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Design and Analysis of Two Novel CPW-Fed Dual Band-Notched UWB Antennas with Modified Ground Structures

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Abstract—In this paper, two novel coplanar waveguide (CPW) fed printed ultra wide band (UWB) monopole antennas with dual band-notching characteristics are proposed. The modified ground technique with symmetric ground plane in antenna 1 and asymmetric ground planes in antenna-2 is exploited to cover UWB application. Both antennas are compact with dimensions of $30 \times 30 \times 1.6\,\mathrm{mm}^3$ and have dual band-notched characteristics with first notched band for integrated band of WiMax 3.5/5.5 GHz and C-band satellite communications 3.7–4.2 GHz and second notched band for WLAN 5.2/5.8 GHz bands. Antenna with symmetric ground plane achieves the impedance bandwidth of 2.9–11.5 GHz, and antenna with asymmetric ground plane achieves the impedance bandwidth of 2.9–11.89 GHz, respectively with VSWR < 2 except in the notched bands. The antennas are designed and optimized in CST Microwave Studio. The simulated VSWR of the proposed antenna designs is compared with the measured VSWR of fabricated antennas, and it is found that they are in a good agreement. Both antennas exhibit monopole-like radiation patterns with significant gain in entire operating band. Maximum gain of the proposed antenna with symmetric ground plane is 5.3 dBi at 8 GHz, and that with asymmetric ground plane is 4.5 dBi at 7 GHz.

1. INTRODUCTION

In 2002, Federal Communication Commission (FCC) granted 7.5 GHz frequency band ranging from 3.1–10.6 GHz for commercial data communications, radar and safety applications along with sensing, military communications and niche applications. Due to various advantages such as wide bandwidth, high speed data transmission within short ranges without interference, low complexity, low cost and lesser power requirement, the UWB communication systems has drawn researches attention [1]. Printed monopole antennas have become a good solution for the ultra wide band (UWB) systems working within the frequency band of 3.1 GHz to 10.6 GHz. Since last decade various planar monopole antennas have been proposed in the literature [1–7], yielding high performance for the UWB systems. Presently, a lot of work has been seen on designing UWB antennas with band-notching characteristics so that the frequency range allotted for UWB system from 3.1 to 10.6 GHz could not cause electromagnetic interference (EMI) to the other existing wireless communication applications, such as the World Interoperability for Microwave Access (WiMax) operating in the 3.3–3.7 GHz and 5.25–5.85 GHz frequency bands, C-band satellite communication existing in the 3.7–4.2 GHz frequency range, IEEE 802.11a wireless local networks (WLAN) operating in 5.15–5.35 GHz and 5.725–5.825 GHz bands [8–21]. Many band-notched UWB antennas with built-in band-notched structures have been proposed to avoid the EMI between the UWB and narrowband communication systems such as WLAN and WiMax systems; some of these band-notched structures consist of a V-shaped slot [9], a pair of flexuous slots on the radiation element, a C-shaped slot on the ground plane [14], adding an inverted-cup strip parasitically to the feed layer [15],

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a U-shaped slot [16], a pair of U-shaped slots on the ground plane and a T-shaped parasitic strip on the backside of the substrate [18], and a pair of inverted-T-shaped filter slots [24].

Recently, many band-notched UWB antennas have been proposed in the literature [14–22], and they are fed by microstrip line with metallisation on both sides of the substrate, and hence they cannot be integrated with other circuits. For easier integration with active devices and realization of series and shunt connections on one side of the substrate, some CPW-fed dual band reject UWB antennas have also been proposed [23–25]. The size of these mentioned antennas [14–25] is larger than our proposed antennas of size $30 \times 30 \times 1.6\,\mathrm{mm}^3$. One of the challenges to design dual- or multi-band notched monopole UWB antenna is to maintain good antenna performance in terms of gain and radiation pattern characteristics. However, in literature various CPW-fed antennas are reported with dual band-notched characteristics [26, 27], but their gain performance is a bit low. In [26], dual band-notching of 3.0–3.8 GHz and 5.1–6.2 GHz has been achieved by inserting a pair of nested C-shaped stubs on the back surface of the substrate, which has resulted in remarkably poor gain performance below 2 dBi in lower UWB till 7 GHz. This is due to mutual coupling of the closely inserted nested C-shaped stubs, which has complicated the design procedure. Also the antenna design approach in [27] has resulted in poor gain performance with a gain less than 2.3 dBi for lower UWB region from 3.1–9.0 GHz and below 2.8 dBi for 9.0–10.6 GHz, making the antenna perform badly in entire UWB region. Various deigns have been proposed in the literature achieving dual or triple band-notching [28–30]. Antenna configurations in [28, 29] lack the coplanar approach, are bigger in size, and achieve lesser gain in entire UWB range than the reported antennas in this paper, while antenna in [30] is based on stepped impedance resonator-defected ground structure (SIR-DGS), possesses complex design, and is susceptible to fabrication errors which has resulted in distortion in radiation patterns in E-plane.

In this paper, we propose a new simple approach of designing the compact UWB antennas with symmetric and asymmetric ground plane configurations without compromising on the antenna performance. Optimised bevels are cut in the radiating patch to control the flow of current on the antenna which has improved various antenna parameters such as VSWR and gain for the desired frequency band. It has been found that the simulated and measured results of the proposed antennas are in good agreement with each other. The next section describes the design evolution methodology to use the optimised and modified stepped ground structures to enhance antenna bandwidth.

2. DESIGN AND ANALYSIS OF ANTENNA CONFIGURATIONS

Here, we have experimented modifications in the ground plane using the symmetric and asymmetric ground plane structures to build two different novel dual band-notched UWB antennas. Both antennas are designed with inexpensive and easily available FR-4 substrate of uniform thickness $h = 1.6\,\mathrm{mm}$, relative permittivity $\varepsilon_r = 4.4$ and having loss tangent of 0.02. The proposed antennas have compact size of $30 \times 30 \times 1.6\,\mathrm{mm}^3$ and have metallisation on one side of the substrate. The antennas are fed by coplanar waveguide structure which consists of central metallic strip of width 'W_f' and gap 'g' between central strip and ground planes with $50\,\Omega$ characteristic impedance. Two staircase-shaped stepped ground planes, formed by cutting steps in the conventional rectangular ground plane are placed symmetrically on each side of the central CPW feed line to improve the matching between the feed line and the patch. However, antenna-1 consists of symmetrical stepped ground planes, and antenna-2 consists of asymmetrical stepped ground planes. Asymmetrical slots are cut from each corners of the radiating patch to increase the impedance bandwidth. However, the slots on the lower edges of the patch near the ground plane play a significant role in achieving the wideband application. In antenna-1, an inverted U-shaped slot and a pair of inverted L-shaped slots are etched, respectively, in the central metallic strip of the CPW line and in radiating patch of the first antenna to obtain dual band-notched characteristics. Antenna-2 consists of asymmetric ground plane employing one U-shaped slot in the radiating element and other U-shaped slot in the central metallic strip of the CPW line of monopole antenna achieving 3.3–4.2 GHz and 5–6 GHz; dual band-notched characteristics respectively.

Figures 1(a) and 1(b) depict the dimensions of two proposed CPW-fed UWB antennas with dual band-notched characteristics. These dimensions are obtained by optimising the antenna designs through various parametric simulations. Both antennas have length and width 'L' = 'W' = 30 mm, ground plane width 'W_g' = 13 mm. The final optimized geometric parameters of the proposed antenna-1 are:

dimension of the modified ground plane 'L_{g1}' = 2.9 mm, 'L_{g2}' = 6.5 mm, 'L_{g3}' = 8.5 mm. Width and length of the central metallic line of CPW feed of this antenna are 'W_f' = 3 mm, 'L_f' = 9.2 mm respectively. Various slot lengths in the radiating patch are 'L_1' = 3.8 mm, 'L_2' = 11.5 mm, 'L_3' = 4 mm, 'L_4' = 11 mm, 'L_5' = 5 mm, 'L_6' = 1 mm, 'L_7' = 1.5 mm. Various slot widths in the radiating patch are 'W_1' = 4 mm, 'W_2' = 3 mm. Optimised parameters of the proposed antenna-2 are: 'L_{g21}' = 3.9 mm, 'L_{g22}' = 7.5 mm, 'L_{g23}' = 9.6 mm. Various slot lengths in the radiating patch of antenna-2 are 'L_1' = 2 mm, 'L_2' = 'L_4' = 11.5 mm, 'L_3' = 4 mm, 'L_5' = 5 mm, 'L_6' = 1.5 mm, 'L_7' = 0.5 mm. The dimensions of the various band notched structures are shown in Tables 1 and 2.

Table 1. Dimensions of various parameters of band-notched structure of antenna-1.

Parameter	L_{s1}	W_{s1}	W_u	L_u	W_s
Value (mm)	5	8	2	8	0.5

Table 2. Dimensions of various parameters of band-notched structure of antenna-2.

Parameter	L_c	W_c	L_u	W_u	W_s
Value (mm)	2	24	8	2	0.5

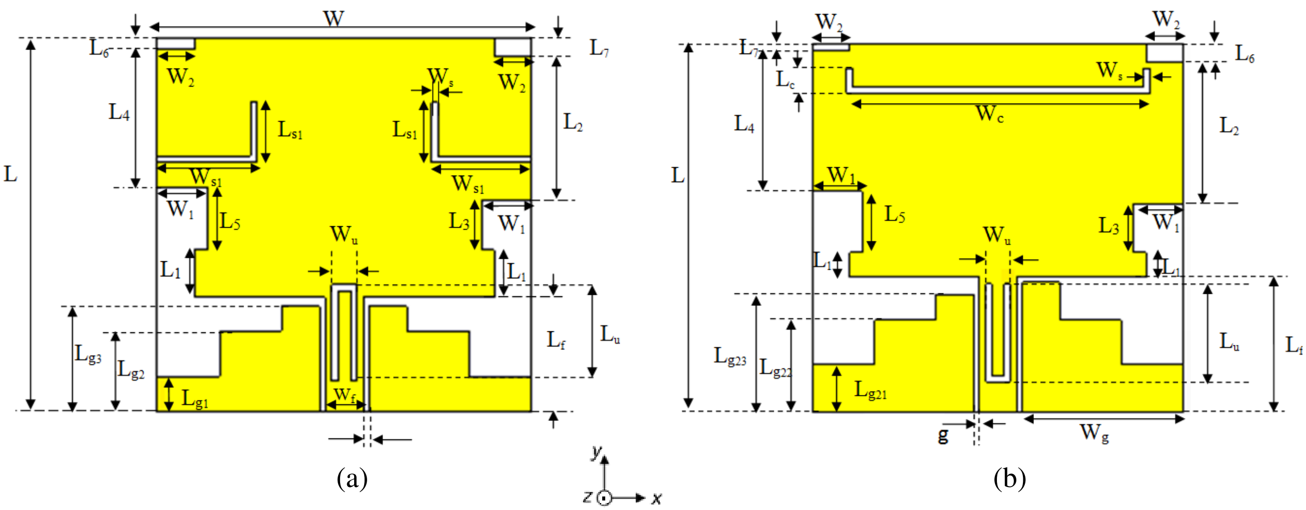


Figure 1. Proposed antenna configurations. (a) Antenna with symmetric ground plane — antenna-1. (b) Antenna with asymmetric ground plane — antenna-2.

Band-notched characteristics in the proposed antennas are obtained by properly locating the quarter wavelength and half wavelength slot resonators (see Figure 1). Band-notched structures employed in antenna-1 are formed by etching a pair of inverted L-shaped slots with length nearly equal to quarter wavelength at the desired center frequency of the notched band in the radiating patch, and a U-shaped slot with total length nearly equal to half wavelength at the desired center frequency of the notched band in the central strip of CPW feed. Antenna-2 has two U-shaped band-notched structures of half wavelength at the center frequency of the desired notched band employed in two different positions; first in radiating patch and second in the central metallic structure of the CPW feed of the antenna. The length of the quarter wavelength slot resonator 'L_{qwr}' (Inverted L-shaped slots in antenna-1) can be calculated by equation:

$$L_{qwr} \approx \frac{c}{4 f_{notch} \sqrt{\dfrac{\varepsilon_{eff}+1}{2}}} \tag{1}$$

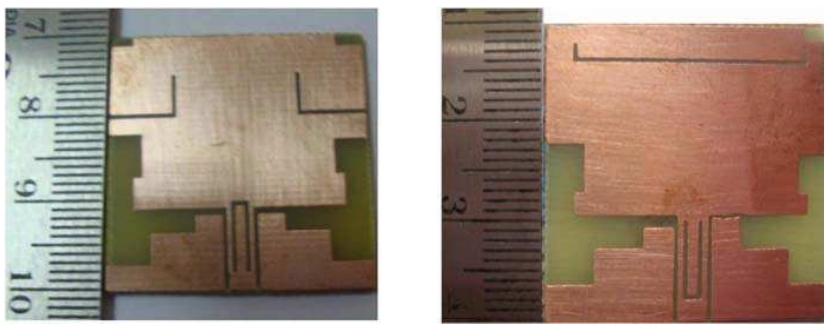
The length of the half wave slot resonators 'L_{hwr}' (U-shaped slots in antenna-1 and antenna-2) can be calculated from:

$$L_{hwr} \approx \frac{c}{2 f_{notch} \sqrt{\dfrac{\varepsilon_{eff}+1}{2}}} \tag{2}$$

with,

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{3}$$

Here 'c' is the speed of light (3×10^8 m/sec); ε_{eff} and ε_r are the effective and relative dielectric constants respectively. However, the desired band-notched characteristics can be tuned by varying the lengths and position of these slots along the patch antenna. For antenna-1; the optimized dimensions of L-shaped band notched structures consists of length of 'L_{s1}' = 5 mm and width 'W_{s1}' = 8 mm, thus making total length of the slot '$L_{s1}+W_{s1}$' nearly equals to quarter of the wavelength of the corresponding band-notching frequency and the optimised dimensions of inverted U-shaped band notched structure consist of slot length 'L_u' = 8 mm and slot width 'W_u' = 2 mm, with '$2L_u + W_u$' nearly half of the wavelength of the corresponding band-notching frequency. Antenna-2 consists of U-shaped band notched structures with total slot lengths '$2L_u + W_u$' and '$2L_c + W_c$' adjusted nearly equal to $\lambda/2$ at the centre frequency of required stop band [16]. All the slots used for the band notching are designed with width 'W_s' equal to 0.5 mm. Figure 2 shows the developed prototypes of the proposed antennas.



(a) (b)

Figure 2. Photographs of the fabricated prototypes of UWB antennas: (a) Antenna-1; (b) Antenna-2.

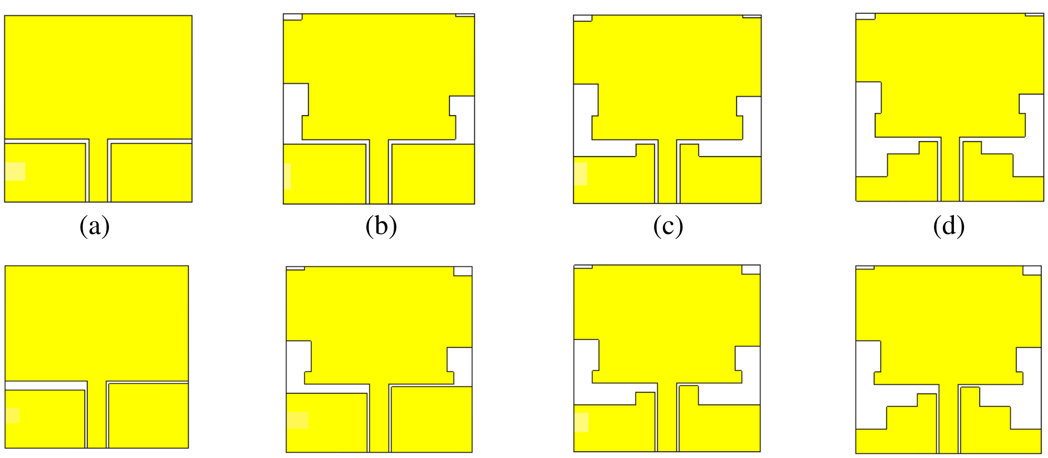
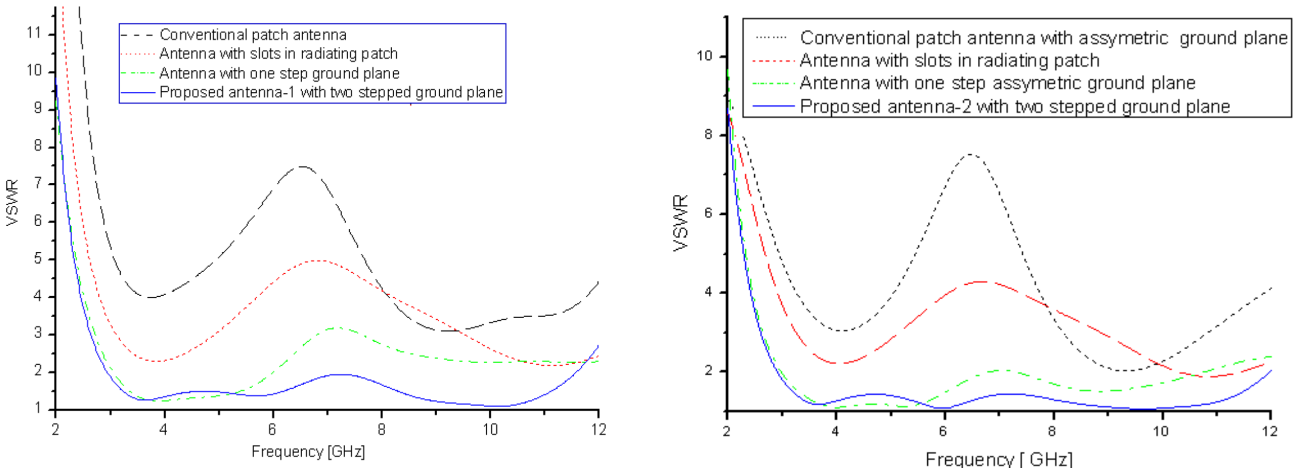


Figure 3. Design evolution of proposed UWB antennas: (a)–(d) Antenna with symmetric ground planes — antenna-1; (e)–(h) Antenna with asymmetric ground planes — antenna-2.

Figures 3(a)–(d) and Figures 3(e)–(h) show the design evolution of the proposed UWB antennas with symmetric and asymmetric ground planes respectively. Figure 3(a) shows the conventional CPW-fed rectangular patch antenna which is used as the base of the design for antenna-1; the dimensions '$L \times W$' of the antenna is 30 mm × 30 mm. Figure 3(b) shows the antenna with slots in the radiating



(a) (b)

Figure 4. VSWR verses frequency curves for: (a) Antennas 3(a)–(d) with symmetrical ground plane; (b) Antennas 3(e)–(h) with asymmetrical ground plane.

patch which results in improved impedance matching. Further Figures 3(c)–(d) show the use of stepped ground plane technique to improve the impedance bandwidth of the antenna to desired UWB range. Similarly, the design evolution of UWB antenna with asymmetrical ground plane (antenna-2) is illustrated in Figures 3(e)–(h). Figure 3(e) shows the conventional CPW-fed rectangular patch antenna with asymmetrical ground planes, which is used as the base of the design with dimension '$L \times W$' equal to 30 mm × 30 mm. Figure 3(f) shows the antenna with slots in the radiating patch which results in improved impedance matching. Further, Figures 3(g)–(h) show the use of stepped ground plane technique to improve the impedance bandwidth.

Figures 4(a) and 4(b) show the VSWR verses frequency response of antennas illustrated in Figures 3(a)–(d) and 3(e)–(h), respectively. From these plots it can be noticed that with modified stepped ground plane configuration the impedance matching is improved. The modified stepped ground plane works as an impedance matching element. Each step in the ground plane behaves as a resonating element leading to resonances quite close to one another, and these adjacent resonances interact to yield a wide bandwidth.

3. RESULTS AND DISCUSSIONS

The fabricated antennas are measured for VSWR variation with frequency by Agilent's PNA E8364C. These variations are compared with and without notched structures, shown in Figures 5(a) and 5(b), respectively. It is noticed that without the band-notched structures on the radiating element, the impedance bandwidths of antennas for symmetric and asymmetric ground plane are 2.9–11.5 GHz and 2.9–11.89 GHz (for VSWR < 2), respectively.

By introducing a pair of inverted L-shaped slots in the radiating element of the antenna-1 as in Figure 3(d) with symmetrical ground planes, the band-notched characteristics are obtained for 3.3–4.2 GHz band (Figure 5(a)), and by introducing the pair of inverted U-shaped structure in the same antenna other band-notched characteristic are obtained from 5–6 GHz (Figure 5(a)) with the 5.5 GHz as the central notching frequency. By employing one U-shaped slot in the radiating element of antenna-2 as in Figure 3(h) with asymmetrical ground plane and other U-shaped slots in the central metallic strip of the same antenna, dual band-notched characteristics are obtained in 3.3–4.2 GHz integrated band of WiMax with C-band satellite communication and 5–6 GHz WLAN band, respectively (Figure 5(b)). The measured results are in good agreement with simulations in CST MWS, except little variation which may be due to some errors in fabrication.

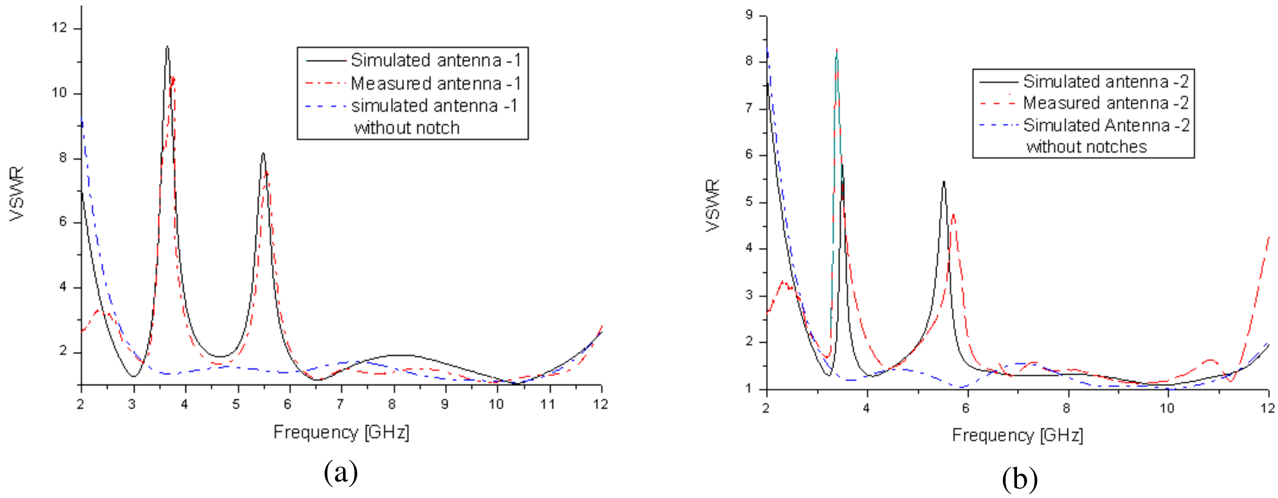


Figure 5. VSWR verses frequency curve: (a) Antenna-1 with symmetrical ground plane; (b) Antenna-2 with asymmetrical ground plane.

3.1. Influences on the Band-Notched Characteristics — Simulations

Parametric analyses on the notched-band characteristics have been simulated in CST MWS on the proposed antennas

3.1.1. Study for Notched-Bands in Antenna-1

This section presents the parametric analysis done on the pair of inverted L-shaped structures to see the effect on the band-notched characteristics. To study the 3.3–4.2 GHz band-notched characteristic of the antenna, the parameters: width 'W_{s1}' and length 'L_{s1}', which form the inverted L-shaped pair (see Figure 1(a)), are varied.

Figure 6(a) depicts that when the length of the slot, 'L_{s1}', is increased from 4.0 mm to 6.0 mm, the notched-frequency of the centre band decreases as per Equation (1). 'L_{s1}' = 4.0 mm yields an undesirable notched band at 3.5–5.0 GHz, and L_{s1} = 6.0 mm yields an undesirable notched band at

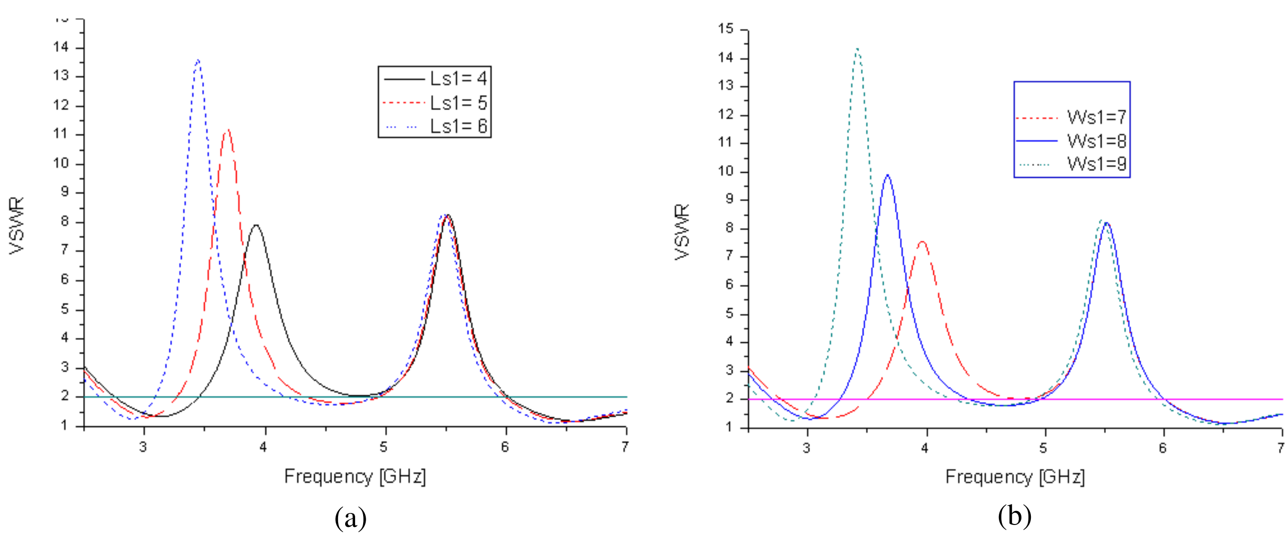
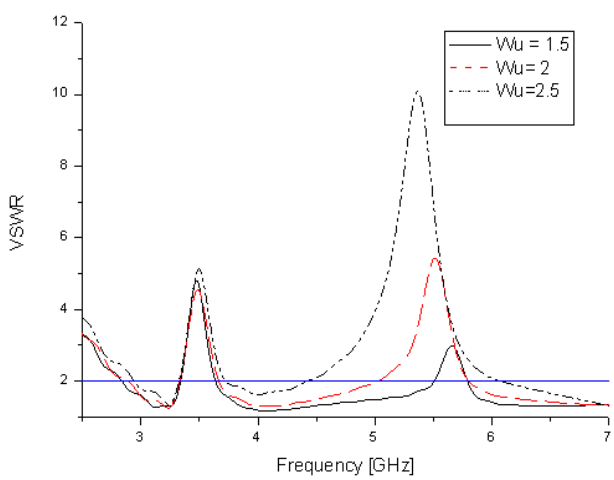


Figure 6. Effect of variation of 'L_{s1}' and 'W_{s1}' on the VSWR of antenna-1.

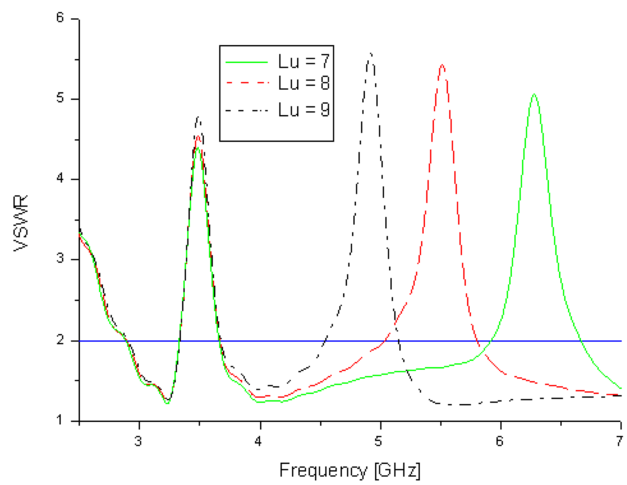
lower frequencies 3.1–4.1 GHz. However, 'L_{s1}' = 5.0 mm yields required band notching at 3.2–4.2 GHz. Also when width 'W_{s1}' is varied from 7 mm to 9 mm (see Figure 6(b)) a significant decrease in notched-frequency is observed with desired band-notched characteristics at width 'W_{s1}' = 8 mm. Whereas 'W_{s1}' = 7.0 mm yields a notched band at undesired higher frequencies, reportedly at 3.5–4.7 GHz, and 'W_{s1}' = 9.0 mm results in a notched band at lower frequencies from 3.1–4.1 GHz. We summarize the optimum results at 'L_{s1}' = 5.0 mm and 'W_{s1}' = 8.0 mm.

3.1.2. Study for Notched-Bands in Antenna-2

Similarly, for antenna-2, the variation in VSWR verses frequency is simulated with respect to change in length 'L_u' and width 'W_u' of the U-shaped half-wave resonator employed in the microstrip line and shown in Figures 7(a) and 7(b), respectively. This U-shaped half-wave slot resonator achieves 5–6 GHz notched-band. Figure 7(a) shows the influence of width 'W_u' from 1.5 mm to 2.5 mm on VSWR with the change in frequency. For 'W_u' =1.5 mm notched-band is small existing at 5.59–5.85 GHz, and for 'W_u' = 2.5 mm the resulted notched-bandwidth is quite large lying in undesired band of 4.5–5.85 GHz. 'W_u' = 2.0 mm yields the required band notching, covering the desired band 5.1–5.85 GHz. With increase in parameter 'W_u', there is a reported increase in bandwidth of notchedband with decrease in center frequency of the rejected band. It is observed that with the variation of length 'L_u' from 7.0 mm to 9.0 mm, the centre frequency of stop band decreases and varies from 4.8–6.3 GHz (Figure 7(b)). 'L_u' = 7.0 mm yields undesired band-notching at higher frequencies from 6.0 GHz–6.9 GHz, and 'L_u' = 9.0 mm results in undesired band notching at lower frequency band of 4.6 GHz–5.2 GHz. 'L_u' = 8.0 mm results in band notching at desired band of 5.1 GHz–5.9 GHz. So these parametric studies give us optimum value of 'W_u' = 2 mm and 'L_u' = 8 mm for desired band-notching function.



(a)

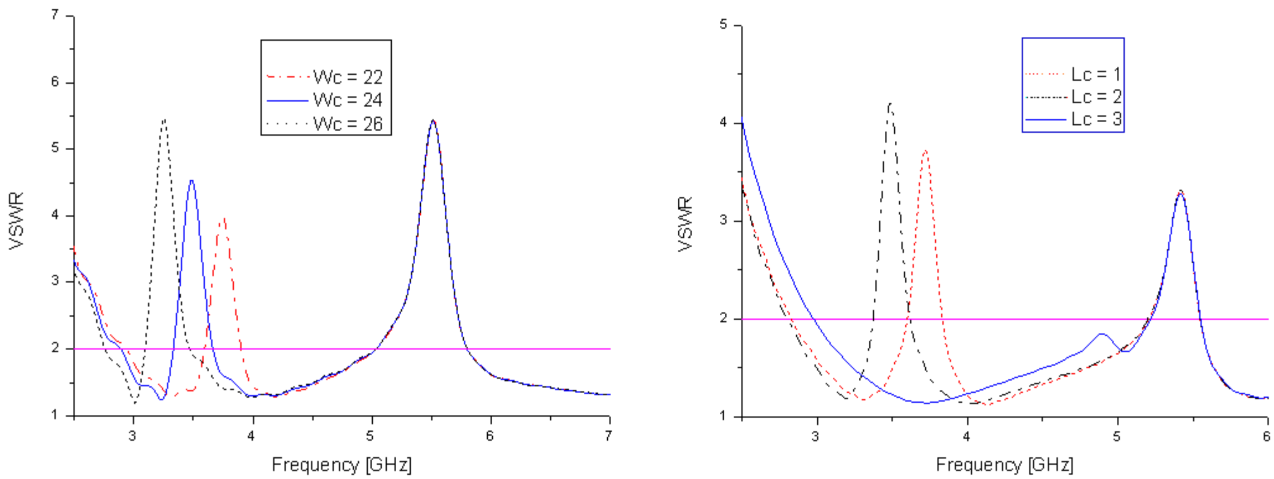


(b)

Figure 7. Effect of variation of width 'W_u' and length 'L_u' on the VSWR of antenna-2.

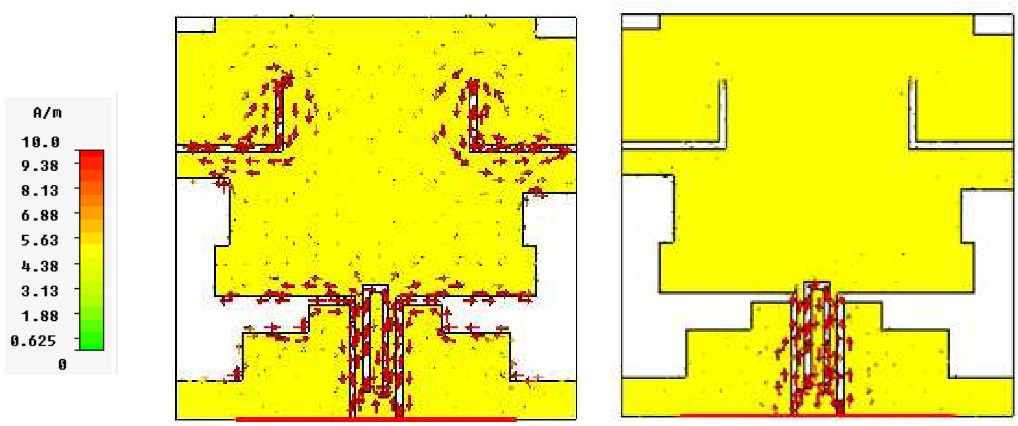
Figures 8(a) and 8(b) show the effect of varying width 'W_c' and length 'L_c' of the U-shaped half wave slot resonator placed in the radiating patch of the proposed CPW-fed antenna with the asymmetrical ground planes (antenna-2). Study shows (see Figure 8(a)) that while increasing the length 'W_c' from 22.0 mm to 26.0 mm, the centre band-notched frequency decreases, and while increasing 'L_c' from 1 mm to 3 mm, the band-notched frequency decreases (see Figure 8(b)). The suitable dimensions are obtained for notching the desired bands, after the parameters are chosen as 'W_c' = 24.0 mm and 'L_c' = 2.0 mm. From the parametric analysis, it is observed that variation in any physical parameter of one band-notched structure of the antenna does not influence the response of the second notched band.

To explain the band-notched characteristics of the proposed antenna-1, the simulated current distributions at 3.75 GHz and 5.5 GHz are investigated and shown in Figures 9(a) and 9(b), respectively.



(a) (b)

Figure 8. Effect of variation of width 'W_c' length 'L_c' and on the VSWR of antenna-2.



(a) (b)

Figure 9. Simulated current distributions for antenna-1 with symmetric ground plane (a) 3.75 GHz; (b) 5.5 GHz.

(a) (b)

Figure 10. Simulated current distributions for antenna-2 with asymmetric ground plane (a) 3.75 GHz; (b) 5.5 GHz.

It is observed that the surface currents at 3.75 GHz are mainly concentrated along the L-shaped quarter-wave slot resonators, whereas the resonant surface currents at 5.5 GHz are mainly distributed along the U-shaped half wave slot resonators which gives desired band-notched characteristics.

Figures 10(a) and 10(b) show the simulated current distributions at notched frequencies 3.75 GHz and 5.5 GHz for proposed antenna-2. It can be noticed that the resonant current is mainly concentrated

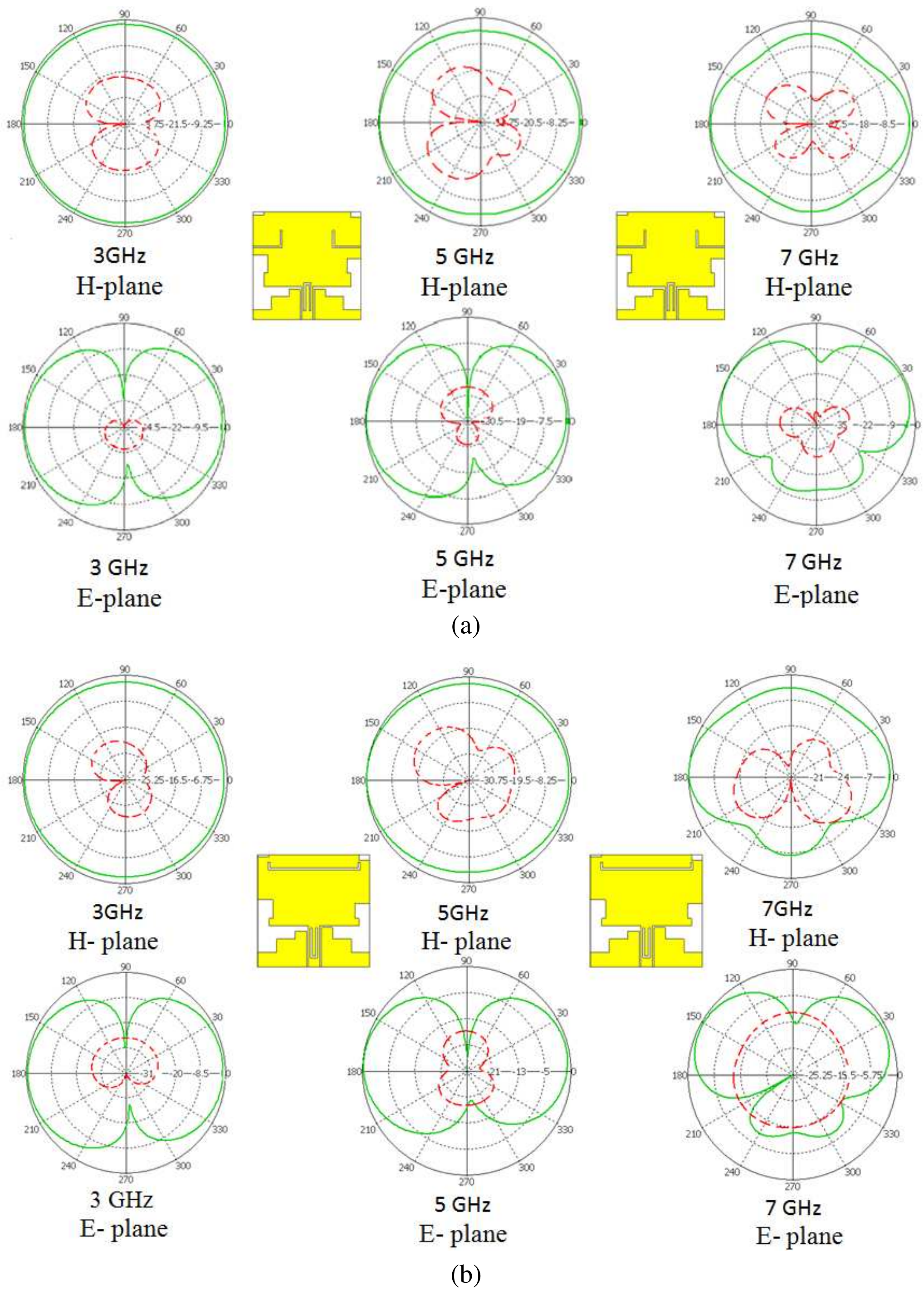
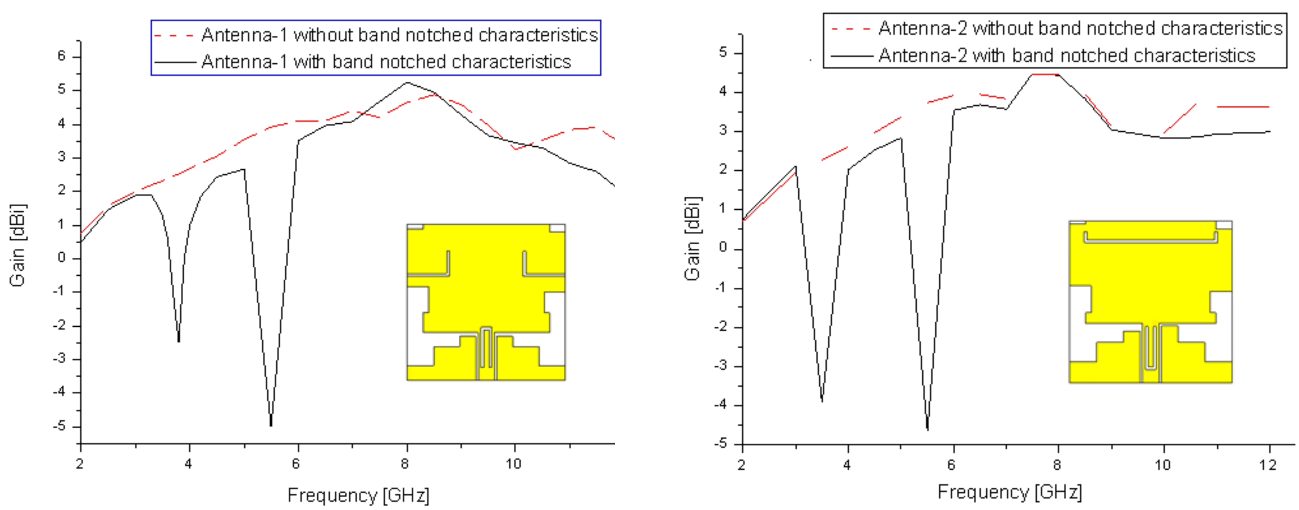


Figure 11. Radiation patterns of proposed antennas: (a) Antenna-1 and (b) antenna-2 at 3 GHz, 5 GHz and 7 GHz respectively. (solid line: co-polar, dashed line: cross-polar component).

near the U-shaped half-wave resonator employed in the radiating patch and the central metallic strip of CPW-fed line at 3.75 GHz and 5.5 GHz, respectively, giving required band notched characteristics. Looking at these current distributions it can be visualised that band-notched characteristics are caused by the oppositely directed current along the perimeter of the U-shaped half wavelength slot resonators. This oppositely directed current distribution makes the antenna impedance high, hence the antenna does not radiate at these notched frequencies.

The simulated radiation patterns of the proposed antenna-1 and antenna-2 in H-plane (xz-plane) and E-plane (yz-plane) of the antenna are presented in Figures 11(a) and 11(b) for three different frequencies at 3 GHz, 5 GHz and 7 GHz, respectively.

The radiation pattern obtained in H plane is purely omnidirectional at 3 GHz and 5 GHz and nearly omnidirectional at higher frequencies such as 7 GHz. The E-plane is similar to dumbbell-shaped monopole kind of antenna at 3 GHz, and close to monopole kind of antenna at 5 GHz and 7 GHz. The simulated peak gains versus frequency curves of the proposed antennas are shown in Figures 12(a) and 12(b). It is seen that the maximum gain of antenna-1 is 5.3 dBi at 8 GHz with dual band-notching characteristics at 3.75 GHz and 5.5 GHz where the gain falls to minimum values of −2.5 dBi and −5 dBi, respectively. Antenna-2 exhibits band notching in 3.3–4.2 GHz and 5–6 GHz with gain falling to −4 dBi and −4.8 dBi at the notched frequencies 3.75 GHz and 5.5 GHz, respectively. It can be noticed that both antennas are capable of performing well throughout the UWB band with desired notching characteristics.



(a) (b)

Figure 12. Gain verses frequency curves: (a) Antenna-1; (b) Antenna-2.

4. CONCLUSION

Two novel compact CPW-fed UWB antennas ($30 \times 30 \times 1.6\,\mathrm{mm}^3$) with dual band-notched characteristics in 3.3–4.2 GHz and 5–6 GHz bands are proposed, designed, analyzed in CST MWS and measured experimentally. These antennas are developed using modified (symmetric and asymmetric) ground plane structures in the CPW feed. Band-notched structures in the form of quarter and half wavelength slot resonators are employed in the proposed antennas to achieve the band elimination characteristics. The dual band-notched characteristics are achieved by using a pair of inverted L-shaped quarter wavelength slot resonators and a U-shaped half wavelength slot resonator in the first antenna, and two U-shaped half wavelength slot resonators in the second antenna. The notched frequency can be varied by changing the length and width of the proposed band-notched structures. The proposed slot antennas have nearly omnidirectional radiation patterns with significant gain in entire band.

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