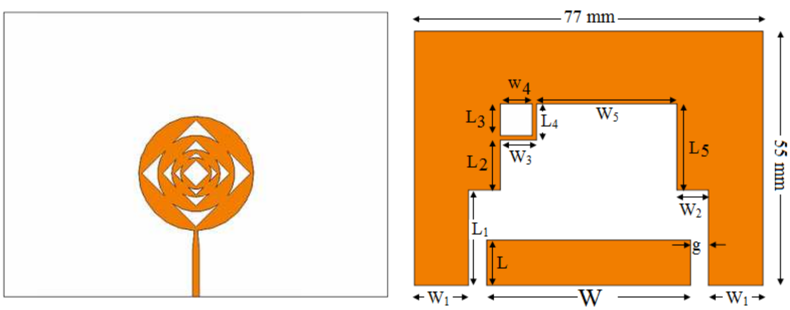
different shapes for the patch and the slot, ultra wideband antenna can be realized [1–10]. In [2], a comparison of the different shapes such as rectangular, circular, square, elliptical and triangular shape for the patch as well as the slot is made. The use of slot in any antenna will provide impedance bandwidth improvement as compared to a simple patch antenna. As using multiple slots gives multiple resonance frequencies, by combining the multiple resonances together, ultra wideband can be achieved. So the use of multiple slots in a patch antenna can result in ultra wideband nature. Slots are also used to give ultra wideband with band notched characteristics [6].

To improve the performance of printed antennas, Electromagnetic Band Gap (EBG) structures can be used. EBG structures can also be used to improve the performance of other microwave components such as filters and waveguides. An EBG structure is a periodic arrangement of metallic or dielectric elements which characterise the stop band and pass band. EBG structure is also characterized by high surface impedance. Unlike other normal conductors, EBG does not support propagating surface waves, and it reflects electromagnetic waves with no phase reversal [11]. The gain of antenna can be improved by using EBG structure in two different ways; EBG structure as a superstrate [12, 13] and EBG structure as a ground plane [14, 15]. The gain of any antenna can be increased by EBG structure in the frequency band where the EBG structure is having high surface impedance behaviour or band stop property such that in that band the propagation of surface wave is suppressed which improves the antenna gain or radiated power [16]. Gain of an antenna can be kept constant by using higher permittivity substrate in comparison to low permittivity substrate and by using a superstrate layer of array of patches (like EBG structures) [17]. EBG is also used to get notched characteristic in ultra wideband antenna [18, 19]. Dual band EBG is used to get high gain and high radiation efficiency over a wider band [20]. EBG is also used for bandwidth improvement of microstrip antennas [21].

In this paper, a circular patch is designed with multiple slots to achieve ultra wideband characteristics and then three types of EBG structures namely mushroom type, Cross-Hair type and Swastika type are employed in the plane of the patch. By using the EBG, an improvement in the gain is achieved while keeping the low profile of antenna intact. The antennas are simulated in Ansoft HFSS and CST Microwave studio. The reflection coefficient characteristic of the fabricated antenna is measured using Rohde & Schwarz Vector Network Analyzer (R&S ZVA-40) while the radiation patterns and gain are measured in the in-house anechoic chamber, and finally the simulated and measured results are compared.

2. DESIGN OF ANTENNA

The antenna is designed using a combination of square slot cut in a circular patch and a defected ground structure (Figure 1). The circular patch antenna was preferred as it has several advantages over antennas with other shapes such as good radiation patterns and wide frequency of operation. The size can be easily changed to give a range of impedance values which is very useful in matching. The square slot was added to reduce the lower cut-off frequency. The electromagnetic coupling with the patch is decided by the shape and size of the slot. So, by varying the slot shape and size, the coupling can be varied and hence the impedance matching. The impedance bandwidth is also decided by the coupling between the slot and the feed line which in turn is governed by the feed gap. This gap must be optimized to get good impedance bandwidth. The feed line itself is tapered at an angle $\theta = 11.38°$ (Figure 2). Tapering makes the impedance of the feed line to vary along its length and thus act like an impedance transformer.



(a) (b)

Figure 1. (a) Circular patch antenna. (b) Defected ground plane.

Figure 1(a) shows the circular patch having the slots while Figure 1(b) shows the defected ground plane for the proposed antenna. All the dimensions of the structure have been optimized to get the ultra wideband characteristics and are given in Table 1. The gap between the two sections of the ground plane as indicated in Figure 1(b) by 'g' is optimized to 4 mm. The substrate used is FR4 with $\varepsilon_r = 4.4$, $\tan\delta = 0.02$ and thickness 1.6 mm.

For any circular patch, the first resonance frequency is given by the following equation

$$f_r = \frac{1.8412 v_o}{2\pi a_e \sqrt{\varepsilon_r}} \tag{1}$$

$$a_e = a\left\{1 + \frac{2h}{\pi a \varepsilon_r}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \tag{2}$$

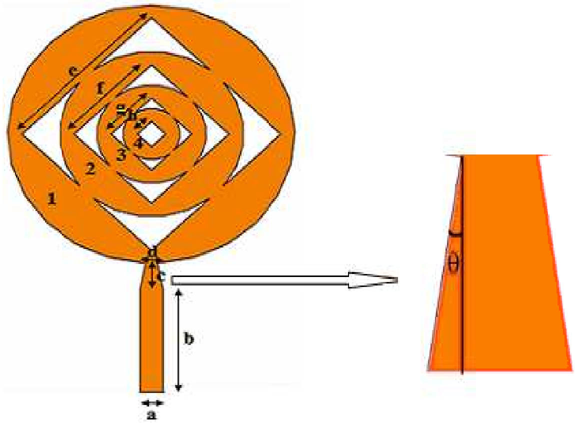


Figure 2. Fractal patch configuration and enlarged view of tapered feed.

Table 1. Dimensions of the patch and the defected ground plane.

S. No	Parameter	Dimensions (in mm)	S. No	parameter	Dimensions (in mm)
1	a	1.600	13	L_2	10.00
2	b	8.000	14	W_2	7.00
3	c	2.000	15	L_3	7.00
4	d	0.800	16	W_3	8.00
5	e	12.726	17	L_4	8.00
6	f	7.580	18	W_4	7.00
7	g	3.945	19	L_5	18.00
8	h	1.374	20	W_5	31.00
9	W	45.00	21	Radius of circle 1	10.0
10	L	10.00	22	Radius of circle 2	6.40
11	L_1	22.00	23	Radius of circle 3	3.80
12	W_1	12.00	24	Radius of circle 4	1.98

where f_r is the resonance frequency of the patch antenna, a_e the effective radius of the patch, 'a' the physical radius of the patch, h the height of substrate, and ε_r the dielectric constant of the substrate. The radius of the outer circular patch (Circle No. 1 in Figure 2) is 10 mm, and then by using the above two equations, the resonant frequency is obtained equal to 4.05 GHz.

3. RESULTS AND DISCUSSIONS

3.1. Reflection Coefficient

The antenna is designed and simulated using Ansoft HFSS and CST Microwave Studio. The antenna is then fabricated with optimized dimensions. A photograph of the fabricated antenna is shown in Figure 3.

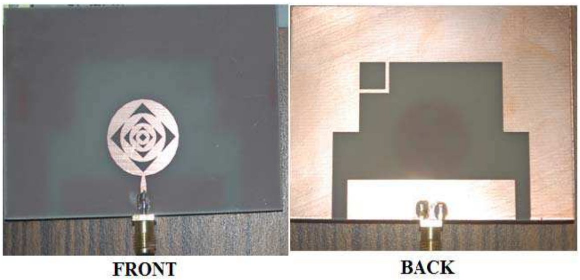


Figure 3. Prototype of fabricated antenna without EBG.

The measurements for the fabricated prototype were taken on a Rohde & Schwarz Vector Network Analyzer (ZVA-40). The measured impedance bandwidth of the antenna shown in Figure 4 is found to be 8.2 GHz (from 2.2 GHz to 10.4 GHz). This measured impedance bandwidth is 117% at the centre frequency of 7 GHz, which clearly indicates the ultra wideband characteristics of the antenna. As it can be seen from the figure, the simulated and measured results are in good agreement except at certain frequencies and this may be due to uncertainty in the dielectric constant of the substrate and assembly misalignments. There is also a slight difference in the two simulated results because of the different types of numerical techniques used by the two simulators. The first resonance seen at 2.44 GHz is due to the slots in the circular patch while the second resonance at about 4 GHz is due to the circular patch (as derived in the previous section). The remaining resonances are due to harmonics. The different harmonics combine and give the ultra wideband behaviour.

The current distributions for the antenna without the EBG are shown in Figure 5. In the figure, the red colour indicates maximum

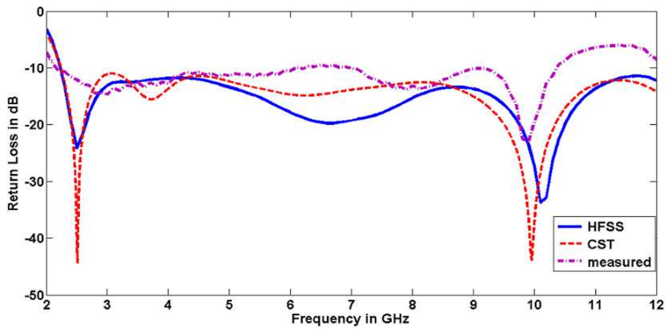


Figure 4. Return loss (dB) vs. frequency (GHz) of antenna without EBG.

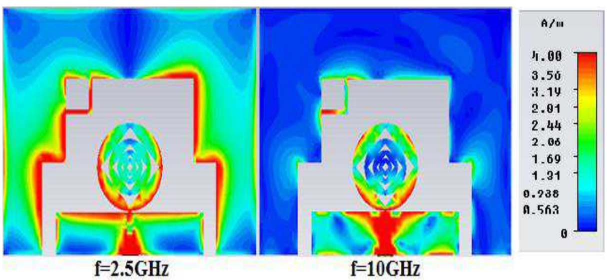


Figure 5. Current distribution of antenna without EBG.

current density while blue indicates the minimum current density. It is clearly seen that the patch current at frequency 2.5 GHz has only one maxima while at 10 GHz it has 4 maxima, so it can be said that the 10 GHz resonance is a 4th harmonic of the lowest resonance at 2.5 GHz.

3.2. Radiation Patterns

The radiation patterns of the proposed ultra wideband antenna are simulated in E and H planes using HFSS and CST Microwave Studio and measured in the in-house anechoic chamber using antenna measurement system. A standard double ridged horn antenna is used as a reference antenna. The simulated and measured radiation patterns are shown in Figure 6 for different frequencies. The simulated and measured results are in close agreement. The H-plane radiation has omni-directional pattern while the E-plane radiation has bidirectional (dumb bell shaped) pattern. At higher frequencies, the radiation patterns deviate from omni-directional in case of H-plane and bidirectional in case of E-plane due to the fractal nature of the proposed antenna and multimode generation at higher frequencies.

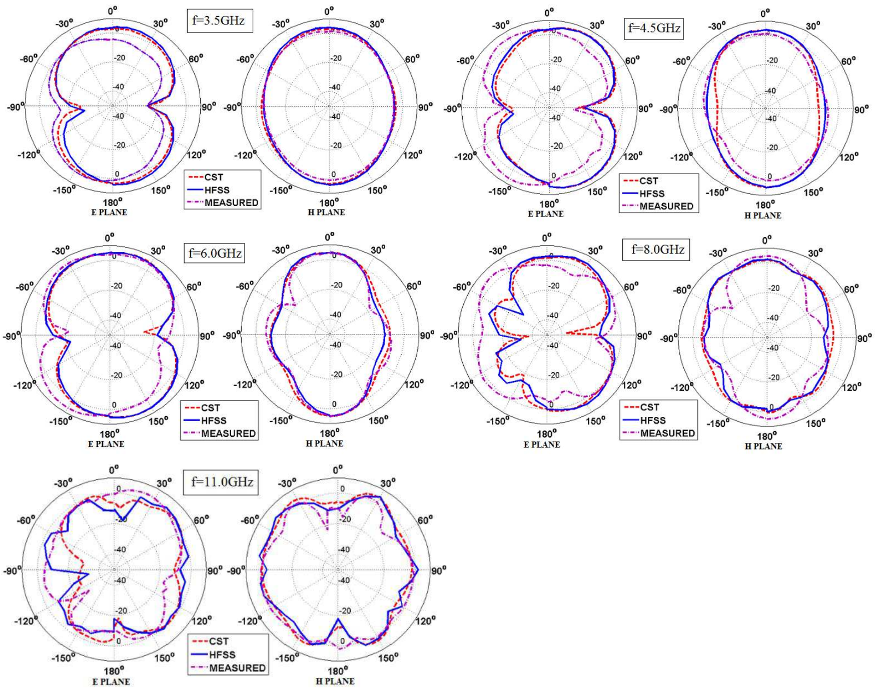


Figure 6. Measured and simulated radiation patterns of antenna without EBG.

4. PARAMETRIC STUDY OF THE ANTENNA

The effect of variation in the size of the ground plane is given in Figures 7 and 8 which clearly show the effect on the impedance bandwidth of the antenna. Figure 7 shows the variation of return loss with a reduction in the ground width 'W' while Figure 8 shows the variation of return loss with a reduction in the ground length 'L'.

From Figure 7, it can be seen that as the ground width decreases, the higher resonances (fourth) shift towards the higher frequency side. Also the impedance matching deteriorates and the return loss curve shifts above the -10 dB line at several frequencies. Similarly from Figure 8, a decrease in the ground length makes the return loss worse besides shifting the higher resonances (fourth) to the lower side.

Figure 9 shows the variation of return loss with a reduction in the gap 'g' in the defected ground plane. As the gap increases, the return loss improves at the lower frequencies while deteriorating at higher frequencies. Hence there is an optimal value of the gap which is found

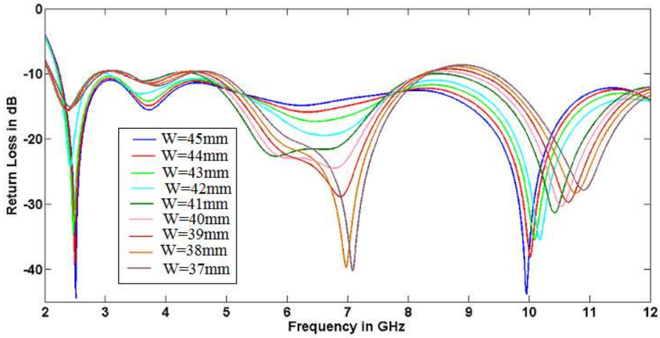


Figure 7. Effect of ground width 'W' on the return loss of antenna without EBG.

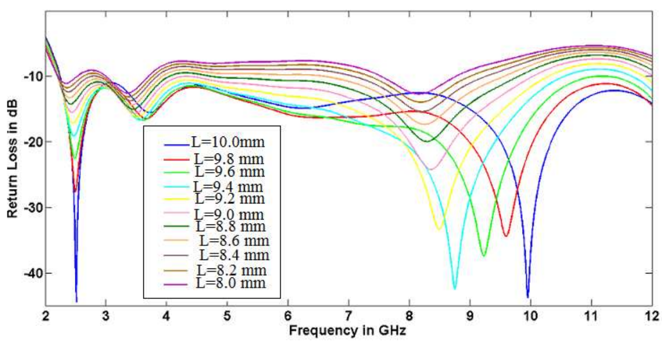


Figure 8. Effect of ground length 'L' on return loss of antenna without EBG.

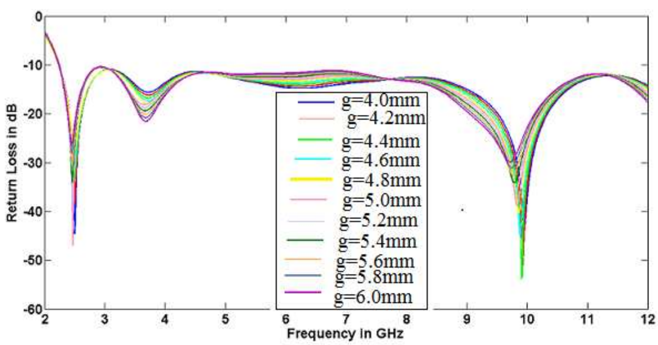


Figure 9. Effect of gap parameter 'g' on return loss of antenna without EBG.

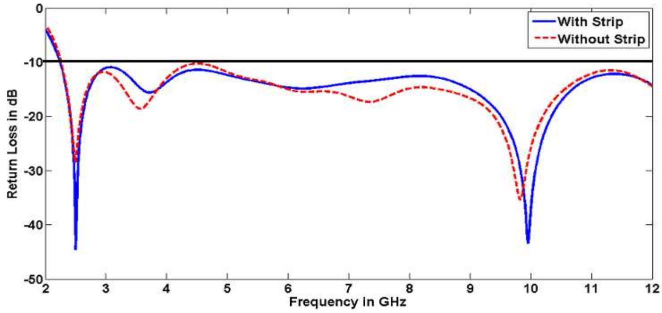


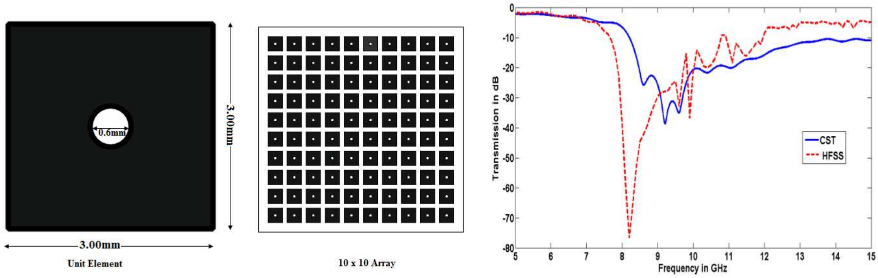
Figure 10. Effect of L shaped strip on return loss.

to be 4 mm. Figure 10 shows the effect of adding the L-shaped strip in the defected ground plane (Figure 1(b)) which indicates that putting the strip improves the return loss performance near 4.5 GHz.

5. DESIGN OF EBG

5.1. Mushroom-type EBG

A mushroom-type EBG is designed having a square patch of dimension 3×3 mm as shown in Figure 11(a), the diameter of via being 0.6 mm. The EBG is designed on FR4 substrate having permittivity 4.4 and thickness 0.8 mm. A 10×10 array EBG having 1 mm gap between the unit elements is simulated using Ansoft HFSS and CST Microwave Studio. The simulated transmission response of the mushroom-type EBG array is shown in Figure 11(b), which clearly indicates that the EBG is having maximum reflection and surface wave stop property in the 8.5 to 10.5 GHz band.



(a) (b)

Figure 11. Mushroom-type EBG. (a) Unit element and 10×10 array. (b) Simulated transmission characteristic of 10×10 array.

5.2. Cross-Hair Type EBG

A cross-hair type EBG is designed by combining a 3×3 mm loop, a 1×1 mm square patch and four microstrip lines as shown in Figure 12(a), the via diameter being 0.6 mm. The dimension of the substrate is taken same as for the Mushroom-type EBG. The overall size of the unit element is 3×3 mm. Like for the previous case, a 10×10 array having 1 mm gap between each unit element is designed and simulated. Figure 12(b) shows the simulated transmission characteristic of the cross-hair type EBG, which shows the maximum reflection and surface wave stop property in the 8.1 GHz to 9.5 GHz band.

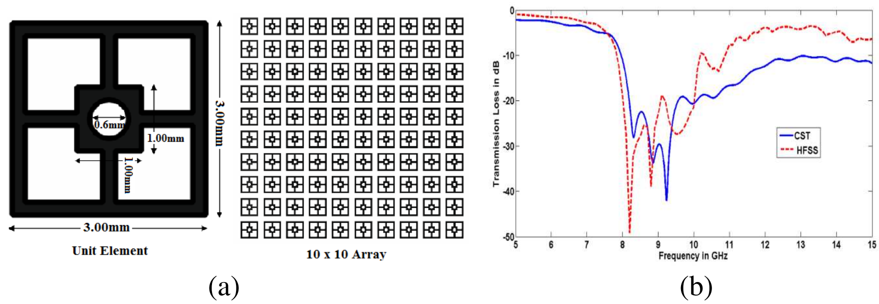


Figure 12. Cross-Hair type EBG. (a) Unit element and 10×10 array. (b) Simulated transmission characteristic of 10×10 array.

5.3. Swastika Type EBG

A swastika-type EBG is designed from the cross-hair type EBG by making the loop discontinuous at four places as shown in Figure 13(a), the via diameter being 0.6 mm. The dimension of substrate is taken same as in the above two cases. The overall size of the unit element is

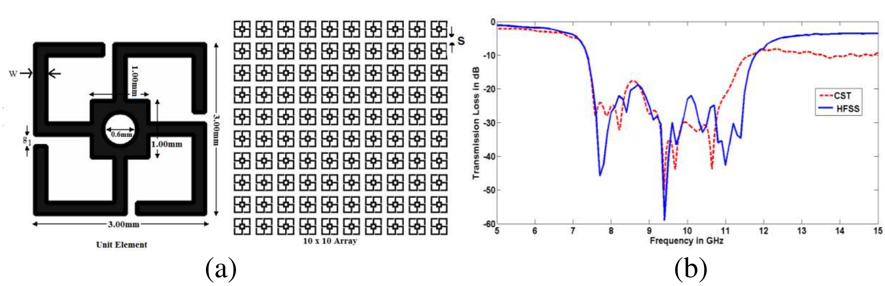


Figure 13. Swastika-type EBG. (a) Unit element and 10×10 array. (b) Simulated transmission characteristic of 10×10 array.

3×3 mm. The width of the strip 'w' is taken to be 0.2 mm while the gap g_1 is 0.2 mm. Like for the above two cases, a 10×10 array having 1 mm gap between each element is designed and simulated. Figure 13(b) shows the transmission characteristic of the swastika-type EBG, which shows the maximum reflection and surface wave stop property in the 7.5 GHz to 11.1 GHz band.

5.4. Comparison of the Three EBGs Characteristics

In Figure 14, a comparison of the transmission characteristic of all the three types of EBGs is presented. From the figure, it can be seen clearly that the swastika-type EBG has greater bandwidth in comparison to all other EBG structures and cross-hair type EBG has the lowest bandwidth.

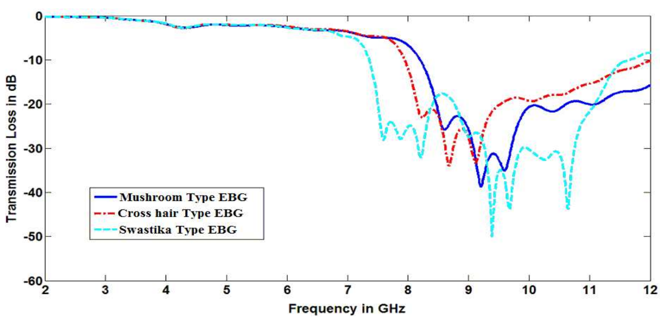


Figure 14. Simulated transmission characteristic comparison of all the above three EBG.

5.5. Parametric Study of Swastika-Type EBG

A parametric study was performed to see the effect of the strip width 'w', gap 'g_1' and the spacing between the unit elements 's' on the transmission characteristics and the results are given in Figure 15, Figure 16 and Figure 17, respectively. The comparison is made in terms of the bandwidth corresponding to -15 dB reference for all the cases. Also while varying one of the parameters, the other two were kept constant. From Figure 15 it can be observed that increase in the gap 'g_1' leads to an increase in the bandwidth. Also there is a shift in the transmission band towards the higher side. The optimized value of g_1 is found to be 1.2 mm. A further increase in g_1 leads to split in the band. The increase in the bandwidth can also be obtained by increasing the strip width 'w' as seen from Figure 16. However in this case there is no shift in the centre frequency. The optimized value of 'w' is taken 0.5 mm. The effect of the spacing between the unit elements

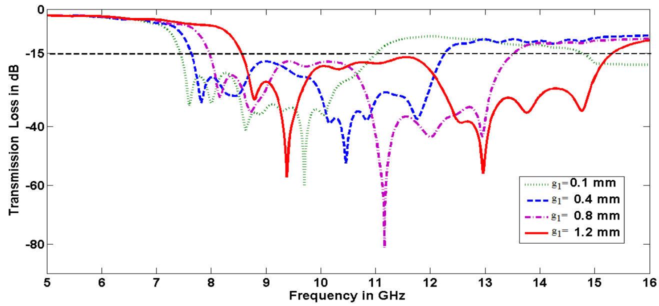


Figure 15. Effect of variation of gap between the strips 'g_1' on transmission characteristics of Swastika-type EBG (with $w = 0.2$ mm and $s = 1$ mm).

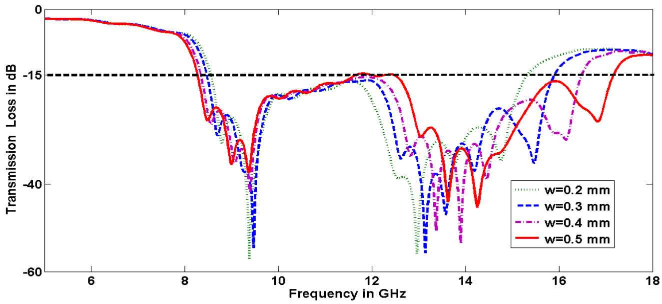


Figure 16. Effect of variation of strip width w on transmission characteristics of Swastika-type EBG (with $g_1 = 1.2$ mm and $s = 1$ mm).

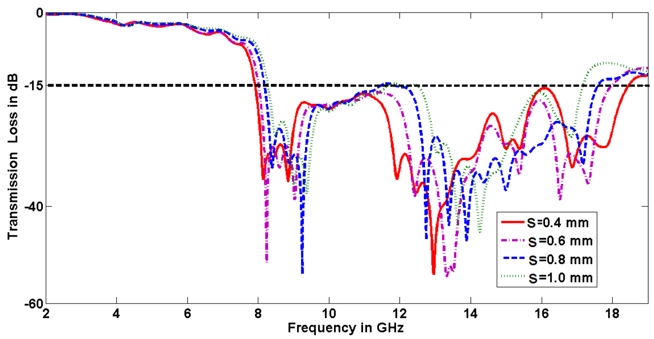


Figure 17. Effect of variation of gap between unit elements 's' on transmission characteristics of Swastika-type EBG (with $w = 0.5$ mm and $g_1 = 1.2$ mm).

on the transmission bandwidth is shown in Figure 17. It is observed that a smaller spacing leads to better characteristics. The optimized value for 's' is found to be 0.4 mm as a further reduction causes the bandwidth to split.

6. EFFECT OF EBG ON IMPEDANCE BANDWIDTH AND GAIN

The EBG is designed on the plane of the circular patch antenna such that the low profile of antenna is not disturbed. The substrate thickness used for the antenna with EBG is 0.8 mm. As the height of the substrate decreases, the efficiency and bandwidth decreases because the electric field gets tightly bound in the dielectric due to the dominating attractive forces between charges, As a result, most of the current flows underneath the patch [10]. After applying the EBG structure, it is found that inspite of decreasing the height of the substrate (from 1.6 mm for antenna without EBG to 0.8 mm for antenna with EBG), nearly same impedance bandwidth is achieved while there is an improvement in the gain in comparison to the antenna without the EBG. This is because the EBG structure suppresses the surface wave which is a major cause of losses and reduced gain and efficiency.

All the three EBG structures were applied to the proposed antenna and fabricated. The effects of the three EBG structures on the antenna are discussed next.

6.1. Mushroom-Type EBG

The fabricated prototype of the antenna with mushroom-type EBG is shown in Figure 18. The simulated and measured return loss is shown in the Figure 19. The antenna clearly shows the ultra wideband

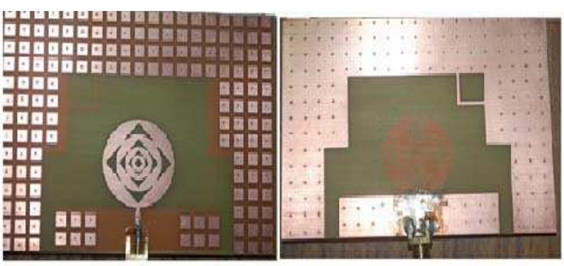


Figure 18. Fabricated prototype of antenna with Mushroom-type EBG.

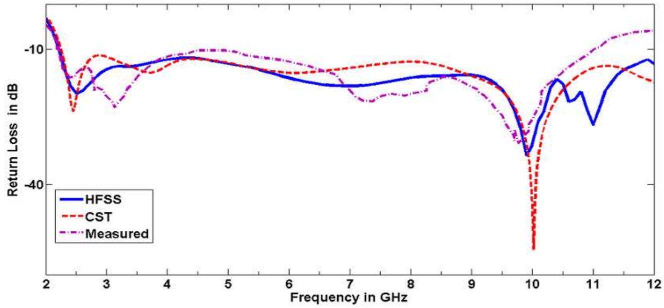


Figure 19. Return loss (dB) vs. frequency (GHz) of antenna with Mushroom-type EBG.

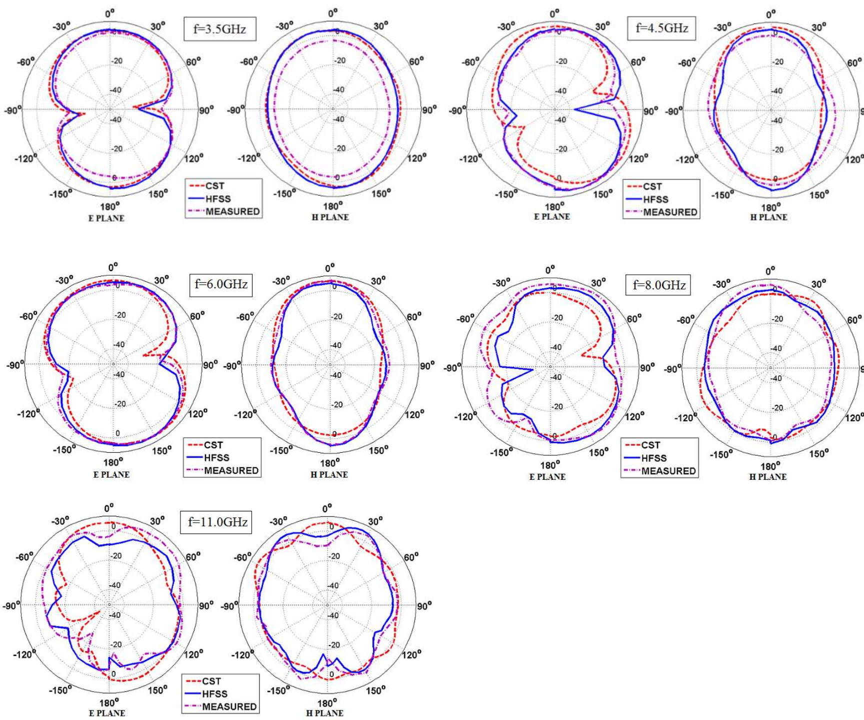


Figure 20. Measured and simulated radiation pattern of antenna with Mushroom-type EBG.

behaviour. The measured impedance bandwidth obtained is 8.9 GHz (from 2.2 GHz to 11.1 GHz) or 127% at the centre frequency of 7 GHz. So the measured bandwidth is around 10% more in comparison to antenna without EBG. Figure 20 shows the measured and simulated radiation pattern of antenna with mushroom-type EBG at different frequencies. From the figure, it can be seen that the antenna has bidirectional pattern in the E plane and Omnidirectional pattern in the H plane.

6.2. Cross-Hair Type EBG

The fabricated prototype of antenna with cross-hair type EBG is shown in Figure 21. The simulated and measured return loss is shown in Figure 22. Here also, the return loss shows ultra wideband behaviour. Figure 23 shows the measured and simulated radiation pattern of antenna with cross-hair type EBG at different frequencies.

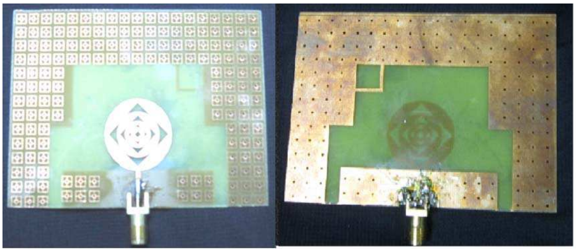


Figure 21. Fabricated prototype of antenna with Cross-Hair type EBG.

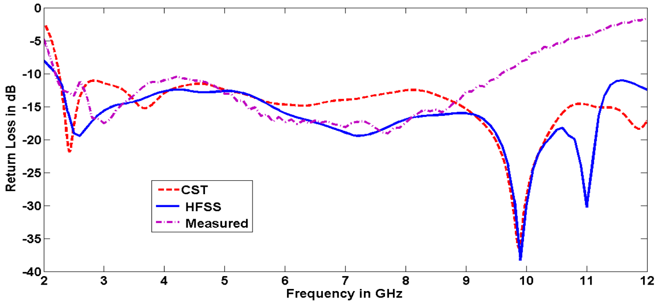


Figure 22. Return loss (dB) vs. frequency (GHz) of antenna with Cross-Hair type EBG.

6.3. Swastika-Type EBG

The fabricated prototype of the proposed antenna with Swastika type EBG is shown in Figure 24. The simulated and measured return loss is shown in Figure 25. The measured return loss is below −10 dB in the

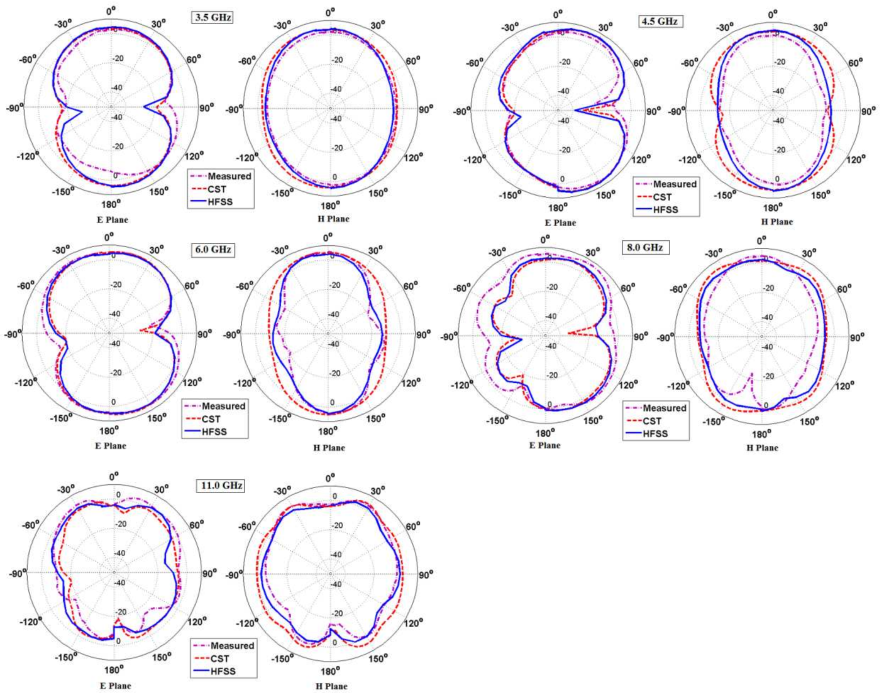


Figure 23. Measured and simulated radiation pattern of antenna with Cross-Hair type EBG.

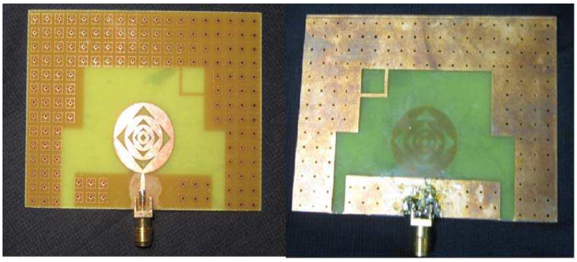


Figure 24. Fabricated prototype of antenna with Swastika-type EBG.

frequency band of 2.2 GHz to 11.2 GHz. Thus, the bandwidth is 9 GHz which is around 129% at the centre frequency of 7 GHz. This is around 12% more in comparison to the antenna without EBG. Figure 26 shows the measured and simulated radiation pattern of antenna with Swastika type EBG at different frequencies. The radiation patterns in case of Swastika type EBG appear to be more stable and smooth

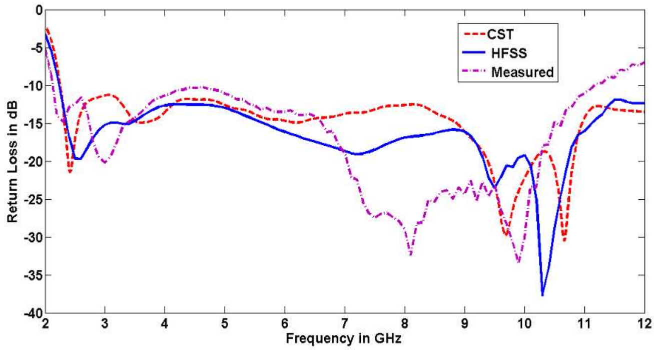


Figure 25. Return loss (dB) vs. frequency (GHz) of antenna with Swastika-type EBG.

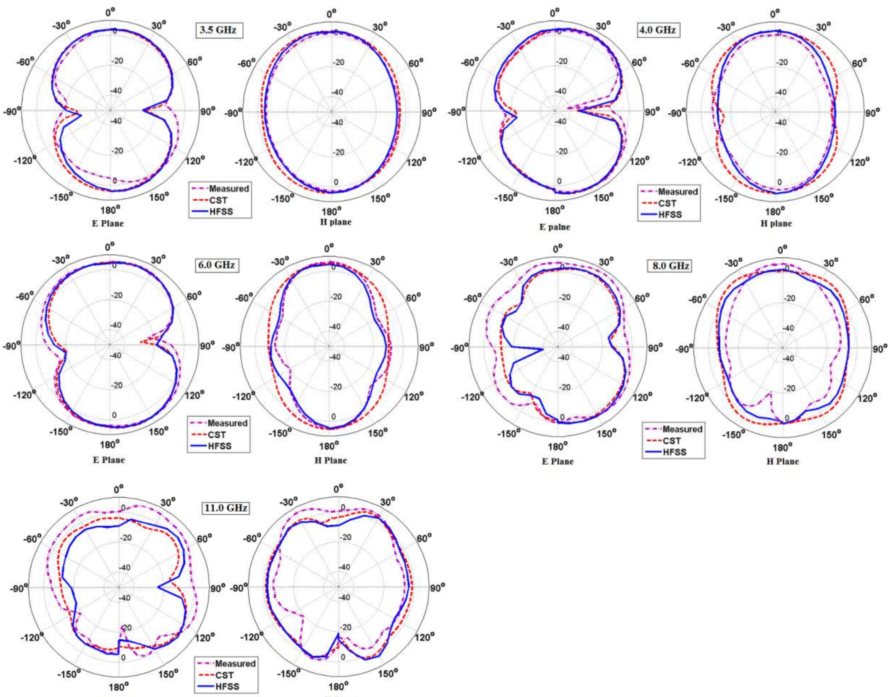


Figure 26. Measured and simulated radiation pattern of antenna with Swastika-type EBG.

in comparison to those obtained with Cross Hair type and Mushroom type EBGs.

7. COMPARISON OF THE THREE EBGs ON THE ANTENNA PERFORMANCE

A comparison of the characteristics of the antenna before and after applying each of the three EBG structures is discussed below.

7.1. Measured Return Loss

The measured return loss comparison for the three EBG structures is shown in Figure 27. As can be seen from the figure, all the antennas show the ultra wideband behaviour. The improvement in the return loss when EBG is applied to the antenna is clearly evident. The improvement in the return loss takes place in that frequency band where the EBG structure shows the maximum reflection and surface wave stop property (shown in Figure 14). This is due to the suppression of surface waves in that frequency band that leads to better impedance matching and hence better returns loss.

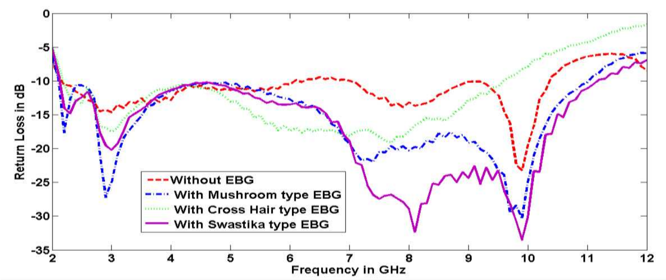
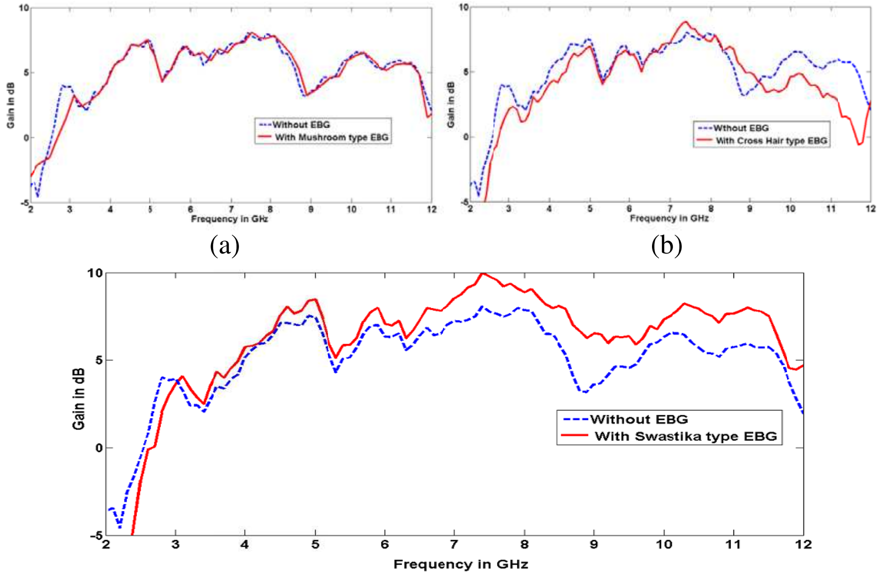


Figure 27. Measured return loss comparison of antenna without and with all the three types of EBG.

7.2. Measured Gain

The measured gain comparison for the three EBG structures is shown in Figure 28. It can be seen from the figure that there is a gain improvement after using the EBG. Again, the improvement in the gain takes place in that frequency band where the EBG material shows the maximum reflection and surface wave stop property and for reasons explained above. The maximum gain improvement is seen with Swastika type EBG which is around 2–3 dB.



(a) (b)

(c)

Figure 28. Measured gain comparison of antenna without and with (a) Mushroom type EBG, (b) Cross Hair type EBG and (c) Swastika type EBG.

8. CONCLUSION

An ultra wideband antenna based on the application of fractal geometry on a circular patch is designed and experimentally validated. To improve the impedance bandwidth and gain characteristics, a compact size Swastika-shape EBG having stop bandwidth (−20 dB) of 3.6 GHz is proposed. The impedance bandwidth (measured) of the antenna is 117% without EBG (2.2 GHz–10.4 GHz) and 129% (2.2 GHz–11.1 GHz) with the proposed EBG. The peak gain of the antenna increases by 2–3 dB with the proposed EBG. The radiation patterns of the antenna are dumbbell-shaped in the E plane and Omni-directional in the H plane. The antenna along with the proposed EBG can be useful for ultra wideband application such as medical imaging, vehicular radar and for Electronic warfare applications.

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