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Design and Development of an Efficient EBG Structures Based Band Notched UWB Circular Monopole Antenna

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Abstract Band notched circular monopole antennas for ultra-wide band applications are proposed in this paper. The proposed antennas in this paper can reject worldwide interoperability for microwave access WiMAX band (3.3–3.8 GHz) and wireless local area network WLAN band (5–6 GHz). Antennas utilises mushroom-type electromagnetic band gap (EBG) structures and I-slot embedded edge located via (ELV) EBG structures to achieve band-notched designs. The advantages of band notched designs using EBG structures like notch-frequency tuning, dual-notch antenna designs and stable radiation pattern are also verified. Various antenna designs with slot in EBG structures, variations in placement of EBG structures, number of EBG structures and ELV type EBG structures are simulated. About 30% reduction in size of EBG structures is obtained if conventional mushroom type EBG is replaced by proposed I-slot embedded ELV-EBG structure. Fabricated and measured results are in good agreement with simulated ones.

Keywords Dispersion diagram · Electromagnetic band gap (EBG) · Notch band · Reflection phase · Ultra wide band (UWB) antenna

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1 Introduction

Features like low profile, inexpensive to manufacture and compatible with monolithic microwave integrated circuits (MMIC) design have made microstrip antenna considerably useful while the major concern of such antennas being lower bandwidth. Since 2002, when the Federal communication commission (FCC) released the bandwidth 3.1–10.6 GHz, there has been increasing interest in the use of UWB systems because of their low power consumption, low cost, precise positioning and promising candidate for short-range high-speed indoor data communications [1–3]. Planar circular monopoles have been found a good example for UWB applications due to their merits such as ease of fabrication, Acceptable radiation pattern, and large impedance bandwidth.

However, some narrowband systems also operate in this frequency like WiMAX (3.3–3.8 GHz) and WLAN (5–6 GHz) and cause interference in UWB range. To overcome any interference with these systems it is desirable to design UWB antenna with band notch characteristics. Various methods have been proposed for band notch designs like cutting slots in patch/ground plane [4–7], putting parasitic elements near patch [8, 9], using tuning stub [10], embedding resonant cells in microstrip feed line [11] and putting filter structures in the ground planes or in antenna feed [12]. The problems with these methods are design specific approach and poor notch width controlling. Furthermore, radiation pattern of antenna and time domain behavior of antenna gets affected using perturbations in radiating elements.

The proposed approach makes use of bandgap property of EBG by placing these structures near microstrip feed line. In this paper property of EBG structures are utilized in substrate design and with the aid of dispersion diagram [13], its band-gap is obtained. EBG structures constitute a specific class of recently discovered microwave objects; Due to their special electromagnetic behavior these provide promising solutions to several microwave problems, especially in the area of communications. Microstrip patch antennas if used with EBG structures can provide a directive radiation pattern with increase in the directivity of the main lobe by minimizing the radiation in undesired direction. EBG structures are being used to reduce mutual coupling between two radiating elements provided they are operated in their band gap [14].

EBG structures can acts as an efficient substitute of conventional ground plane in low-profile antennas [15] since the radiation efficiency of a low-profile wire antenna is very poor when a conventional electrical conductor is used as a ground plane. This is because of far-zone destructive interference of wire field and field generated by image current of ground plane. Alternatively it can also be said that the ground plane can be considered to be an ideal conductor, which is useful as a reflector but it causes phase reversal of the reflected wave due to its negative reflection coefficient. Ideal conductor also supports propagation of TM surface waves which has detrimental effects on antenna performance. This is analogous to concluding that the image currents in the conductive sheet cancel the currents in the antenna, resulting in poor radiation. EBG structures can acts as an efficient substitute of conventional ground plane in Low–profile antennas [15], however limited research is done on their property of obtaining notches in UWB antenna.

Researchers in [16, 17] proposed UWB antenna with one or two notches with EBG structures but within a WLAN band only. The authors in [16] used four EBG structures to obtain single notch. Placement of WiMAX EBG cells without effecting WLAN notched frequencies is a challenge. In [17] neither notch width nor notch locations are justified using dispersion diagram. Notched frequency in [17] is even not related with formulas for inductance and capacitance. MIMO (Multi input multi output) antennas with dual notches both in WiMAX and WLAN bands without modifying radiators are also a requirement. In [18] MIMO antennas with notched characteristics were studied without modifying the radiator but suppress interference from the WLAN systems only. In [19] a two layer EBG structures for reducing the mutual coupling between two closely spaced UWB antennas on a common ground plane is shown. In [20] reconfigurable band notched antenna with EBG structures is proposed. Miniaturized EBG structures [21] have also been used for different applications. The proposed method of obtaining notches in this paper can also be extended to work like a dual notched MIMO antenna with reduced mutual coupling among individual antenna elements. Multi notches antennas with antennas design specific approach are discussed by various researchers in [22–24]. With size reduction of EBG structures triple and quad notched antenna designs can also be obtained without altering the radiator.

This paper presents Dual notch UWB circular Monopole antenna with notch in both WiMAX and WLAN bands. The paper begins by designing a simple Circular UWB monopole antenna. Dispersion diagrams are used to obtain the band gaps of different EBG structures. Then, UWB designs with EBG structures are shown and lastly size reduction of EBG structure with I-slot embedded ELV-EBG type is proposed.

2 Conventional Antenna Design

A circular monopole microstrip antenna [25] with a defected ground plane is known as Common UWB planar antenna structure shown in Fig. 1.

This antenna acts as a basic Structure for further designs and only EBG unit cells are placed in the vicinity of microstrip line without affecting the dimensions of basic structures in antenna 2 to antenna 6. All antennas proposed are designed on low cost substrate FR-4 with dielectric constant (ε_r) 4.4, height = 1.6 mm and loss tangent of 0.02. The antenna design parameters are shown in Table 1.

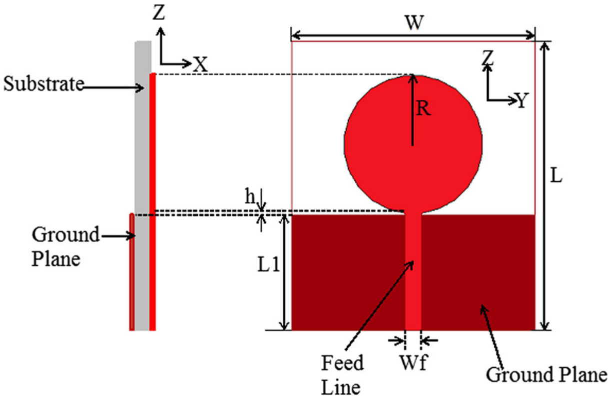


Fig. 1 Geometry of circular UWB monopole antenna (antenna 1)

Table 1 Antenna design parameters

S.no	Optimized parameters (mm)	Antenna 1	Antenna 2	Antenna 3	Antenna 4	Antenna 5	Antenna 6
1	R	12	12	12	12	12	12
2	L_1	20	20	20	20	20	20
3	W	42	42	42	42	42	42
4	L	50	50	50	50	50	50
5	W_f	3	3	3	3	3	3
6	h	0.3	0.3	0.3	0.3	0.3	0.3
7	2r	1	1	1	1	1	1
8	W_1	NA	9.25	NA	9.25	NA	NA
9	g_1	NA	3.05	5	0.75	5	5
10	d_1	NA	0.3	0.25	0.3	0.2	0.2
11	W_2	NA	NA	6.1	6.1	NA	NA
12	g_2	NA	NA	NA	0.45	NA	NA
13	d_2	NA	NA	NA	0.25	NA	NA
14	d_3	NA	NA	NA	NA	5.7	4.7
15	d_4	NA	NA	NA	NA	5.7	2.37
16	d_5	NA	NA	NA	NA	3	0.85
17	d_6	NA	NA	NA	NA	1.35	3
18	d_7	NA	NA	NA	NA	1.35	0.85
19	d_8	NA	NA	NA	NA	0.3	1
20	d_9	NA	NA	NA	NA	1	0.3
21	d_{10}	NA	NA	NA	NA	NA	4.7
22	d_{11}	NA	NA	NA	NA	NA	1.75

3 Selective Band Gap Formation with EBG Structures for Propagating Surface Waves

EBG structures are a kind of frequency selective surface also known as artificial magnetic conductor (AMC) or high impedance surface (HIS). These structures acts as band stop filters in a specific band gap, at the same time provides very high impedance hence given the name high impedance surface [26–30]. Mushroom EBG structure consists of metallic

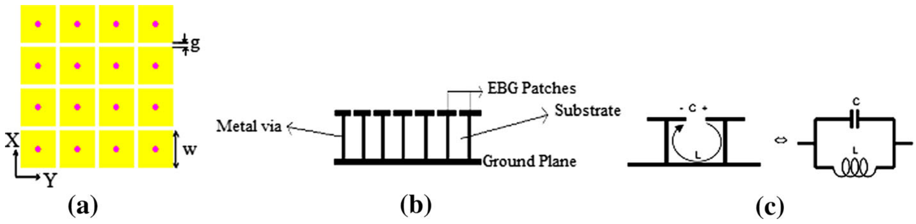


Fig. 2 Geometry of EBG-like surface. **a** Top view, **b** side view, **c** equivalent circuit

patches and shorted pins named via that connect patches into the ground planes as shown in Fig. 2. The operation of mushroom EBG can be seen as a LC filter where L is due to current flow through via and C is due to gap effect between adjacent patches. The various parameters of Mushroom EBG structures are formulated in Eq. 1–5 [31].

$$L = 0.2h\left[\ln\left(\frac{2h}{r}\right) - 0.75\right] \tag{1}$$

$$C = \varepsilon_0 \varepsilon_r \frac{w^2}{h} \tag{2}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{3}$$

$$BW = \frac{1}{\eta}\sqrt{\frac{L}{C}} = \frac{\Delta\omega}{\omega_0} \tag{4}$$

where $\eta = 120\pi$ is the free space impedance. Frequency dependence of surface impedance may be written as

$$Z_S = \frac{j\omega L}{1 - \omega^2 LC} \tag{5}$$

Practically near the resonant frequency there is a stop band for surface waves (in the region where the propagation factor for the TM wave is very large but TE waves still cannot propagate). However to fully characterize the mushroom structure and to conform its CRLH (combined right/left handed) a dispersion diagram is required.

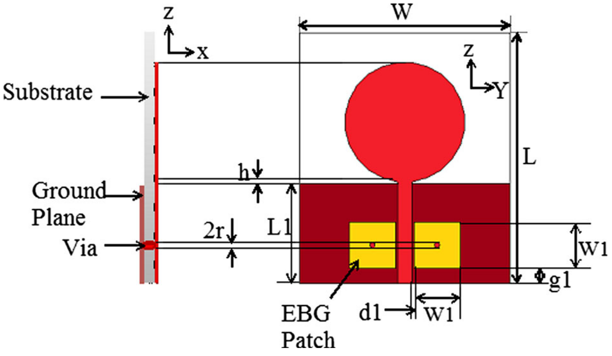


Fig. 3 Geometry of circular UWB antenna with notch in WiMAX band (antenna 2)

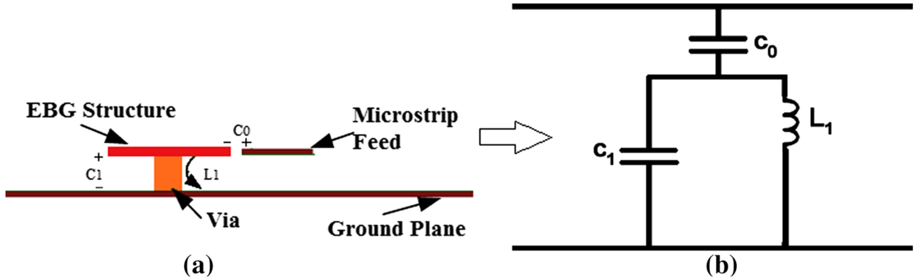


Fig. 4 **a** EBG structure in the vicinity of transmission line, **b** equivalent circuit

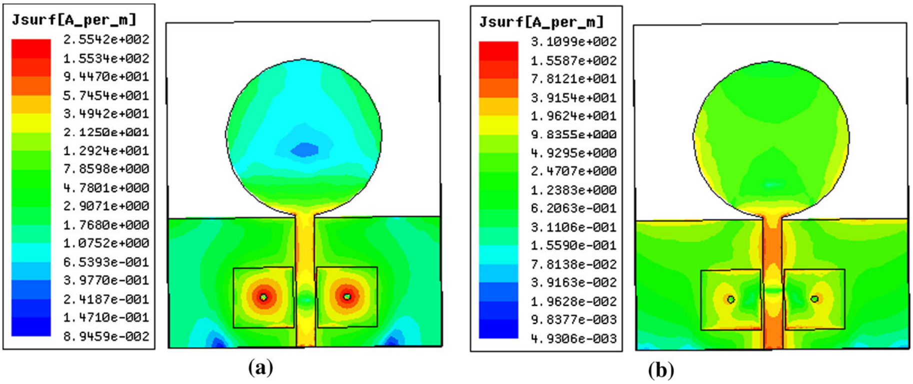


Fig. 5 Surface current distribution of UWB circular monopole antenna with EBG for notch in WiMAX band. **a** 3.5 GHz, **b** 5.5 GHz

4 UWB Monopole with Notch in WiMAX Band

When there exists only one interference band in the UWB operating band then UWB with single notch is required. Hence the EBG unit cells can be placed in the vicinity of microstrip feed to obtain the desired notch. Figure 3 shows the dimensions of prototype UWB antenna with notch in WiMAX band. Figure 4 shows the equivalent circuit of EBG cell [16] in the vicinity of microstrip feed and Eq. 6 gives the resonant frequency which is analogous to Eq. 3. The simulated current distribution of antenna 2 is shown in Fig. 5 for further investigations. The operational mechanism of antenna 1 and antenna 2 are identical. It can be seen easily in Fig. 5 that EBG structures have a little effect on surface current outside their band gap.

$$f_r = \frac{1}{2\pi\sqrt{L_1(C_1 + C_0)}} \tag{6}$$

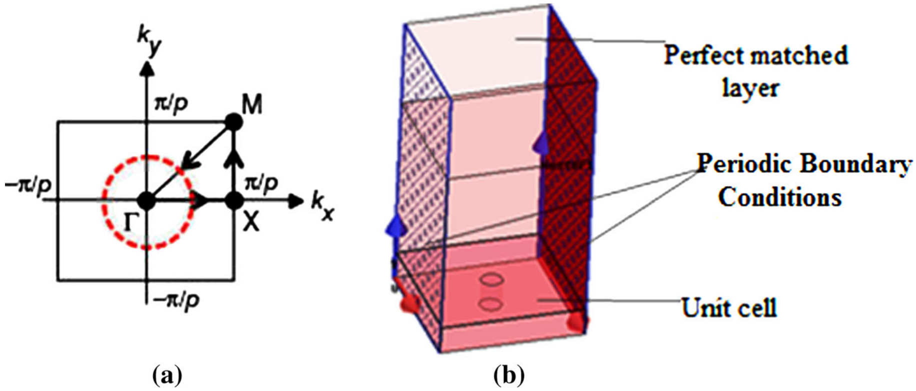


Fig. 6 **a** Representation of reciprocal space with physical space, **b** HFSS model to plot dispersion diagram

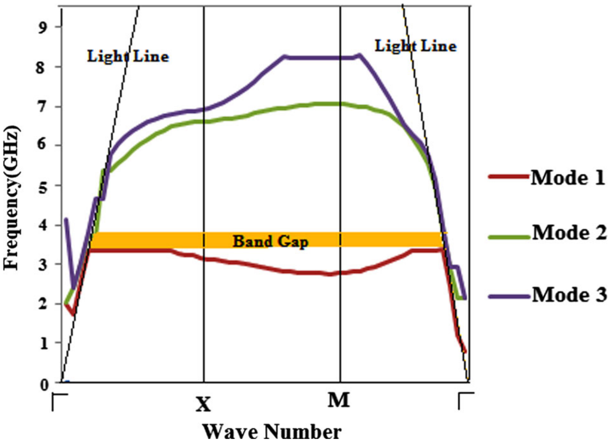


Fig. 7 Dispersion Brillouin diagram of mushroom type EBG structure obtained by HFSS with periodic boundary conditions

To generate the dispersion diagram one has to move along the path given below of irreducible Brillouin zone shown in Fig. 6 and no source excitations are required for this approach.

The path traced is as given below:

$$\Gamma\text{-X}\ (\mathrm{K_x} = 0^\circ, \mathrm{K_y} = 0^\circ \rightarrow 180^\circ)$$
$$\text{X-M}\ (\mathrm{K_x} = 0^\circ \rightarrow 180^\circ, \mathrm{K_y} = 180^\circ)$$
$$\text{M-}\Gamma\ (\mathrm{K_x}, \mathrm{K_y} : 0^\circ \rightarrow 180^\circ)$$

where $\mathrm{K_x}$ = phase offset in x-direction, $\mathrm{K_y}$ = phase offset in y-direction.

In particular a two-dimensional dispersion diagram is desired in order to observe the unit-cell propagation constants for different angles of propagation. HFSS's Eigen mode

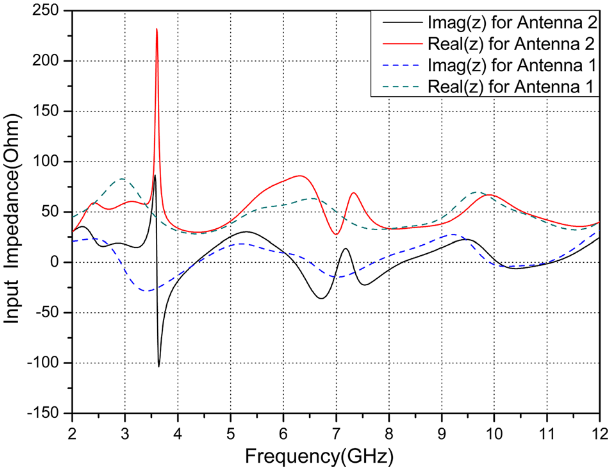


Fig. 8 Variation of input impedance of antenna 1 and antenna 2(WiMAX notch)

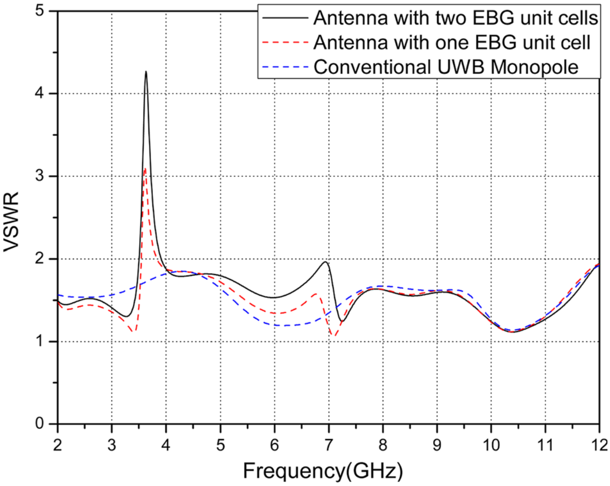


Fig. 9 VSWR of antenna 2 with notch in WiMAX bands with one and two EBG

solver is used. The dimensions of squared unit cell used to plot Fig. 7 have length and width equals to W_1. Figure 7 shows it's dispersion diagram with band gap in WiMAX frequency range.

Figure 8 shows the high impedance mismatch in WiMAX band. The real and imaginary parts of input impedance of antenna 2 in the band gap are 239.02 and 84.35 Ω at 3.6 and 3.55 GHz respectively. The real and imaginary part of antenna 1 lies around 50 and 0 Ω respectively.

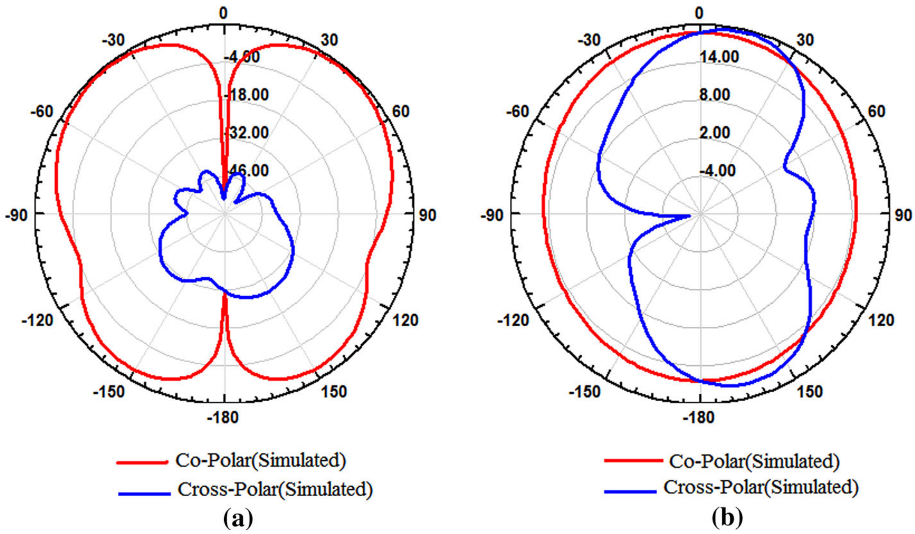


Fig. 10 E-plane and H-plane radiation pattern of WIMAX notch antenna 2 at 5.5 GHz

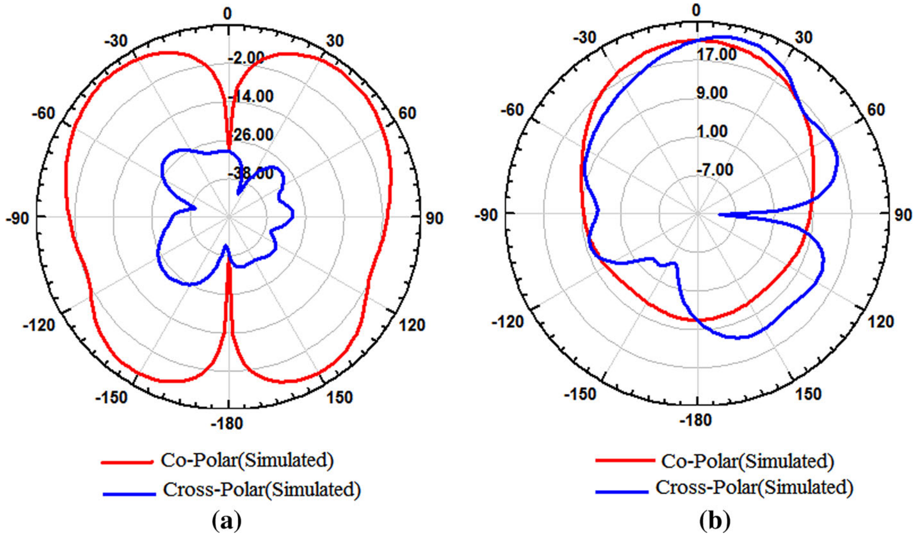
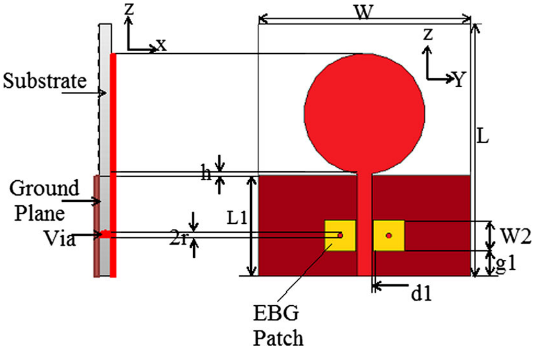


Fig. 11 E-plane and H-plane radiation pattern of WIMAX notch antenna 2 at 7.2 GHz

Figure 9 shows the VSWR of antenna 2 with one and two EBG unit cell. It can be seen that though one EBG cell can be used to obtain notch band characteristics but magnitude of VSWR increases if two EBG cells are used. Antenna 2 acts as UWB antenna but has a notch in WiMAX band centered at 3.55 GHz with a VSWR of 4.47. All simulations are carried out using Ansoft HFSS v.14 [32].

Fig. 12 Geometry of circular UWB antenna with notch in WLAN band (antenna 3)



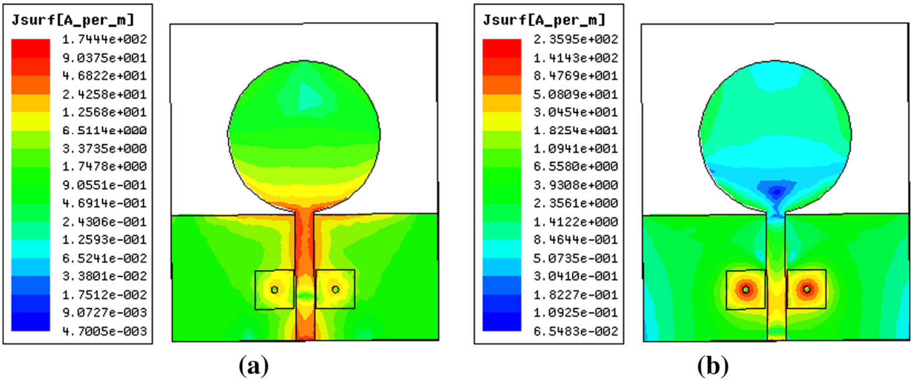
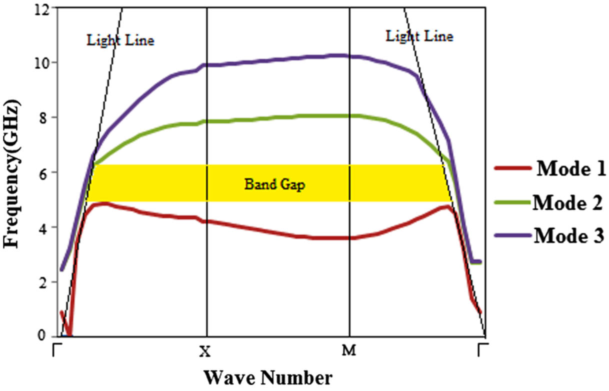


Fig. 13 Surface current distribution of UWB circular monopole antenna with EBG for notch in WLAN band. **a** 3.5 GHz, **b** 5.5 GHz

Fig. 14 Dispersion Brillouin diagram of mushroom type EBG structure obtained by HFSS with periodic boundary conditions



The radiation pattern of antenna 2 is shown at 5.5 and 7.2 GHz in Figs. 10 and 11 respectively. Generally speaking, the radiation patterns in E-plane are roughly a dumbbell shape and the patterns in H-plane are quite Omni-directional, as expected.

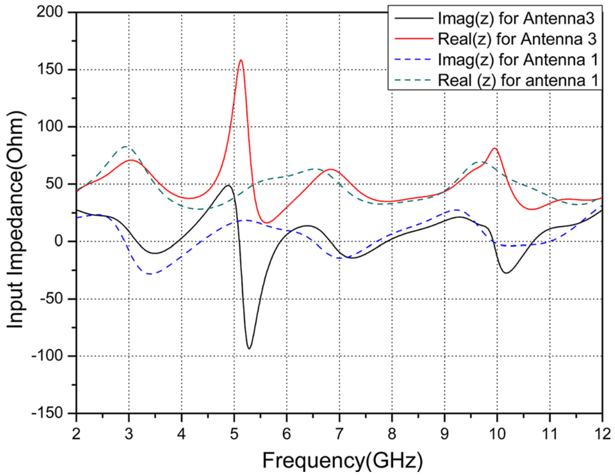


Fig. 15 Variation of input impedance of antenna 1 and antenna 2(WLAN notch)

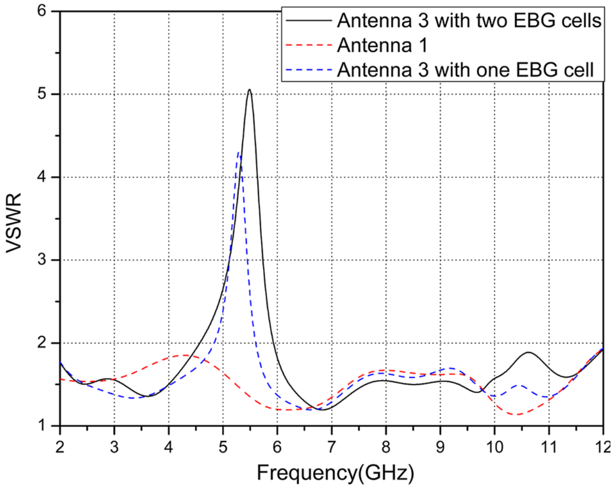
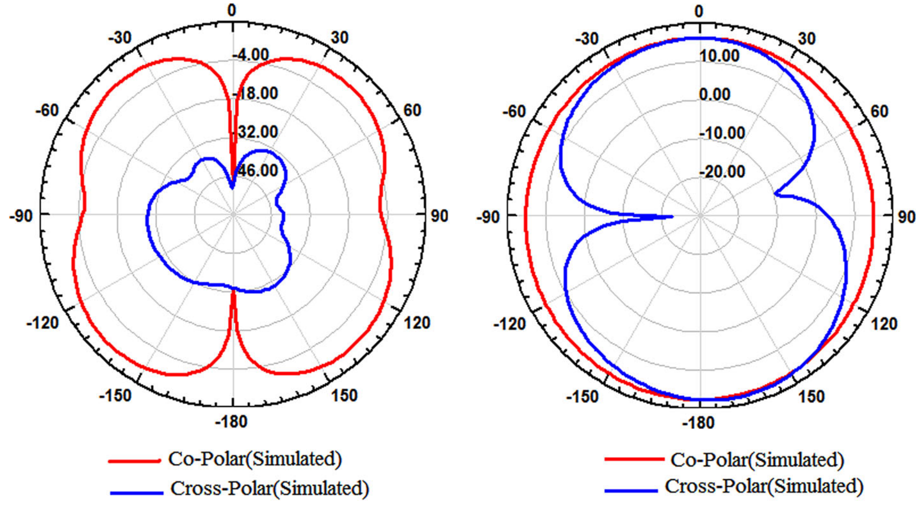


Fig. 16 VSWR of antenna 3 with notch in WLAN bands with one and two EBG unit cells

5 UWB Monopole with Notch in WLAN Band

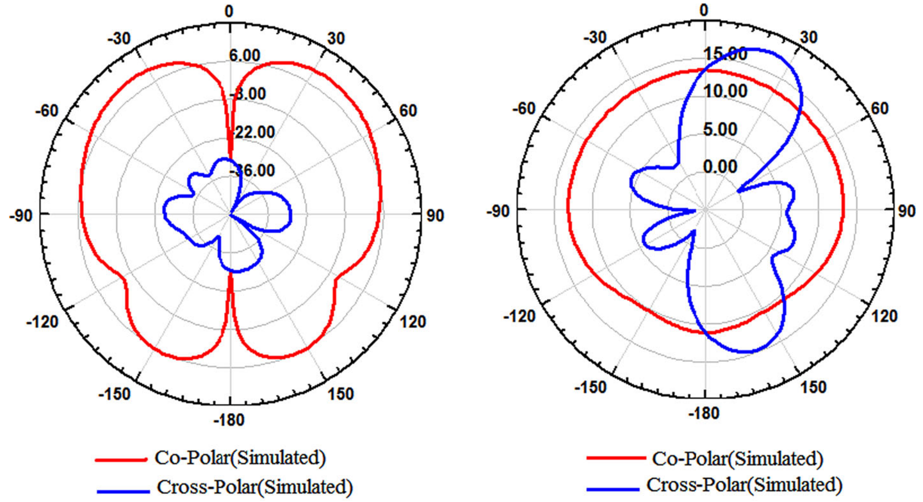
Figure 12 shows the dimensions of prototype UWB antenna with notch in WLAN band. Figure 13 shows the surface current distribution and it can be easily seen that EBG cells acts like band stop filter in WLAN band also. Figure 14 shows the dispersion diagram for WLAN EBG cell.

Figure 15 shows high input impedance mismatch of antenna 3 in WLAN band with real and imaginary part as 163.99 and 49.1 Ω at 5.1 and 5 GHz respectively. Figure 16 shows VSWR of antenna 3 with WLAN notch band centered at 5.4 GHz with VSWR value as 5.18. Figures 17 and 18 shows the radiation pattern of antenna 3 at 3.5 and 6.7 GHz respectively.



(a) (b)

Fig. 17 E-plane and H-plane radiation pattern of circular monopole antenna 3 at 3.5 GHz



(a) (b)

Fig. 18 E-plane and H-plane radiation pattern of circular monopole antenna 3 at 6.7 GHz

6 UWB Monopole with Notch in Both WiMAX and WLAN Band

In application where it is desired to have notch in both WiMAX and WLAN bands, the EBG structures set up for that is shown in Fig. 19. Figure 20 shows the surface current distribution of antenna 4 with EBG structures. It is clearly visible that at 3.5 GHz maximum current is concentrated at bigger EBG unit cells used for WiMAX band notch.

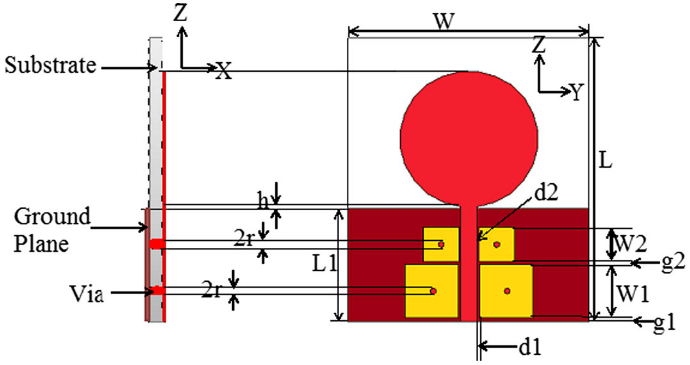


Fig. 19 Geometry of circular UWB antenna with notch in botch WiMAX and WLAN band (antenna 4)

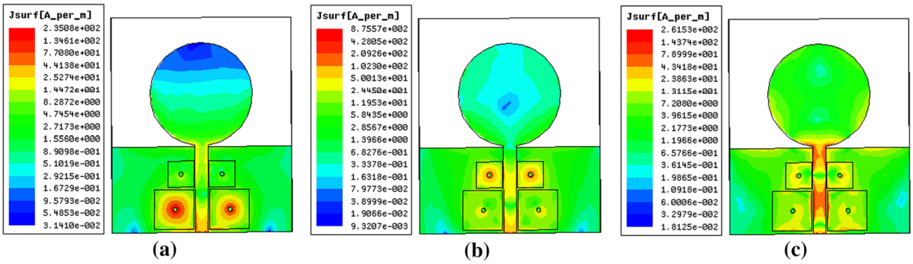


Fig. 20 Surface current distribution of UWB circular monopole antenna 4 with EBG for WLAN and WiMAX notch band applications. **a** 3.5 GHz, **b** 5.5 GHz, **c** 7.5 GHz

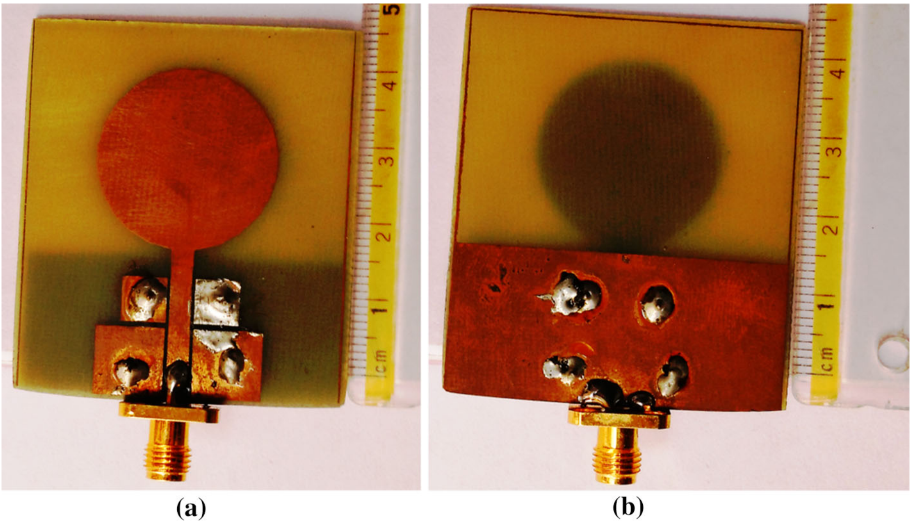


Fig. 21 **a** Top view, **b** bottom view of fabricated prototype of antenna 4

Furthermore at 5.5 GHz maximum current is concentrated at smaller EBG used for WLAN band notch. As expected at 7.5 GHz maximum current is propagated to the radiating element. It has been demonstrated in that the optimal design of this type of antenna can

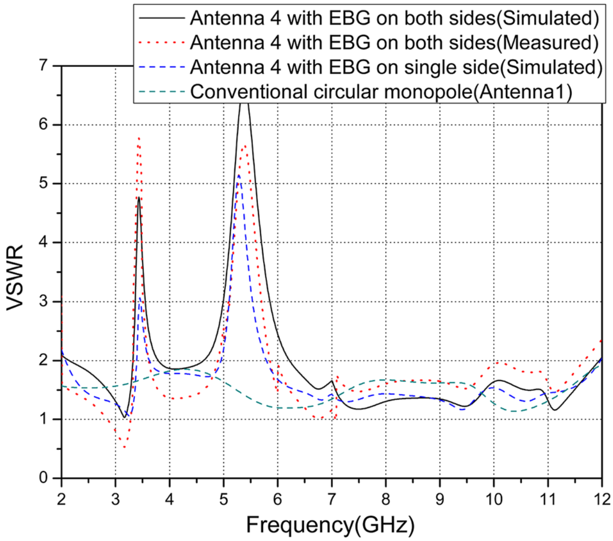


Fig. 22 VSWR of Antenna4 with notch in WiMAX and WLAN bands with EBG unit cells on one and two sides of microstrip line

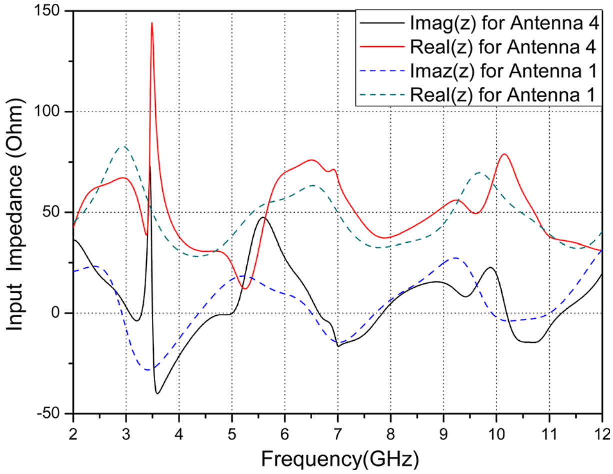


Fig. 23 Variation of input impedance of antenna 1 and antenna 4

achieve an ultra-wide bandwidth with satisfactory radiation properties and band rejections. Furthermore, the simulations have also shown that the proposed monopole antennas are non-dispersive, which is very important for UWB systems. Figure 21 shows the fabricated prototype of antenna 4. The VSWR of fabricated antennas are measured using Agilent$^{\text{TM}}$ Network analyzer PNA-L series.

Figure 22 shows the VSWR of antenna 4 with one and two EBG unit cells with dual notches. It can be seen that though one EBG cell can be used to obtain notch band characteristics but magnitude of VSWR increases if two EBG cells are used. The notch in

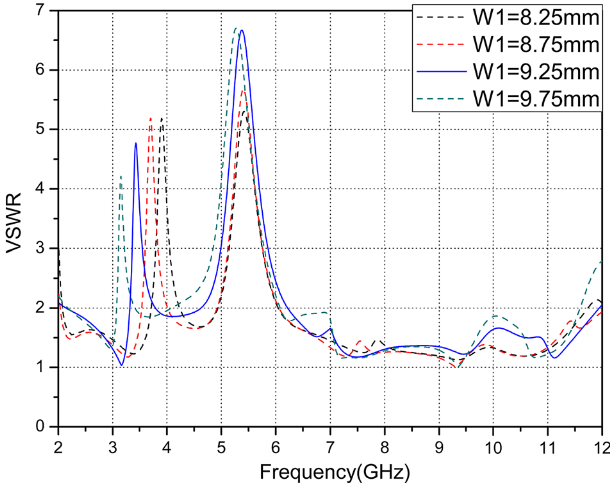


Fig. 24 Effect of variation of Size of EBG unit cell used for WiMAX notch in antenna 4 while EBG cells for WLAN band intact

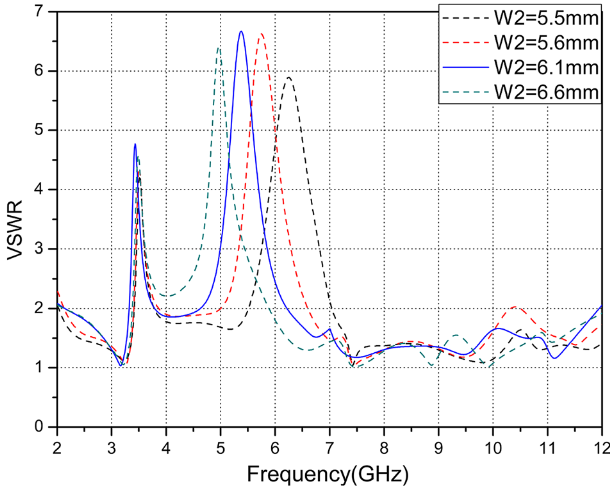


Fig. 25 Effect of variation of size of EBG unit cell used for WLAN notch in antenna 4 while EBG cells for WiMAX band kept intact

WiMAX band is centered at 3.44 GHz with VSWR value of 4.74 and in WLAN band the notch is centered at 5.4 GHz with VSWR value of 6.67. The measured values of VSWR at 3.44 and 5.4 GHz are found to be as 5.74 and 5.67 respectively.

Figure 23 shows that the real and imaginary parts of input impedance of antenna 4 in the WiMAX band gap are 144 and 72 Ω at 3.5 and 3.45 GHz respectively. The real and imaginary parts of input impedance of antenna 4 in WLAN notch band gap are 69.5 and 47.37 Ω at 5.9 and 5.6 GHz respectively. The radiation mechanism of antenna can be understood from input impedance versus frequency plots of antenna shown in Fig. 23. It

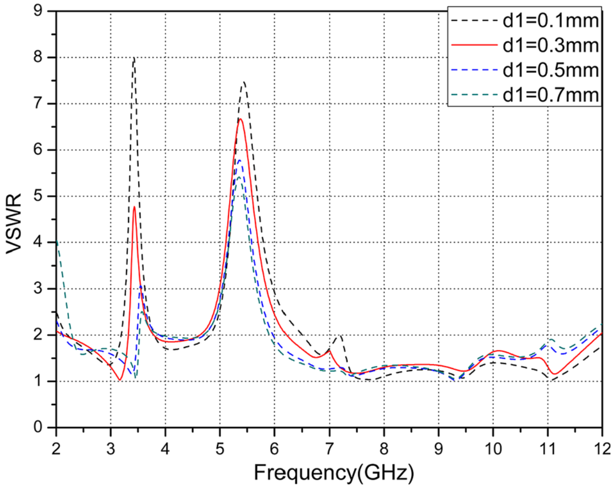


Fig. 26 Effect of variation of Size of distance (d_1) b/w microstrip feed and EBG unit cell for WiMAX notch

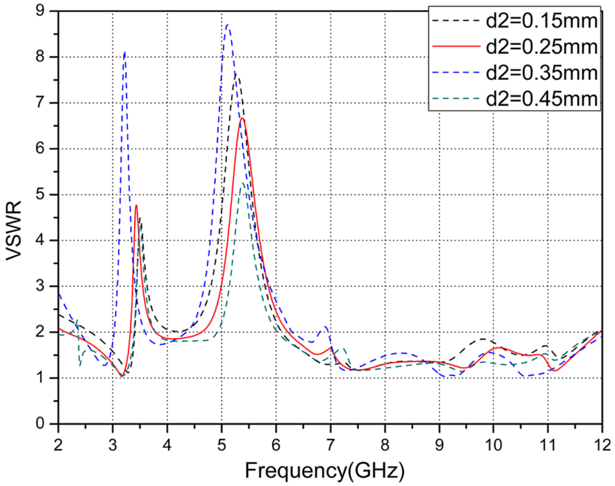


Fig. 27 Effect of variation of Size of distance (d_2) b/w microstrip feed and EBG unit cell for WLAN notch

can be seen that real and imaginary part of antenna 1 without EBG and antenna 4 outside the band gap of EBG lies around 50 and 0 Ω respectively. However, in the EBG band gap of antenna 4 there is a high mismatch in both real and imaginary parts of antenna, hence input power does not get transmitted to antenna and no radiation takes place.

Figure 24 shows variation of VSWR with variations of size of square EBG which is used for WiMAX notch applications. It is shown that as the size of EBG patch (W_1) increases the approximate capacitance associated with it increases using Eq. 2 and thereby decreasing the Resonant frequency (f_r) given in Eq. 6. Similarly, Fig. 25 shows the effect of variation of size of EBG patch (W_2) for WLAN notch band applications. Figures 26 and

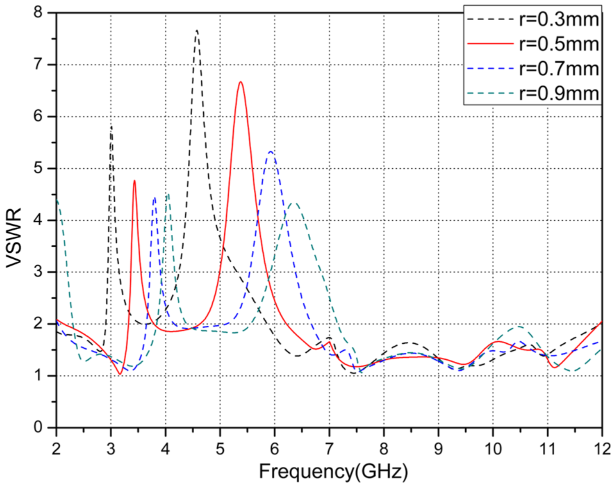


Fig. 28 Effect of variation of radius (r) of EBG unit cells

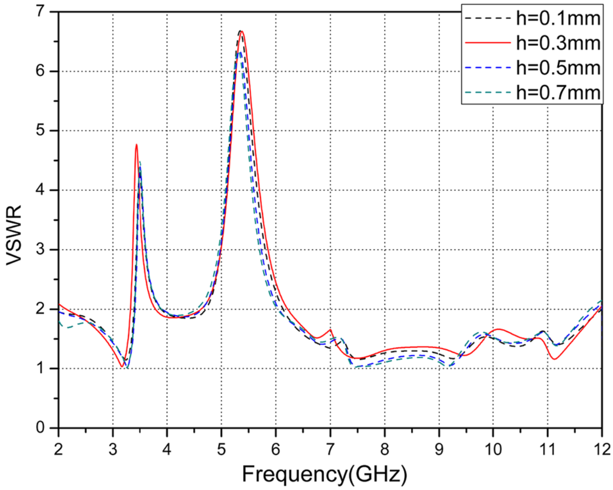


Fig. 29 Effect of variation of gap between ground and circular disc (h)

27 shows the variation in VSWR and Frequency when d_1 and d_2 i.e. gap between EBG and microstrip feed are varied. It is observed that as the gap decreases the mutual coupling between microstrip feed and EBG structures increases and a strong band notch is obtained. Figure 28 shows that as the radius of via decreases the Center frequency of notched band shifts at lower frequency band. This can be easily verified using Eq. 1 and 6 i.e. as the radius of via (r) decreases the inductance associated with it (L) increases which thereby decreasing the resonant frequency (f_r) given in Eq. 6. The variation of parameters of antenna 4 i.e. h, g_1, g_2 causes little variations in notch bands as seen in Figs. 29, 30, and 31 respectively. Figure 32 presents the radiation pattern of antenna 4 at 3.1 GHz. The addition of EBG structures has little effect on radiation pattern. Though at high frequencies as

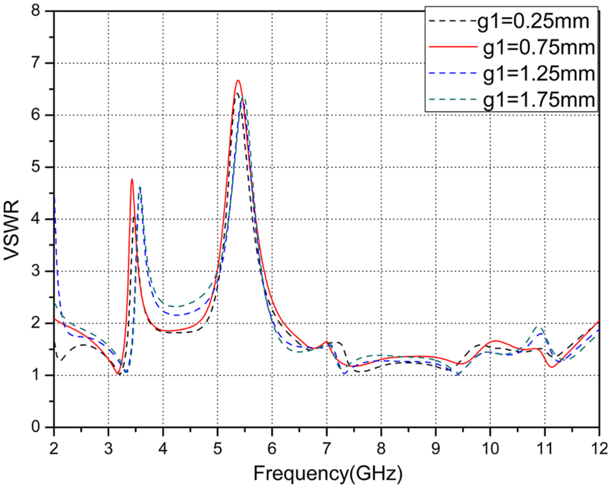


Fig. 30 Effect of variation of gap (g_1) between antenna feed and WiMAX band EBG

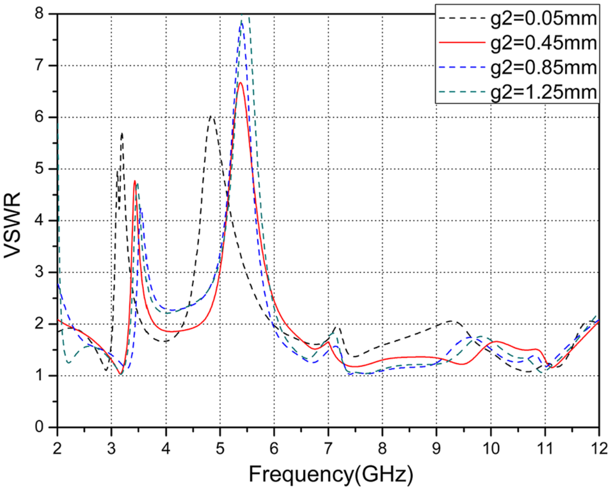


Fig. 31 Effect of variation of gap (g_2) between WiMAX and WLAN band EBG

shown in Fig. 33 at 7.5 GHz, in H-plane there is slight deviation in radiation pattern, however, generally the radiation pattern in E-plane is roughly dumbbell shape and the pattern in H-Plane is quite omnidirectional.

Figure 34 shows that gain of antenna 4 becomes negative at the notched frequencies.

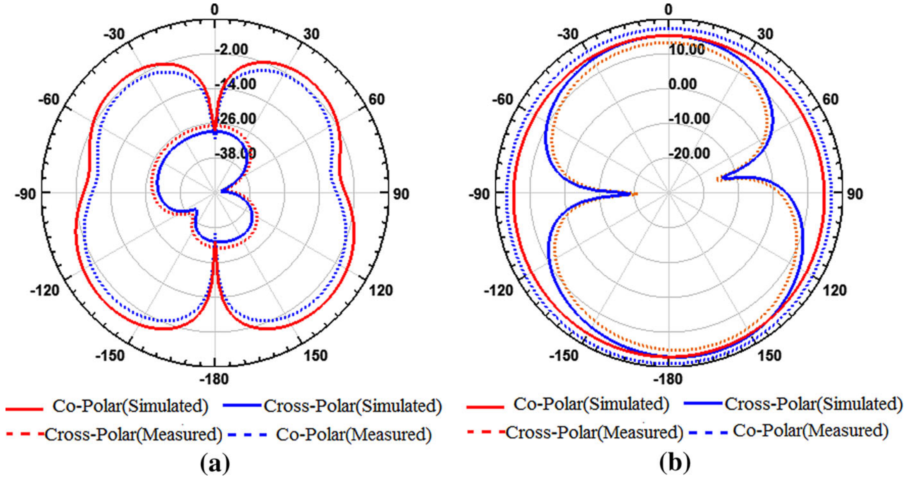


Fig. 32 E-plane and H-plane radiation pattern of WIMAX and WLAN notched antenna 4 at 3.1 GHz

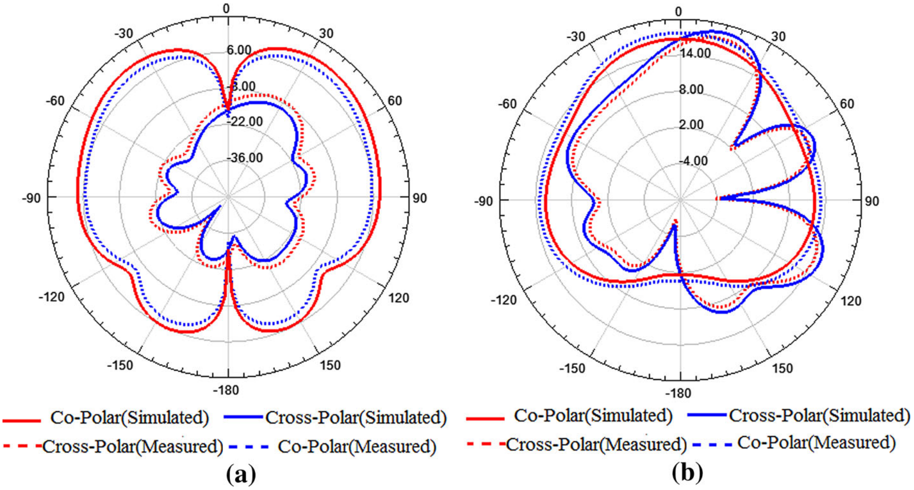


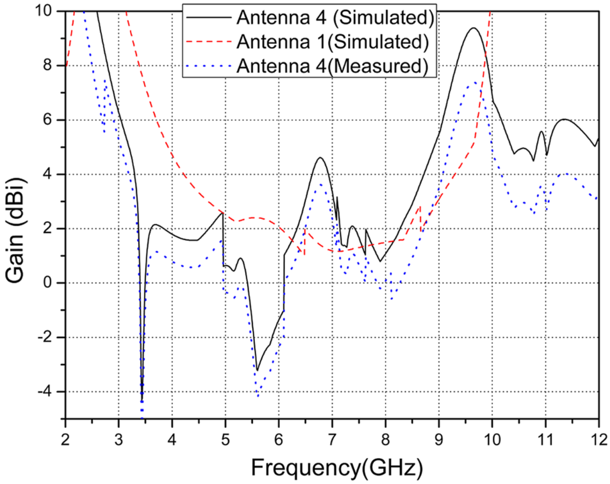
Fig. 33 E-plane and H-plane radiation pattern of antenna 4 at 7.5 GHz

7 WLAN Band Notched UWB Monopole with Reduced EBG Structures Size

Figure 35 shows that if any slot is made in the EBG structure, reduction in size of EBG structure can be obtained. Antenna 3 uses conventional Mushroom type EBG to obtain WLAN band notch with Edge length of unit cell as 6.1 mm which is reduced to 5.7 mm for antenna 5 and to 4.7 mm in antenna 6.

Figure 36 shows the simulated VSWR of antenna 3, antenna 5 and antenna 6. Measured VSWR of antenna 6 is also shown in the same figure. It can be seen that though one EBG

Fig. 34 Variation of gain with frequency for antenna 1 and 4



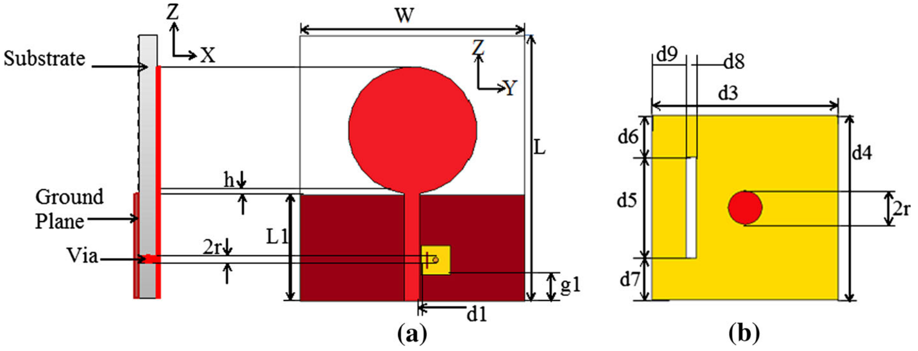
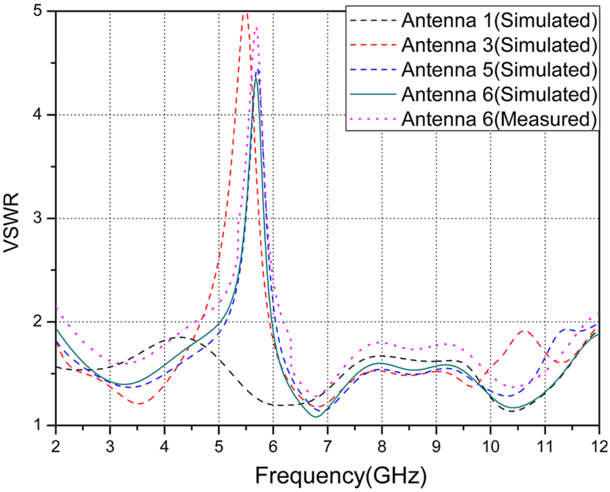


Fig. 35 Geometry of circular UWB antenna with notch in WLAN band. (antenna 5)

Fig. 36 VSWR of UWB circular antenna and proposed notch antenna with notch in WLAN band



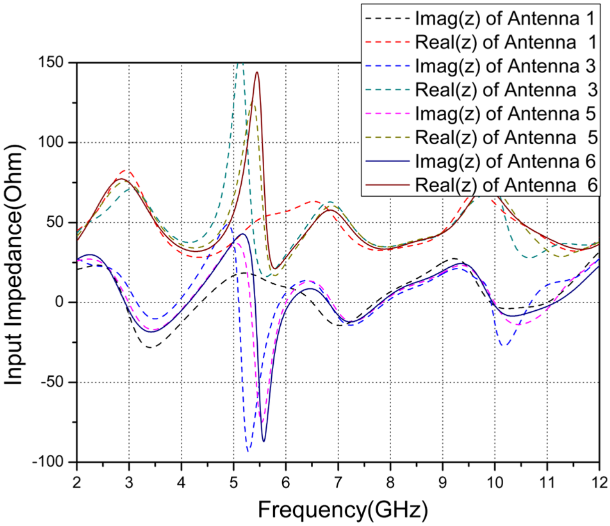


Fig. 37 Variation of input impedance of antenna 1 and antenna 3, antenna 5 and antenna 6

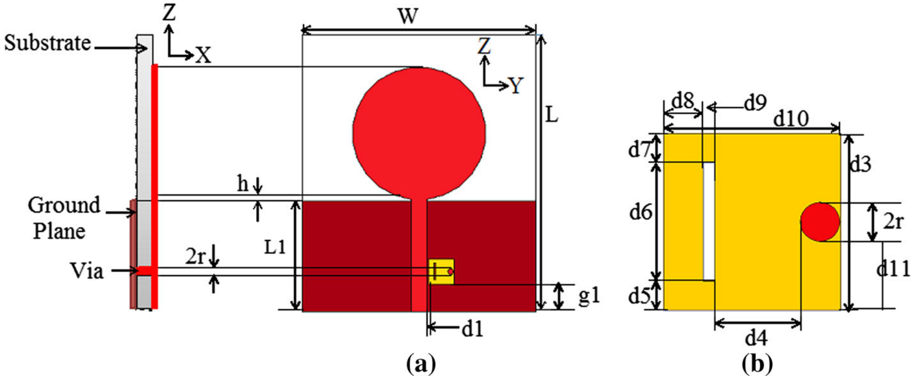


Fig. 38 Geometry of UWB antenna with notch in WLAN band with edge located via (antenna 6)

cell can be used to obtain notch band characteristics but magnitude of VSWR increases if two EBG cells are used.

Antenna 3 has a notch in WLAN band centered at 5.4 GHz with a VSWR of 5.18. Antenna 5 has a notch in WLAN band centered at 5.7 GHz with a VSWR of 4.45. Antenna 6 also has a notch in WLAN band centered at 5.7 GHz with a VSWR of 4.27. The measured value of antenna 6 shows a notch in WLAN band centered at 5.69 GHz with a VSWR of 4.84.

Antenna 5 and antenna 6 has a lower value of peak VSWR then antenna 3 where notch is centered in WLAN band. This is due to reason that in antenna 5 and antenna 6 only one EBG cell is used to obtain WLAN notch. Figure 37 shows the input impedance of antenna 1, antenna 3, antenna 5 and antenna 6. The real and imaginary parts of input impedance of antenna 6 in the band gap are 144.22 and 42.83 Ω at 5.45 and 5.2 GHz respectively. The real and imaginary part of antenna 6 lies around 50 and 0 Ω respectively outside WLAN

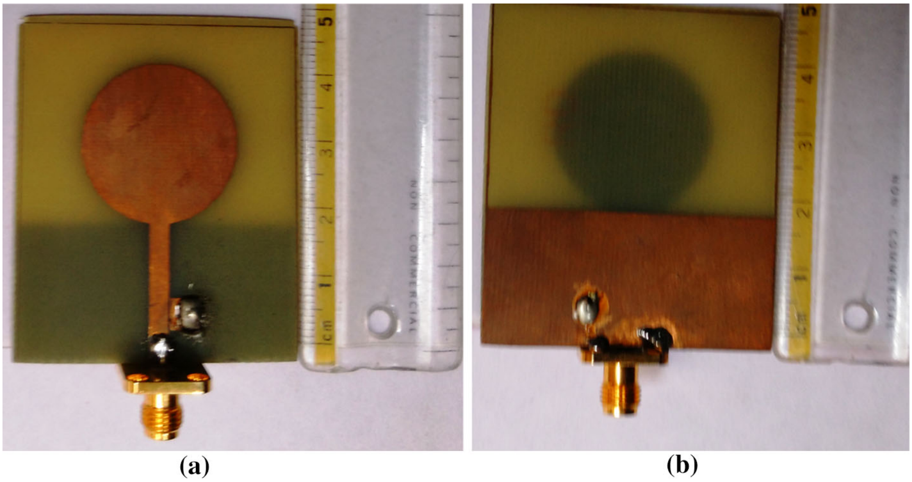


Fig. 39 **a** Top view, **b** bottom view of fabricated prototype of antenna 6

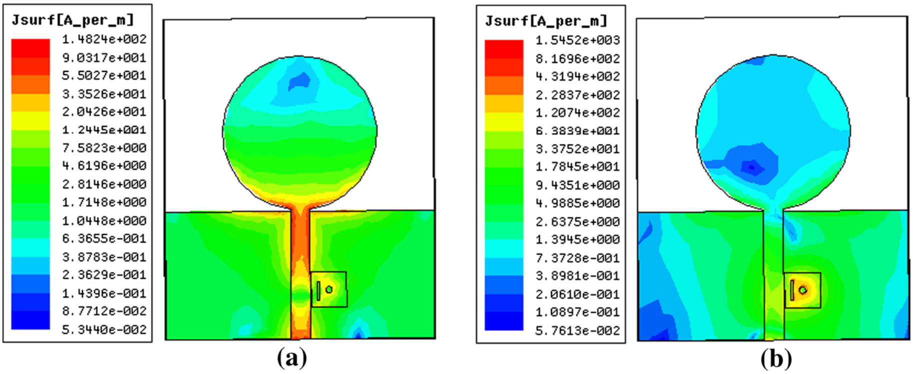


Fig. 40 Surface current distribution of UWB circular monopole antenna 5. **a** 3.5 GHz, **b** 5.5 GHz

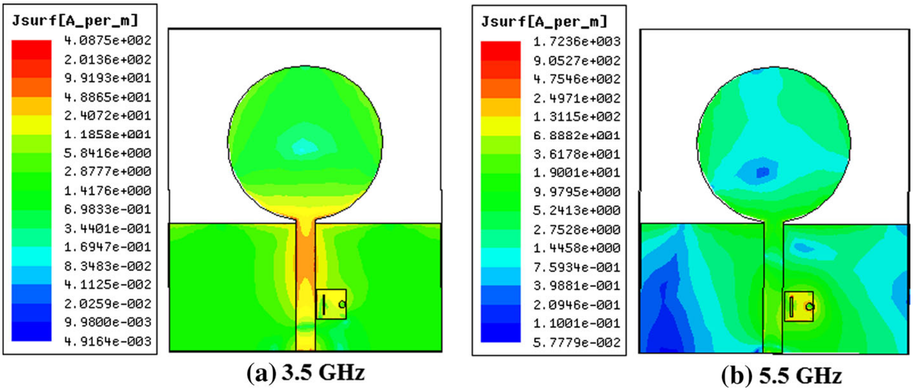
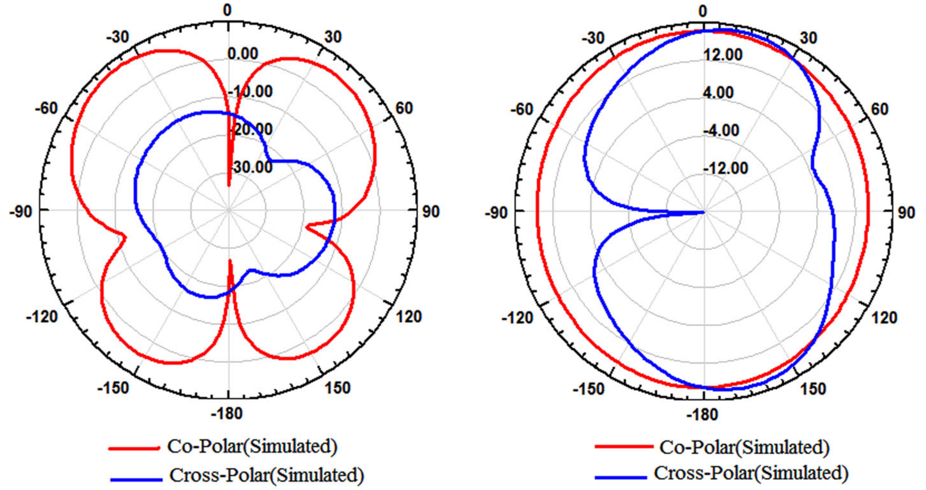
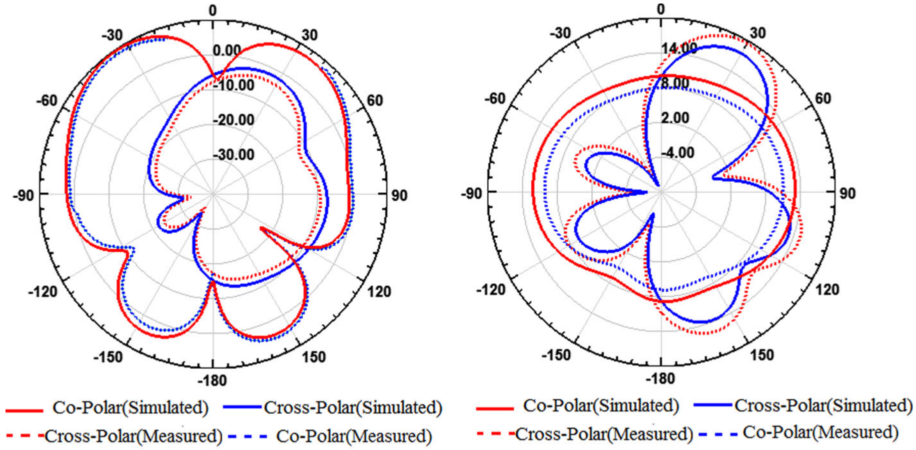


Fig. 41 Surface current distribution of UWB circular monopole antenna 6. **a** 3.5 GHz, **b** 5.5 GHz



(a) (b)

Fig. 42 E-plane and H-plane radiation pattern of antenna 5 at 5 GHz



(a) (b)

Fig. 43 E-plane and H-plane radiation pattern of antenna 6 at 7 GHz

band. Figure 38 shows reduction in size of EBG structure by about 30%, changing the position of metallic via of slotted mushroom from center to its edge, the bandgap moves towards lower frequencies [33]. Figure 39 shows the fabricated prototype of Antenna 6 with slot loaded ELV-EBG. Figure 40 shows clearly that slot loaded EBG cell in antenna 5 acts as a WLAN band stop filter with maximum current distribution at 5.5 GHz. Figure 41 shows the current distribution on antenna 6 with slot loaded ELV-EBG at 3.5 and 5.5 GHz. Figure 42 shows the radiation pattern of antenna 5 at 5 GHz and Fig. 43 shows the simulated and measured radiation pattern of antenna 6 at 7 GHz.

8 Conclusion

In this paper Dual notch UWB circular Monopole antenna with notch in both WiMAX and WLAN bands is presented. Initially, a conventional simple Circular UWB monopole antenna without notch is shown. Dispersion diagrams are used to obtain the band gaps of different EBG structures. The proposed antennas can rejects worldwide interoperability for microwave access WiMAX band (3.3–3.8 GHz) and wireless local area network WLAN band (5–6 GHz). Finally, With I-slot embedded edge located via type EBG, size reduction of EBG structure up to 30% is shown. Measured results are found in good agreement with simulated one.

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