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Design and Analysis of a Compact Triple Band Slotted Microstrip Antenna with Modified Ground Plane for Wireless Communication Applications

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Abstract—A novel single layer, coaxial probe feed compact triple band slotted microstrip patch antenna with modified ground plane for wireless application has been designed and analyzed. The presented antenna, occupying a compact size of $24 \times 22 \times 1.6\,\text{mm}^3$, embodies a rectangular slotted patch and a rectangular ground plane modified with open ended step graded slots. The step graded slots are introduced on the ground plane to reduce the size of the antenna by reducing the resonant frequency and also to improve the operating bandwidth of the proposed antenna. The size of the antenna has been reduced by 74% by introducing slots on the ground plane. The measured bandwidths for -10 dB reflection coefficient are 360 MHz (1.72–2.08 GHz) at lower band, 300 MHz (3.36–3.66 GHz) at middle band and 3650 MHz (4.85–8.5 GHz) at upper band which cover the bandwidth requirements of 1.92 GHz PCS, 1.9 GHz PHS, 3.5/5.5 GHz WiMAX, 5.2/5.8 GHz WLAN, 5.2 GHz HisWaNa and 5 GHz HiPERLAN wireless application bands.

1. INTRODUCTION

The popularity of wireless communication systems has increased remarkably during the last decade and the market demand still continues to increase. As a fundamental part of these systems, antenna is one of the most important design issues in modern wireless communication units. The microstrip antenna has drawn maximum attention of the antenna community in recent years for wireless communication applications. In spite of its various attractive features like light weight, low cost, easy fabrication, and so on, microstrip antenna suffers from an inherent limitation of narrow impedance bandwidth typically of about 2–4%. So, along with other developments, widening the bandwidth of microstrip antenna has become a major branch of activities in the field of printed antennas [1–8]. Researchers have offered numerous methods like aperture coupling [1], stacked patch [2], modifications in the feed [3], staggering effect [4] and introducing slots on the radiating patch [5, 6] to enhance the bandwidth of microstrip antennas. Some microstrip antennas with simple radiating patch and slotted ground plane were also proposed by researchers [7] to provide compact broadband performance. Maximum bandwidth of 16% has been achieved ranging from 2.25–2.65 GHz using aperture coupled feeding [1] but it is not suitable for 3.5 GHz/5 GHz WiMAX and 5 GHz high speed WLAN systems. The microstrip antenna proposed in [2] provides bandwidth of 47% but it uses thick substrate which normally provides higher bandwidth. The L probe feed microstrip patch antenna proposed in [3] has achieved bandwidth of only 11% which is not sufficient to cover the bandwidth requirement of most of the modern wireless communication systems. Recently, Mandal et al. [4] has increased the bandwidth of microstrip antenna up to 27% using staggered effect but the large size of the antenna is a major problem. The frequency reconfigurable U slot microstrip antenna proposed in [5] has achieved bandwidth of 750 MHz ranging from 2.6–3.35 GHz but

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the antenna does not cover the bandwidth requirement of modern high speed 5 GHz WLAN systems. The small patch antenna proposed in [6] achieves a size reduction of only 50% and bandwidth of 53%. The microstrip line fed rectangular microstrip antenna with open end meandering slots in the ground [7] has increased the operating bandwidth up to 40% but the large size of this antenna is still a major challenge. Recently, Mukherjee and Raj [8] has proposed the hemispherical dielectric resonator antenna with maximum bandwidth 16.44% but this antenna requires high dielectric constant substrates which is not readily available.

Due to recent advancements in mobile and wireless communication system, the increasing demands for wireless connectivity necessitate a single antenna to cover several allocated wireless frequency bands. One simple way to cover all frequency bands is using wideband antennas. However when these antennas are used in wireless communication systems, additional band pass filters are required to avoid collision and minimize frequency interference with other coexisting wireless application bands. So, the demand for the design of an antenna with multiband operation has increased since such an antenna is vital for integrating more than one communication standards in a single compact system. For this demand, the planar monopole antenna [9–14] has become an important candidate because of its attractive characteristics, such as low profile, simple structure, compact size, and easy integration with circuit. Different from these monopole antennas, a novel ground structure named defected ground structure has recently been investigated and found to be a simple and effective method to reduce the antenna size as well as excite additional resonance modes [15–17]. However, the major challenge for designing triple band antenna for last few years is that the ratio of centre frequency between each successive band should be a minimum of 1.6 for better frequency rejection and less interference between the frequency bands. In past few years, triple band antennas were designed but their band ratios are within 1.6 and also bands are not very broad. In this article, single layer coaxially fed slot loaded microstrip patch antenna with defected ground plane has been presented. The proposed antenna is novel because the same antenna covers two important design issue of microstrip patch antenna, such as size reduction and bandwidth enhancement. The novelty of our work is that we have achieved triple frequency bands with wide impedance bandwidth without using thick foam substrate, shorting pin, stacked patch or modifications in the feed. The proposed antenna is designed with thin, inexpensive, low dielectric constant FR-4 substrate. The work presented in this paper clearly represents a new design method to achieve triple band operation by using the combinations of slotted patch and defected ground plane. The proposed antenna provides much better size reduction and bandwidth enhancement in comparison to the antennas reported in [1–8]. The advantages of the proposed antenna in comparison to the triple band antennas [9–17], are as follows:

i) It provides sufficiently large triple frequency bands (1.72–2.08 GHz, 3.36–3.66 GHz and 4.85–8.5 GHz).
ii) The centre frequency ratios are $\frac{f_{c2}}{f_{c1}} = 1.84$ and $\frac{f_{c3}}{f_{c2}} = 1.88$, which suggest less interference with other coexisting wireless application bands.
iii) The structure of the antenna is less complex.
iv) The size of the antenna is much small.

The proposed antenna could be promising for a number of modern wireless communication application bands such as PCS (1.85–1.99 GHz), PHS (1.88–1.93 GHz), WiMAX (3.4–3.6 GHz, 5.25–5.85 GHz), High speed WLAN (5.15–5.35 GHz, 5.725–5.825 GHz), HisWaNa (5.15–5.25 GHz) and HiPERLAN (5.47–5.725 GHz) due to its low cost, light weight, small size, wide-bandwidth and better working characteristics.

2. ANTENNA STRUCTURES

2.1. Antenna 1

The design of the antenna begins with a rectangular microstrip antenna with patch length $(L) = 12$ mm and width $(W) = 16$ mm. The FR-4 substrate chosen for realizing the antenna has dielectric constant, $\varepsilon_r = 4.4$ and thickness (h) of 1.6 mm. The structure of proposed antenna 1, designed with simple ground plane is shown in Figure 1. The proposed antenna is incorporated with two vertical and one

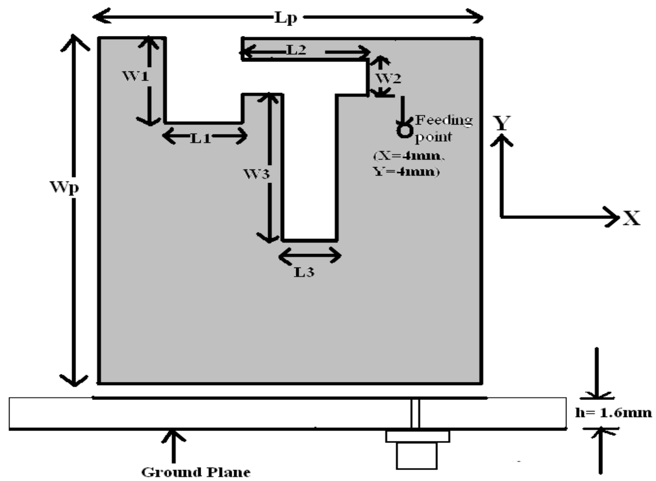


Figure 1. Configuration of antenna 1.

(a) (b)

Figure 2. Photograph of fabricated antenna 1 (a) patch, (b) ground plane.

horizontal connected slot. The first vertical slot ($W_1 = 4\,\text{mm}$, $L_1 = 3\,\text{mm}$) is introduced to generate dual resonant frequency. The horizontal slot ($W_2 = 2\,\text{mm}$, $L_2 = 3\,\text{mm}$) is introduced to further shift the higher resonant frequency for the improvement of frequency ratio. The addition of second vertical slot ($W_3 = 6\,\text{mm}$, $L_3 = 2\,\text{mm}$) shifts the lower resonant frequency, resulting in much better size reduction and frequency ratio. The optimal dimensions of proposed antenna 1 are $W_P = 16\,\text{mm}$, $L_P = 12\,\text{mm}$, $W_1 = 4\,\text{mm}$, $L_1 = 3\,\text{mm}$, $W_2 = 2\,\text{mm}$, $L_2 = 3\,\text{mm}$, $W_3 = 6\,\text{mm}$, $L_3 = 2\,\text{mm}$. The coaxial probe feeding point is located at an optimized position ($X = 4\,\text{mm}$, $Y = 4\,\text{mm}$) from centre ($X = 0\,\text{mm}$, $Y = 0\,\text{mm}$) of the patch. The photograph of the fabricated antenna 1 is shown in Figure 2.

2.2. Antenna 2

The proposed antenna 2 is designed with identical slotted patch of antenna 1 and rectangular ground plane modified with open ended step graded slots. One vertical slot and two unequal connected horizontal rectangular slots are introduced on the ground plane of the proposed antenna to reduce the size of the antenna and also to enhance the operating bandwidth. The structure of antenna 2 is shown in Figure 3. The connected horizontal slots ($W_{g1} = 5\,\text{mm}$, $L_{g1} = 4\,\text{mm}$ and $W_{g2} = 4\,\text{mm}$, $L_{g2} = 7\,\text{mm}$) of unequal dimensions are introduced in the ground plane to provide better size reduction by reducing the lower resonant frequency and also to improve the operating bandwidth of the proposed antenna by exciting additional resonance modes. Further shift in lower resonant frequency and enhancement in operating bandwidth is achieved by addition of a vertical slot ($W_{g3} = 4\,\text{mm}$, $L_{g3} = 7\,\text{mm}$) with

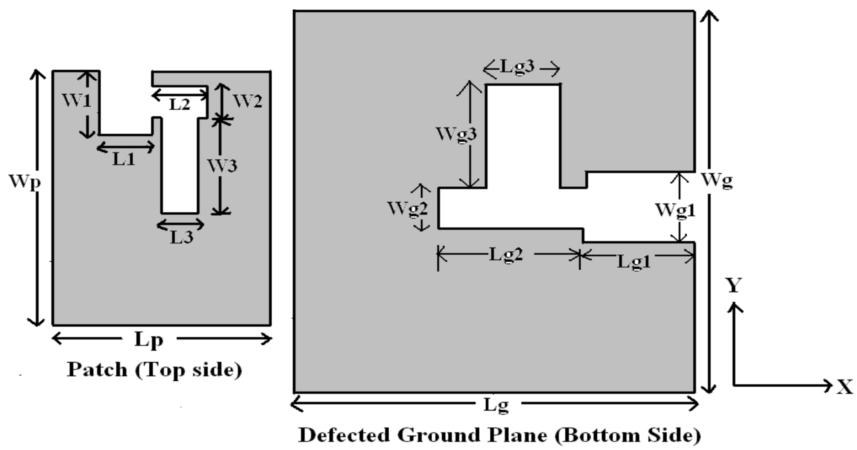


Figure 3. Configuration of antenna 2.

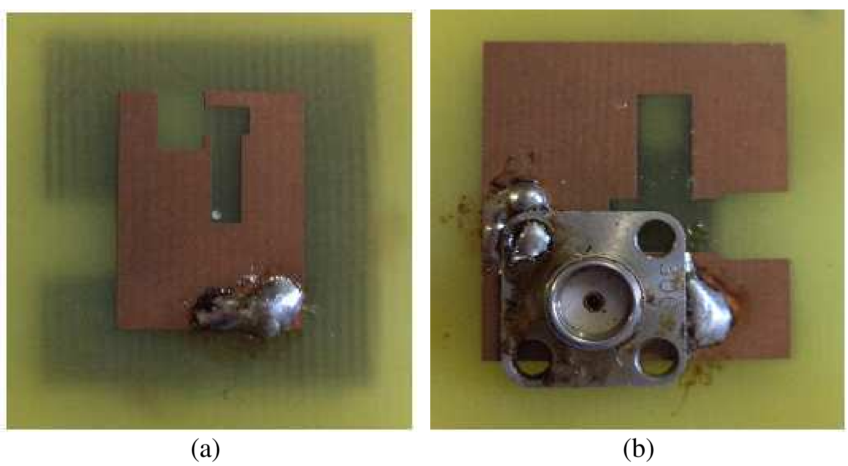


Figure 4. Photograph of fabricated antenna 2 (a) patch, (b) defected ground plane.

the existing slots in the ground plane. For detailed model, all parameters of the proposed antenna are optimized using method of moment based software IE3D [18]. The optimum result is achieved for ground plane of width $W_g = 24\,\text{mm}$ and Length $L_g = 22\,\text{mm}$. The width of the ground plane can be calculated using the empirical formula $W_g = W_P + 5.1\,\text{h}$ and the length of the ground plane can be calculated by the empirical relation $L_g = L_P + 6.3\,\text{h}$, where h is the thickness of the FR-4 substrate. The optimal dimensions of proposed antenna 2 are $W_g = 24\,\text{mm}$, $L_g = 22\,\text{mm}$, $W_{g1} = 5\,\text{mm}$, $L_{g1} = 4\,\text{mm}$, $W_{g2} = 4\,\text{mm}$, $L_{g2} = 7\,\text{mm}$, $W_{g3} = 4\,\text{mm}$, $L_{g3} = 7\,\text{mm}$. The feeding point is located at a position $(X, Y) = (3\,\text{mm}, -7\,\text{mm})$ from centre ($X = 0\,\text{mm}$, $Y = 0\,\text{mm}$) of the patch to give best impedance matching at the desired frequency bands. Alteration of the location of the feed point results in narrower $-10\,\text{dB}$ bandwidth and less sharp resonances. The photograph of the fabricated antenna 2 is shown in Figure 4.

3. PARAMETRIC STUDY OF ANTENNA 1

The effects of varying the dimensions of the slot on the resonant frequencies of the proposed antenna structure were studied using Method of moment based IE3D software. The effect of variations of slot parameters on the resonant frequency of the proposed antenna is shown in Figure 5. The results of Figure 5 are summarized in Table 1.

From the results mentioned in Table 1, it is clear that tuning of higher resonant frequency is

Table 1. Simulated results of antenna 1 by varying the dimensions of the slots.

	Dimension of slots (mm)	Ratio of removed area /Total patch area (%)	Resonant frequency (GHz)	Reflection Coefficient (dB)	Size reduction (%)	Centre frequency ratio
Antenna 1	$W_1 = 3$, $L_1 = 2$ $W_2 = 1$, $L_2 = 2$ $W_3 = 5$, $L_3 = 1$	6.77	8.34	-10.64	0	0
	$W_1 = 4$, $L_1 = 3$ $W_2 = 2$, $L_2 = 3$ $W_3 = 6$, $L_3 = 2$ (Proposed)	15.62	4.3, 8.03	-19.44, -17.4	44	1.867
	$W_1 = 5$, $L_1 = 4$ $W_2 = 3$, $L_2 = 4$ $W_3 = 7$, $L_3 = 3$	27.60	4.41	-17.43	41	0

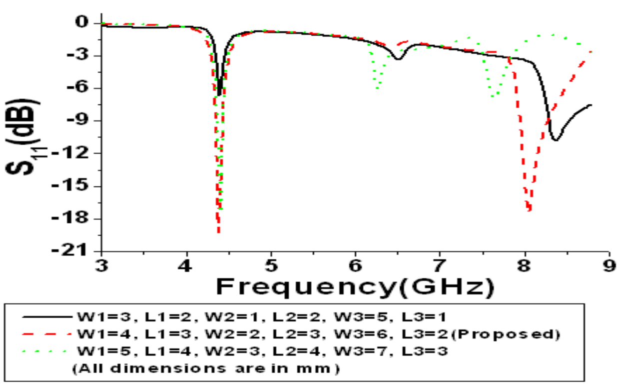


Figure 5. Reflection coefficient vs. frequency of antenna 1 as a function of varying dimension of slots.

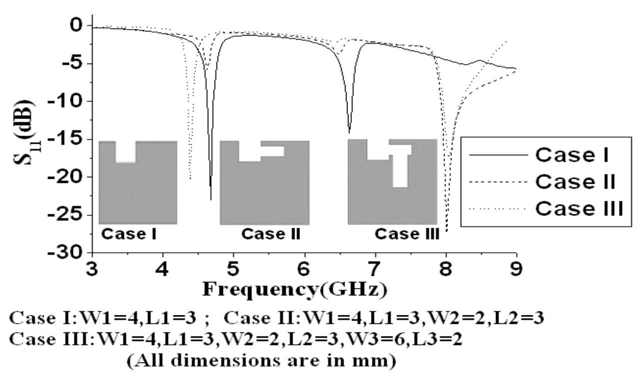
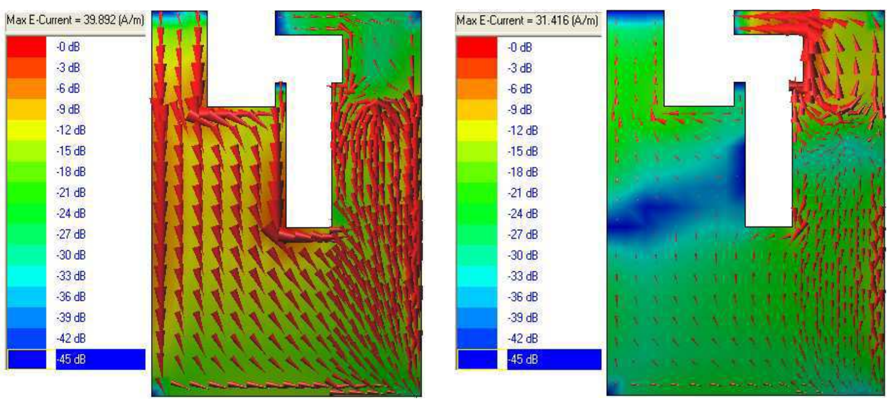


Figure 6. Effect of each optimized slots on reflection coefficient of antenna 1.

possible by decreasing the dimensions of slots, but due to this, the reflection coefficient of the lower resonant frequency gets affected and decreases to -6.6 dB. The antenna offers dual resonant frequencies with reflection coefficient below -10 dB, better frequency ratio and size reduction with the proposed slot dimensions. Tuning of lower resonant frequency is also possible by increasing the dimension of the slots, but the tuned frequency is still higher than the lower resonant frequency, achieved with proposed dimensions. The antenna is also not offering any higher order resonant frequency if designed with increased value of slot parameters compared to the proposed dimensions. So, the proposed slot parameters are the optimal dimensions of the antenna.

4. ANALYSIS AND WORKING OF ANTENNA 1

The effect of each optimized slot on the resonant frequency of the antenna 1 is analyzed using Method of Moment based IE3D software, and the result is depicted in Figure 6. In case I, when the first optimized slot of dimension $W_1 = 4$ mm and $L_1 = 3$ mm is introduced on the patch, the antenna resonates at $f_1 = 4.7$ GHz and $f_2 = 6.63$ GHz below -10 dB reflection coefficient with frequency ratio (ratio of second resonant frequency to first resonant frequency) $f_2/f_1 = 1.41$. The size of the antenna has been reduced by 32.69% in comparison to conventional rectangular microstrip antenna operating at 4.7 GHz with patch area ($19.42 \times 14.69\,\text{mm}^2$). In case II, the higher resonant frequency is further shifted to 8.03 GHz with the incorporation of second slot, $W_2 = 2\,\text{mm}$, $L_2 = 3\,\text{mm}$. In case III, when the patch is incorporated with another slot of dimension, $W_3 = 6\,\text{mm}$, $L_3 = 2\,\text{mm}$, the first resonant frequency is achieved at $f_1 = 4.3\,\text{GHz}$ and second resonant frequency at $f_2 = 8.03\,\text{GHz}$ with reflection coefficients below $-10\,\text{dB}$. The size of the antenna is further reduced to 44%, and the frequency ratio is enhanced to 1.867. It can be observed from Figure 7(a) that the current density is much stronger around the edges of the slot (W_1, L_1 and W_3, L_3) at 4.3 GHz. So, the slots (W_1, L_1 and W_3, L_3) have influence on the resonant frequency 4.3 GHz. The first resonant frequency 4.3 GHz is mainly generated and controlled due to the addition of the optimized slots $W_1 = 4\,\text{mm}$, $L_1 = 3\,\text{mm}$, $W_3 = 6\,\text{mm}$, $L_3 = 2\,\text{mm}$. As shown in Figure 7(b), the surface current density is much concentrated around slot (W_2, L_2) at 8.03 GHz. So, the resonant frequency 8.03 GHz is mainly generated by the optimized slot of dimension $W_2 = 2\,\text{mm}$, $L_2 = 3\,\text{mm}$ of the proposed antenna 1. Because of the presence of the slots, there is a change in the surface current of the microstrip patch that changes the resonance behavior of the patch. This is because when slots are cut along the surface of the rectangular patch, the electric and magnetic field distribution changes due to the lengthening of the surface current around the slots. The current mainly concentrates at edges of the slots and thereby increases the current path. Due to lengthening of the surface current around the slots, the resonant frequency decreases.



(a) (b)

Figure 7. Surface current distributions of Antenna 1 at (a) 4.30 GHz, (b) 8.03 GHz.

5. PARAMETRIC STUDY OF ANTENNA 2

The parametric study of the proposed antenna has been carried out using Method-of-Moment-based IE3D software to study the effect of ground plane slot dimensions on the performance of the proposed antenna and the results are shown in Figure 8. The result of Figure 8 is shown in Table 2.

It is clear from results mentioned in Table 2 that with any further decrease in the ground plane slot parameters compared to the proposed slot dimensions, the miniaturization of the antenna, centre frequency ratio in the lower band and fractional bandwidth are much less. The further increase in slot dimension improves the operating bandwidth in upper band, but lower resonant frequency 2.1 GHz is not achieved. As a result, size reduction of only 17% is achieved. So, the proposed slot parameters are the optimal dimensions of the antenna.

6. ANALYSIS AND WORKING OF ANTENNA 2

The working principle of antenna 2 can also be explained with the help of distribution of surface current. The effect of each optimized ground plane slot on the resonance behavior of the proposed antenna 2 is depicted in Figure 9. The simulated surface current distributions at the defected ground plane of the proposed antenna 2 at different frequencies (2.1 GHz, 3.33 GHz and 7.14 GHz) are shown in Figures 10(a)–10(c), respectively. As depicted in Figure 9, the resonance behavior of antenna 2

Table 2. Simulated results of antenna 2 by varying the dimensions of the ground plane slots.

Ground plane Slot dimensions (mm)	Ratio of removed area/ Total ground plane area (%)	Operating Centre frequency (GHz)	−10 dB bandwidth (GHz)	Size reduction (%)	Fractional Bandwidth (%)	Centre frequency ratio
$W_{g1}=4$, $L_{g1}=3$, $W_{g2}=3$, $L_{g2}=6$, $W_{g3}=3$, $L_{g3}=6$	48/528 = 9.09	$f_{c1}=2.63$, $f_{c2}=3.33$, $f_{c3}=6.445$	(5.95–7.39)	43.24	21.6	$\frac{f_{c2}}{f_{c1}}=1.266$ and $\frac{f_{c3}}{f_{c2}}=1.935$
$W_{g1}=5$, $L_{g1}=4$, $W_{g2}=4$, $L_{g2}=7$, $W_{g3}=4$, $L_{g3}=7$ (Proposed)	76/528 =14.39	$f_{c1}=2.1$, $f_{c2}=3.33$, $f_{c3}=6.375$	(4.75–8.0)	64	49	$\frac{f_{c2}}{f_{c1}}=1.585$ and $\frac{f_{c3}}{f_{c2}}=1.915$
$W_{g1}=6$, $L_{g1}=5$, $W_{g2}=5$, $L_{g2}=8$, $W_{g3}=5$, $L_{g3}=8$	110/528 = 20.83	$f_{c1}=3.17$, $f_{c2}=6.505$	(4.68–8.33)	17	56	$\frac{f_{c2}}{f_{c1}}=2.052$

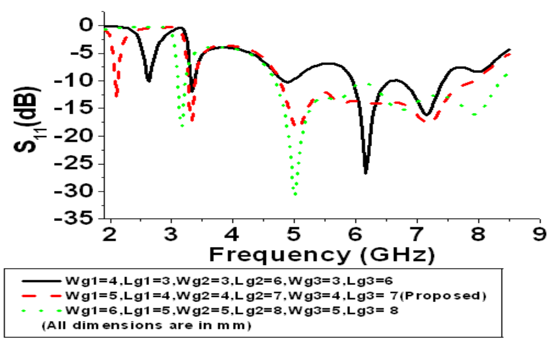


Figure 8. Reflection coefficient vs. frequency of antenna 2 as a function of varying dimension of ground plane slots.

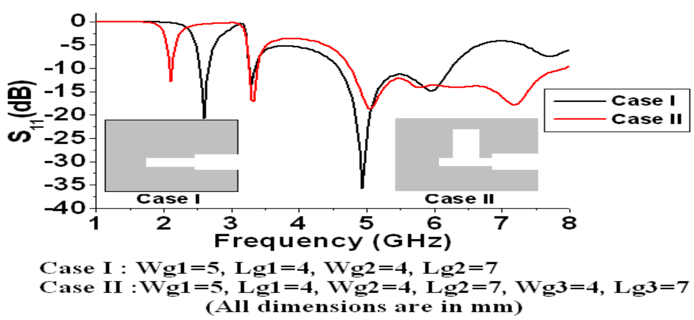


Figure 9. Effect of optimized ground plane slots on reflection coefficient of antenna 2.

changes drastically with the addition of each optimized slot on the ground plane of the antenna. In case I, the introduction of step graded rectangular horizontal optimized slot of dimensions, $W_{g1} = 5$ mm, $L_{g1} = 4$ mm and $W_{g2} = 4$ mm, $L_{g2} = 7$ mm on the ground plane makes the antenna resonate at 2.59 GHz, 3.29 GHz with reflection coefficients below −10 dB, and the antenna also provides a broad impedance bandwidth of 1.70 GHz (4.55–6.25 GHz) for $S_{11} < -10$ dB. Finally in case II, the incorporation of an optimized vertical slot $W_{g3} = 4$ mm, $L_{g3} = 7$ mm has further reduced the first resonant frequency to 2.1 GHz, but the other resonant frequency 3.29 GHz remains unaltered. It has also increased the operating bandwidth of the antenna. The frequency band gets wider by 1750 MHz, and the −10 dB bandwidth of the antenna is 3.25 GHz (4.75–8.0 GHz). It is also clear from Figure 10(a) that the surface current density at 2.1 GHz is much stronger around the slot (W_{g2}, L_{g2}, and W_{g3}, L_{g3}) for which it is generated. The current density at 3.33 GHz is mainly concentrated around the step graded rectangular horizontal slot (W_{g2}, L_{g2}, and W_{g1}, L_{g1}) as shown in Figure 10(b). It can be verified from Figure 10(c) that the incorporation of vertical slot has enhanced the operating bandwidth by widening the frequency at the upper side bands. It can be observed from Figure 10(c) that at upper band frequency 7.14 GHz, the current density is very strong and mainly circulates around the slot (W_{g3}, L_{g3}) which creates extra resonance path and varies the resonant frequency of the antenna. The currents along the edges of the step graded slots introduce additional resonance, in conjunction with the resonance of the patch produce an overall broadband frequency response characteristic. The bandwidth enhancement process

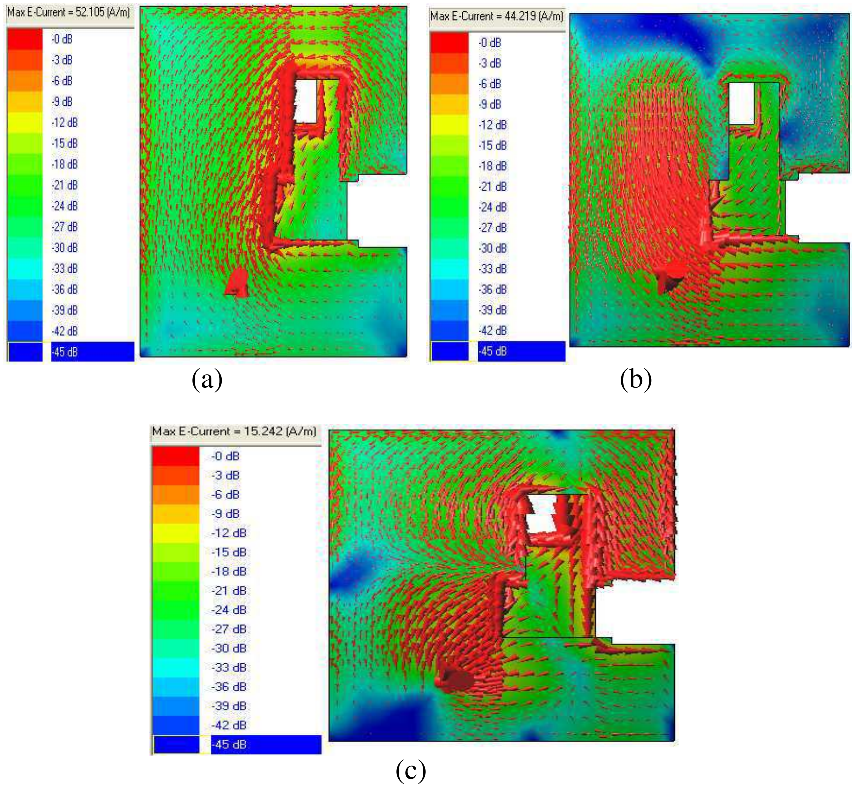


Figure 10. Current distributions on defected ground plane of antenna 2 at (a) 2.1 GHz, (b) 3.33 GHz, (c) 7.14 GHz.

may also be realized by obtaining multiple resonant frequencies that radiate very close to each other under −10 dB level, and their resonance envelopes provide the desired bandwidth.

7. SIMULATION AND EXPERIMENTAL RESULTS

The simulated and measured reflection coefficient curves of proposed antenna 1 and antenna 2 are shown in Figures 11–12. The reflection coefficient of the fabricated antenna structuresis measured using Agilent E5071B vector network analyzer. As shown in Figure 11, the simulated resonant frequencies of antenna 1 are obtained at 4.3 GHz and 8.03 GHz with reflection coefficients of about −19.44 dB and −17.4 dB, respectively. The measured result of antenna 1 provides first resonant frequency at 4.25 GHz and second resonant frequency at 7.78 GHz with reflection coefficients −17.5 dB and −16.3 dB, respectively.

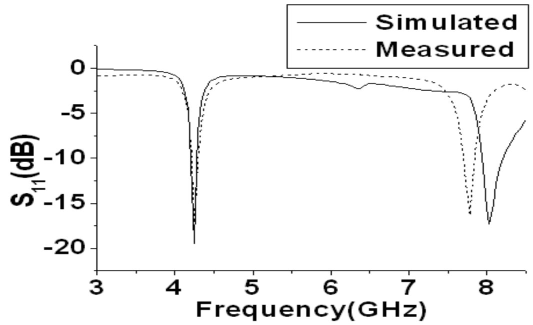


Figure 11. Simulated and measured reflection coefficient of antenna 1.

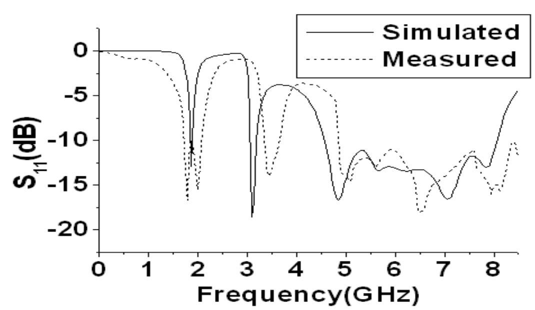


Figure 12. Simulated and measured reflection coefficient of antenna 2.

In Figure 12, the simulated result of antenna 2 shows two different resonant frequencies at 2.1 GHz and 3.33 GHz with reflection coefficients of about −13 dB and −18.5 dB, respectively. The simulated result also shows a wide bandwidth of 3250 MHz (4.75–8.0 GHz) for −10 dB reflection coefficient. The measured result shows first resonant frequency at 1.79 GHz with bandwidth ($S_{11} < -10$ dB) about 360 MHz from 1.72–2.08 GHz at lower band, second resonant frequency at 3.5 GHz with bandwidth about 300 MHz from 3.36–3.66 GHz at middle band and a wide operating bandwidth of 3650 MHz from 4.85–8.5 GHz at the upper band. The slight discrepancy between the measured and simulated results is due to the effect of improper soldering of SMA connector or fabrication tolerance. The measured result shows that the size of the proposed antenna 2 has been reduced by 74% in comparison to the conventional rectangular microstrip antenna operating at 1.79 GHz with patch area ($51 \times 39.65\,\text{mm}^2$). The measured peak gain of antenna 1 is 4.9 dBi at 8.03 GHz. The gain variation of the proposed antenna 2 is shown in Figure 13. The measured peak gain about 3.1 dBi is achieved at middle band frequency 3.34 GHz, and 2.84 dBi is achieved at upper band frequency 7.15 GHz for antenna 2, which is better than the peak gains of triple band antennas designed with defected ground plane [16, 17]. The normalized E plane radiation patterns of antenna 1 at 4.25 GHz and 7.78 GHz are shown in Figures 14(a) and 14(b), respectively. The radiation pattern of antenna 1, designed with simple ground plane exhibits unidirectional characteristics with maximum radiation along 0°. The normalized E plane radiation patterns of antenna 2 at 2.1 GHz, 3.4 GHz and 7.14 GHz are shown in Figures 15(a)–15(c), respectively. Due to defected ground plane, antenna 2 shows bidirectional characteristics. The bidirectional characteristics are achieved due to partial removal of conducting material below the radiating patch. The removed (defected) area is only 14.39% of the total ground plane dimension. Depending on the shape and dimensions of the defect on the ground plane, the shielded current distribution in the ground plane is disturbed which results in a controlled excitation and propagation of the electromagnetic waves through the substrate layer. This disturbance will cause change in radiation characteristics of the proposed antenna. The measured 3 dB beam width of antenna 2 is 71° at 2.1 GHz, 72° at 3.4 GHz and 74° at 7.14 GHz.

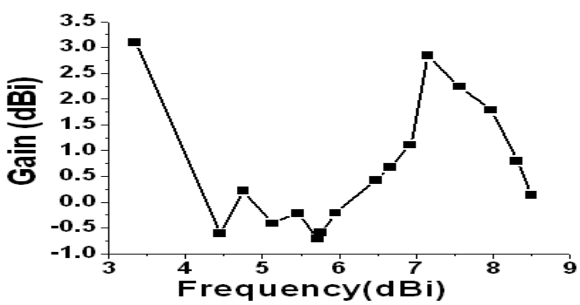
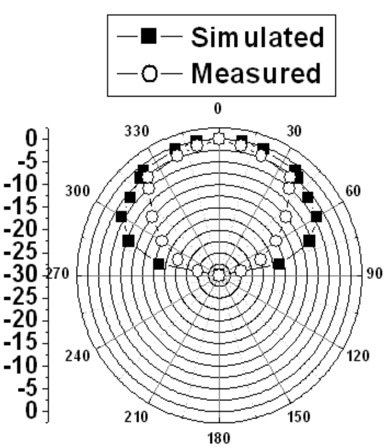
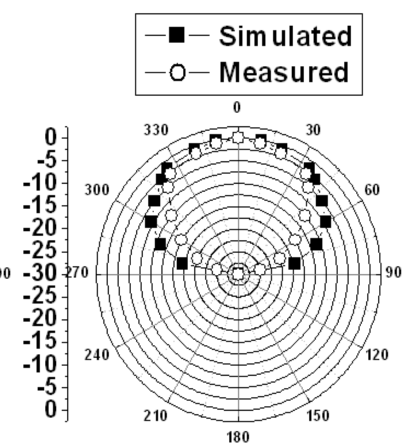


Figure 13. Plot of peak gain vs. frequency of proposed antenna 2.



(a)



(b)

Figure 14. Normalized E plane radiation pattern of antenna 1 (a) 4.25 GHz, (b) 7.78 GHz.

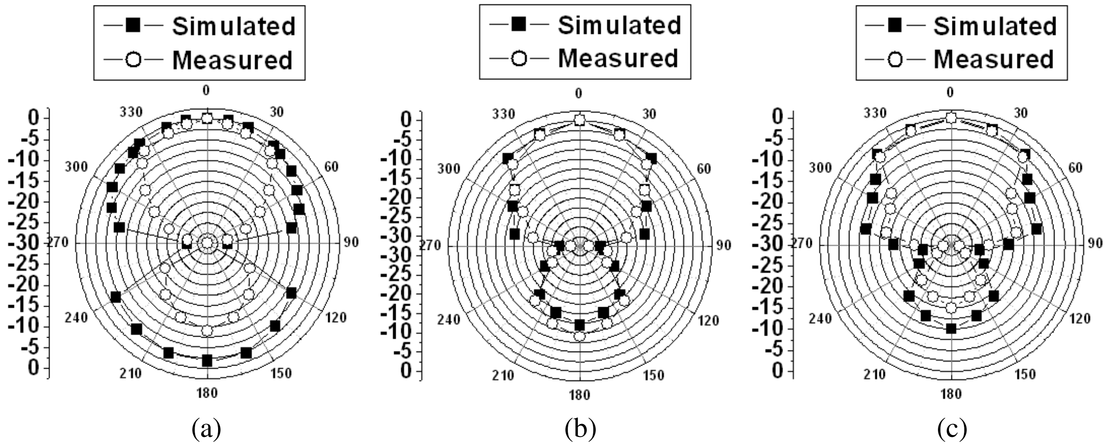


Figure 15. Normalized E plane radiation pattern of antenna 2 (at) 2.1 GHz, (b) 3.4 GHz, (c) 7.14 GHz.

8. PERFORMANCE COMPARISON OF THE PROPOSED ANTENNA WITH OTHER REFERENCE WORKS

The performance comparison of the proposed antenna with some other triple band antennas is shown in Table 3. It is clear from the table that the proposed antenna has not only smaller size, but also better impedance bandwidth and centre frequency ratio. The proposed antenna covers the bandwidth requirement of a number of modern wireless communication application bands such as PCS (1.85–1.99 GHz), PHS (1.88–1.93 GHz), WiMAX (3.4–3.6 GHz, 5.25–5.85 GHz), High speed WLAN (5.15–5.35 GHz, 5.725–5.825 GHz), HisWaNa (5.15–5.25 GHz) and HiPERLAN (5.47–5.725 GHz).

Table 3. Performance comparison of the proposed antenna with other triple band antenna.

Works	Antenna Dimensions mm^2	Operating Bands (GHz)	Centre frequency ratio
Ref. [9]	20×38	2.36–2.56, 3.48–4.10, 5.65–7.03	1.54, 1.67
Ref. [10]	25×38	2.35–2.8, 3.4–3.7, 5.05–5.91	1.37, 1.55
Ref. [11]	35×35	2.37–2.7, 3.3–3.74, 5.05–5.91	1.38, 1.55
Ref. [12]	27×39.5	2.42–2.70, 3.46–4.46, 5.72–5.85	1.56, 1.46
Ref. [13]	26×36	2.38–2.82, 3.32–3.88, 5.13–6.53	1.38, 1.61
Ref. [14]	20×37	2.40–2.65, 3.3–4.05, 5–5.98	1.45, 1.49
Ref. [15]	20×30	2.14–2.52, 2.82–3.74, 5.15–6.02	1.48, 1.59
Ref. [16]	25×38	2.4–2.7, 3.1–4.15, 4.93–5.89	1.42, 1.49
Ref. [17]	20×27	2.38–2.56, 3.39–3.77, 5.08–5.36	1.44, 1.45
This Paper	22×24	1.72–2.08, 3.36–3.66, 4.85–8.5	1.84, 1.88

9. CONCLUSIONS

Theoretical and practical investigations on single-layer, single-feed microstrip patch antennas have been carried out in this work. Antenna 1 provides dual-frequency operation by introducing slots on the radiating patch. The proposed miniaturized antenna 2, designed with combination of slotted patch and defected ground plane, provides triple-frequency band with fractional bandwidths about 19%, 8.5% and 54.7%. Bidirectional radiation pattern characteristics with acceptable amount of 3 dB beam width over the operating bands are also obtained for the proposed antenna 2. The proposed antenna 2 is suitable for a number of wireless communication application bands such as PCS, PHS, WLAN, HiPERLAN, HisWaNa and Wi-MAX due to its compact size, low cost and wide operating bandwidth.

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