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Design Analysis and Modeling of Directional UWB Antenna with Elliptical Slotted Ground Structure for Applications in C- & X-Bands

Madan L. Meena*, Mithilesh Kumar, Girish Parmar, and Ram S. Meena

Abstract—A modified technique to design directional ultra-wideband (UWB) antenna with slotted ground structure approach on the ground plane has been presented for applications in C- and X-bands. Initially, elliptical slot is inserted into ground and thereafter, the axis of ellipse is rotated 45 degrees in direction of the substrate. Minor axis of the ellipse is optimized to locate it symmetrically around the circular patch in order to obtain the full C- and X-band operations and also to enhance directivity. Thereafter, for further improvement in the directivity as well as gain, an elliptical slot in circular patch has also been introduced. The impedance bandwidth approximates about 95% covering the frequency ranging from 4.18–11.50 GHz. The return losses (S_{11}) are −38 dB and −43 dB through simulation, which are −24 dB and −32 dB by measurement at 6.3 GHz, 9.3 GHz resonant frequencies, respectively. Simulated gain and half power beam width (HPBW) are 2.5–8.4 dB and 49–22 degrees in 4.18–11.50 GHz band, respectively. Gain and half power beam width (HPBW) of the proposed antenna improves by 1–2 dB and 5–10 degrees, respectively compared with previously designed antennas. Simulation of the antenna has been carried out on Computer Simulation Technology (CST) software on an FR-4 substrate having dielectric constant 4.3 of thickness 1.6 mm. The measured results show good agreement with equivalent circuit model and CST simulation.

1. INTRODUCTION

Compactness, low cost and high speed of data rate are requirements of directional ultra-wideband (UWB) antennas in modern communication systems. The Federal Communication Commission (FCC) has allotted 7.5 GHz of bandwidth which covers the frequency range of 3.1 to 10.6 GHz for unlicensed UWB applications [1]. Numeral designs of directional ultra-wideband antennas have already been reported with coplanar waveguide (CPW) and microstrip feed line. These UWB antennas can be realized by different shapes of patch and slots or defected structures in ground [2–12]. The comparisons of different shapes such as octagonal, fractal, circular and triangular shapes of the patch as well as slot were carried out in ground to reduce the antenna size with respect to conventional antennas [2–12].

The impedance bandwidth can be improved by using Defected Ground Structure (DGS) or slot in any antenna. The multiple resonance frequency can be achieved while using multiple slots. Therefore, the result in ultra-wideband nature can be obtained by combining multiple resonances jointly [13]. Recently, the concept of DGS and fractal geometry (FG) are in use to enhance the performance of an antenna. Fractal shapes of the radiating element give multi-band resonance with single antenna as well as miniaturize the antenna design [14, 15]. One of the significant aspects of choosing a directional UWB antenna design is to ensure that the design will not cause the pulse to spread over large bandwidth and in low power pulses [16].

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* Corresponding author: Madan Lal Meena (madan.meena.ece@gmail.com).
The authors are with the Department of Electronics Engineering, Rajasthan Technical University, Kota, India.

The main aim of directional antenna is to increase directivity as it optimizes the half power beam width (HPBW) for long distance communication systems [17, 18]. Various designs have recently been introduced which demonstrate wide impedance bandwidth, high flat gain and directional radiation patterns including the Horn or Vivaldi antennas [19, 20]. The parabolic shaped ground plane acts as a reflector or L-shaped wideband monopole antennas have been demonstrated for see-through-wall, radar and microwave breast cancer imaging applications [21–23]. The optimization of the ground plane with CPW feed has already been reported with different shapes of antenna patch [24, 25].

Recently, a directional ultra-wideband (UWB) antenna has been designed with modified parabolic ground plane by inserting the T-slots diagonally at corners of parabolic ground plane [26]. In [27], a wideband planar antenna was designed with slotted ground plane having optimized radiating patch controlled by disturbing antenna current circulation. The deviation of slot length and width in ground as well as patch can increase/decrease the effective inductance and capacitance of the antenna [28, 29].

In the present work, a modified technique to design directional ultra-wideband (UWB) antenna with slotted ground structure approach has been given. The proposed antenna is appropriate for operation in C- and X-bands. Inserting an elliptical slot in a circular patch, the antenna resonates in five modes. The first three resonant frequencies 4.5 GHz, 6.3 GHz, 7.5 GHz cover up C-band, and the last two frequencies 9.3 GHz, 10.8 GHz cover up X-band operation entirely, compared to previously designed antennas [29–33]. The proposed design achieves 95% impedance bandwidth in UWB frequency range 4.10–11.5 GHz. The half power beam width (HPBW) moves between 49° and 22° degrees, and the gain improves between 1–2 dB in comparison to previously reported antennas [21–26].

The proposed research is planned as follows. Section 2 elaborates the design and arrangement of the proposed antenna. Development process of directional ultra-wideband antenna is given in Section 3. The modeling analysis of slotted ground structure and elliptical slotted circular patch UWB antenna is demonstrated in Section 4. Parametric analysis, simulation and experimental results are given in Section 5. Comparative results analysis and their discussions are presented in Section 6. Finally, based on the above, conclusions are reported in Section 7.

2. DESIGN AND ARRANGEMENT OF PROPOSED ANTENNA

The proposed antenna is designed by arrangement of elliptical slotted ground structure and circular patch as shown in Fig. 1. The circular patch with radius r of the antenna has been executed by subtracting an elliptical slot from the patch. To preserve the impedance bandwidth and directivity of the proposed antenna, it has been designed and fabricated on an FR-4 substrate with dielectric constant $\varepsilon_r = 4.3$ of loss tangent $\tan\delta = 0.02$ and dimensions $L = 50$ mm, $W = 50$ mm and $H = 1.6$ mm, which are the length, width and height (thickness) of the substrate, respectively. The microstrip feed line width $W_F = 3$ mm and length $L_F = 7.2$ mm have been selected in the x, y directions, respectively to obtain the $50\,\Omega$ impedance matching. In the reverse of substrate there is an elliptical shaped ground plane as shown Fig. 1(b), which is designed carefully to improve the directivity. As can be seen in Fig. 1, major and minor axis of elliptical slotted curve on ground plane has been inserted based on the equation:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1 \tag{1}$$

where, a and b are the lengths of major and minor axes along x and y directions, respectively. The major and minor axes of the elliptical slotted curve are placed in x and y directions at $a = 24$ mm, $b = 20$ mm, respectively. The minor axis of the ellipse is optimized to locate it symmetrically around the circular patch. The elliptical curve is rotated 45 degrees in direction of the substrate to increase the impedance bandwidth (higher cut-off frequency). The main purpose of this effort is to obtain complete C & X-bands operation and to increase directivity. Also, for the purpose of improvement in reflection coefficient, gain and directivity, an elliptical slot is inserted in circular patch with the help of Equation (1). The major and minor axes of elliptical slotted curve on the patch are located at $a_1 = 6$ mm, $b_1 = 3$ mm, in x and y directions, respectively. The detailed design parameters of the proposed antenna have been given in Table 1.

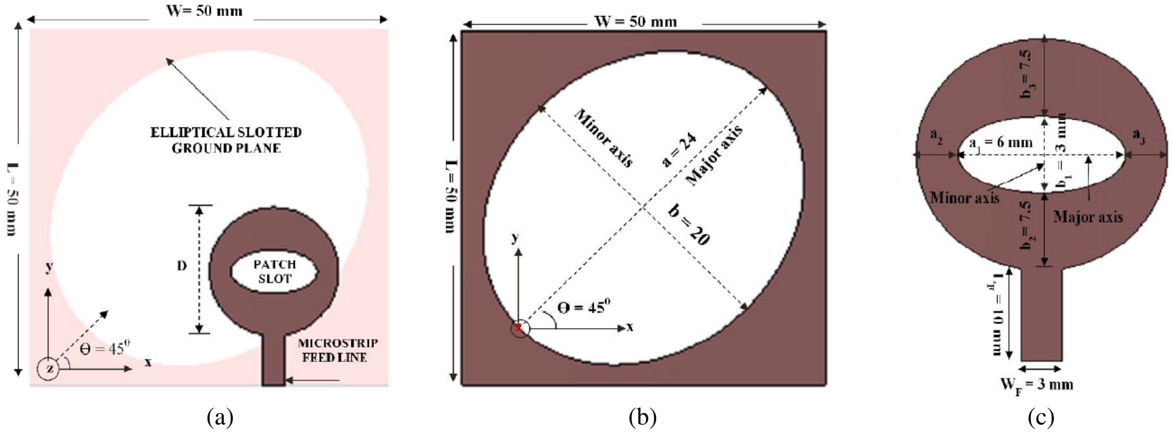

Figure 1. Arrangement of proposed UWB Antenna: (a) Systematic front view structure; (b) Back View of elliptical slotted ground structure; (c) Front view of elliptical slotted circular patch with all dimensions.

Table 1. Design parameters of the proposed UWB antenna.

Parameters	L	W	H	D	r	ε_r	$\tan\delta$
Dimensions (mm)	50	50	1.6	18	9	4.3	0.02
Parameters	L_F	W_F	a	b	a_1	b_1	Θ
Dimensions (mm)	10	3	24	20	6	3	45°
Parameters	a_2	b_2	a_3	b_3			
Dimensions (mm)	6	7.5	6	7.5			

The lowest resonance frequency of the circular patch can be obtained by the equations [10]:

$$f_r = \frac{1.8412 \cdot v_0}{2\pi \cdot a \cdot \sqrt{\epsilon_{reff}}} \tag{2}$$

$$a = r\left\{1 + \frac{4H}{2\pi \cdot r \cdot \varepsilon_r}\left[\ln\left(\frac{2\pi \cdot r}{4H}\right) + 1.77\right]\right\}^{0.5} \tag{3}$$

where, f_r is the antenna resonance frequency, v_0 the light in free space, and a and r are the effective radius and physical radius of the circular patch, respectively. When, $r = 9$ mm, then from Equations (2)–(3), the first resonance frequency of the proposed antenna can be calculated which is 4.5 GHz.

3. DEVELOPMENT PROCESS OF UWB ANTENNA

The configuration and performance of the proposed antenna can be enhanced by slotted ground structure approach and by modifying the radiating elements. The step by step development process of the designed directional UWB antenna and its subsequent simulated return loss (dB) variation plots are shown in Figs. 2 and 3, respectively. According to the design, without rotation of elliptical slotted ground as shown in Fig. 3, the impedance bandwidth of 79% in the band of 3.9–9 GHz at double resonance frequencies 5.4 GHz and 7.3 GHz can be obtained. Further, to improve impedance matching, axis of elliptical slot is rotated 45 degrees in the direction of the substrate as shown in Fig. 2(b). As shown in Fig. 3, the higher cut-off frequency at 9 GHz shifts below −10 dB. Hence, 93% impedance bandwidth can be obtained, which can cover up the UWB band of 4.2–11.5 GHz which in turn increases the higher cut-off frequency up to 11.5 GHz. Furthermore, to enhance the impedance bandwidth as well as directivity, an elliptical slot in the circular patch has been introduced as shown in Fig. 2(c). As can be seen in Fig. 3, the lower cut-off frequency is reduced by 0.1 GHz; therefore, the 95% impedance bandwidth can be achieved in the UWB band of 4.1–11.5 GHz.

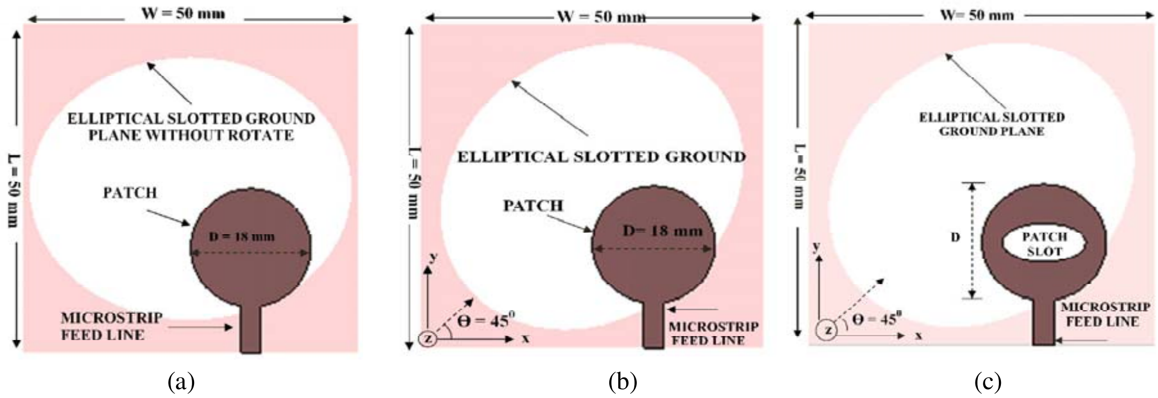

Figure 2. Development process of proposed UWB antenna: (a) Elliptical slotted ground structure without rotation; (b) Elliptical slotted ground structure rotate at $\Theta = 45°$; (c) Elliptical slotted circular patch antenna.

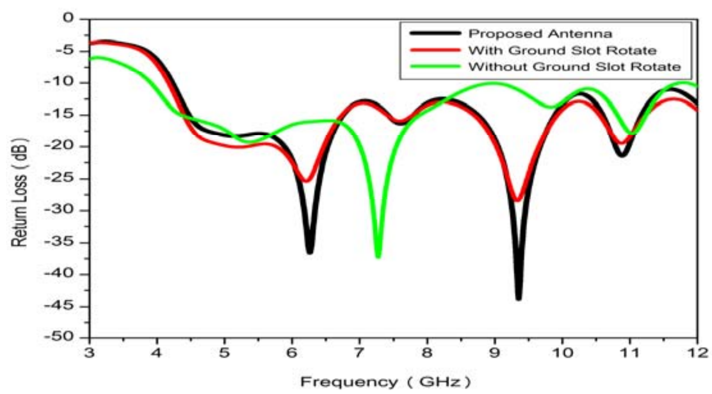

Figure 3. Simulated return loss (S_{11} dB) variation plot for antenna without ground slot rotation, with ground slot rotation and proposed elliptical slotted circular patch antenna.

Finally, it can be concluded that the slotted ground structure with modified circular patch antenna improves the impedance matching characteristic at lower as well as higher resonance frequencies. Impedance bandwidth is 95% (4.1–11.5 GHz) at 4.5 GHz, 6.3 GHz, 7.5 GHz, 9.3 GHz and 10.8 GHz resonance frequencies. Hence, the proposed directional ultra-wideband antenna is appropriate for C- and X-band operations in comparison to previously designed antenna [33].

4. MODELING ANALYSIS

4.1. Modeling Analysis of Slotted Ground Structure

The equivalent circuit model for the proposed elliptical slotted ground plane is shown in Fig. 4. Elliptical slotted ground structure generally consists of more than one emission resistors in parallel, with L_s-C_s tank circuit arrangement, as shown in Fig. 4. The proposed slotted ground structure produces resonance frequencies, while the current propagates along the slot edges. Therefore, inductance L_s and capacitance C_s can be introduced in the circuit model. Increasing length of major axis of the elliptical slot is analogous to enhancement in the value of the inductor whereas; minor axis length of the elliptical slot is similar to a capacitor. It can be noted that the impedance bandwidth and resonance frequency can be controlled or adjusted by changing the values of inductor L_s and capacitor 'C_s' [28].

The input admittance of the proposed elliptical slotted ground resonator can be given by:

$$Y_{in} = j\omega \cdot C_s + \frac{1}{j\omega \cdot L_s} + \frac{1}{R_{(n+1)k}} \quad (4)$$

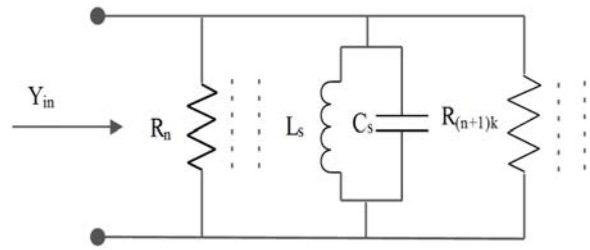

Figure 4. Equivalent circuit model of elliptical slotted ground structure.

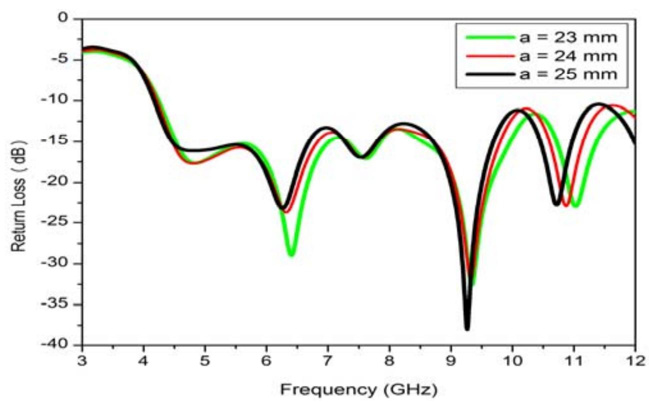

Figure 5. Effect of elliptical ground slot major axis length 'a' on return loss of the antenna.

where, n stands for the location of the elliptical slot resonator. Also, the radiation resistances (R_n to $R_{(n+1)k}$) are given by:

$$\frac{1}{R_n} = \frac{1}{R_1} + \cdots + \frac{1}{R_n}, \quad \frac{1}{R_{(n+1)k}} = \frac{1}{R_{(n+1)}} + \cdots + \frac{1}{R_k} \tag{5}$$

The impedance bandwidth of the proposed directional UWB antenna depends on the position of the elliptical slot axis location a and b. Figs. 5–6 show the simulated return loss variation with different positions of the elliptical slot major/minor axis length, respectively. It can be observed from Fig. 5 that as the elliptical slot axis length increases, the higher cut-off frequency shifts to lower side, and lower resonances are slightly shifted to lower cut-off side. Further, when the major axis length is fixed at $a = 24$ mm, the impedance matching improves at lower resonance frequency of 4.5 GHz (see Fig. 5). Hence, 93% impedance bandwidth in the frequency band of 4.2–11.5 GHz can be obtained. The return losses are −17 dB, −23 dB, −16 dB, −34 dB and −23 dB at resonance frequencies 4.5 GHz, 6.2 GHz, 7.5 GHz, 9.3 GHz and 10.8 GHz, respectively.

On the other hand, the simulated return loss variations with minor axis slot length b are shown in Fig. 6. When minor axis of the elliptical slot is located between $b = 19$ mm and 21 mm, the frequency bands of 4.1–7.0 GHz, 4.1–11.5 GHz and 6.0–12 GHz at different minor axis slot locations of $b = 19$ mm, $b = 20$ mm and $b = 21$ mm, respectively, have been observed. Further, minor axis of the ellipse has also been optimized and is located symmetrically around the circular patch at $b = 20$ mm. Hence, the lower cut-off frequency is shifted from 6 GHz ($b = 19$ mm) to 4.1 GHz with respect to −10 dB reference line. Therefore, the UWB frequency band of 4.1–11.5 GHz can be achieved by selecting the elliptical slot minor axis location at $b = 20$ mm. This band is suitable for whole C- and X-band applications.

From the above analysis, it can be concluded that the impedance bandwidth and resonance frequency can be controlled by increasing the length of the major/minor axis of elliptical slot. Therefore, increasing the length of elliptical slot axis is similar to increase in the value of inductor L_s. Similarly, increase in the length of minor axis slot is equivalent to decrease in the value of capacitor C_s.

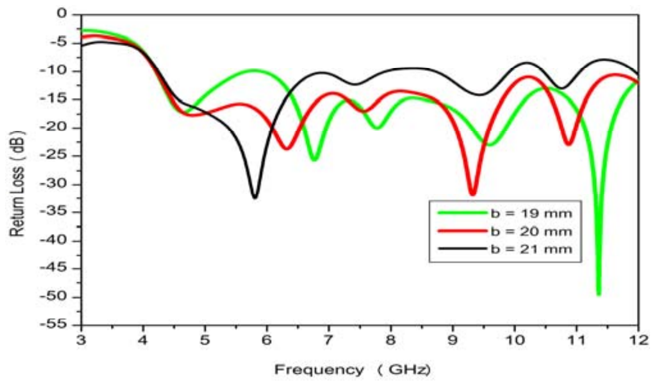

Figure 6. Effect of elliptical ground slot minor axis length 'b' on return loss of the antenna.

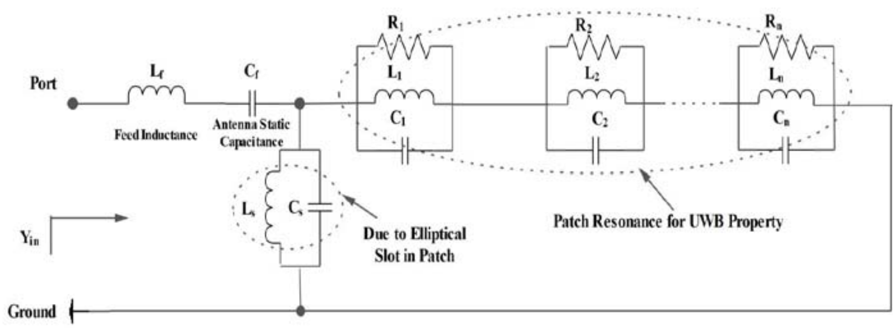

Figure 7. Equivalent circuit model for elliptical slotted circular patch UWB antenna.

4.2. Modeling Analysis of Elliptical Slotted Circular Patch UWB Antenna

In communication systems, the antenna can be represented by 50 ohm load impedance for the purpose of perfect matching. For the design of ultra-wideband antenna, matching bandwidth can be achieved by a number of nearby resonances, and each resonance can be represented by parallel R-L-C tank circuit in series arrangement [34]. The equivalent circuit model of the proposed elliptical slotted circular patch UWB antenna is shown in Fig. 7. Equivalent circuit consists of L_f-C_f series cell, which can be represented by the microstrip feed inductance and static capacitance of the antenna, respectively. The parallel L_s-C_s cell stands for the inductance and capacitance due to elliptical slot in the circular patch, and the values of inductance (L_s) and capacitance (C_s) depend on the length of major axis a_1 and minor axis b_1 slots of the designed antenna.

The input impedance without considering component (L_s-C_s) of the circuit model can be expressed by:

$$Z_{in} = j\frac{(\omega^2 \cdot L_f C_f - 1)}{\omega \cdot C_f} + \sum_{n=1}^{k} j\frac{\omega \cdot R_n L_n}{R_n \cdot (1 - L_n C_n \cdot \omega^2) + j\omega \cdot L_n} \tag{6}$$

To calculate the values of the components, only real part is considered:

$$R_r = \sum_{n=1}^{k} \frac{R_n}{1 + R_n \left(\frac{1}{\omega \cdot L_n} - \omega \cdot C_n\right)^2} \tag{7}$$

Further, the proposed equivalent circuit model is discussed by considering the elliptical slot element (L_s-C_s) and real radiation resistance (R_r) of the antenna element, as given in Equation (7). The total input admittance of the equivalent circuit model is given by:

$$Y_{in} = \frac{1}{R_r} + \frac{1}{j\omega \cdot L_s} + j\omega \cdot C_s \tag{8}$$

Again, the effects of the values of inductor and capacitor on bandwidth and resonance frequencies due to the parallel R-L-C and L_s-C_s slot resonator have been discussed. The resonance frequency can be expressed as [28]:

$$\omega_o = \frac{1}{\sqrt{L_s C_s}} \quad \text{and} \quad \omega = \omega_o + \Delta\omega \tag{9}$$

Simplifying the Equation (8):

$$Y_{in} = \frac{1}{R_r} + \frac{j}{\omega \cdot L_s}(\omega^2 \cdot L_s C_s - 1) \tag{10}$$

From Equations (9) and (10):

$$\begin{aligned} Y_{in} &= \frac{1}{R_r} + \frac{j}{\omega \cdot L_s}\left(\Delta\omega^2 + 2\omega_o \cdot \Delta\omega\right) \cdot L_s C_s \\ Y_{in} &\approx \frac{1}{R_r} + j\Delta\omega \cdot 2C_s \end{aligned} \tag{11}$$

Y_{in} is equal to the input admittance of a parallel R_r and $2C_s$ circuit near zero GHz. Therefore, -3 dB bandwidth of the equivalent R-L-C resonance circuit almost doubles -3 dB bandwidth of the parallel R_r and $2C_s$ circuit, as given by:

$$\text{Bandwidth (BW)} = \frac{2}{R_r \cdot 2C_s} = \frac{1}{R_r \cdot C_s} \tag{12}$$

Now, from the above analysis, it can be concluded that the bandwidth (BW) and resonance frequencies can be increased/shifted by increasing the length of major axis slot, which is similar to increase in the value of inductor. On other hand, increase in the length of minor axis slot is equivalent to decrease in the value of capacitor.

The real and imaginary parts of the input impedance have been simulated by CST Microwave Studio software with numerous impedance data, as shown in Fig. 9. The six resonance modes are generated at 4 GHz, 6.2 GHz, 7.5 GHz, 9.3 GHz, 10.8 GHz and 11.5 GHz in the UWB range of 3.5–12 GHz. Inserting these data in Equations (7)–(9), the curve-fitting and iterative techniques have been used to calculate all the equivalent circuit components R_n, L_n, C_n, L_s and C_s [34]. The values of the circuit components are $R_1 = R_3 = R_5 = 3\,\Omega$, $R_2 = R_4 = R_6 = 4\,\Omega$, $L_1 = L_2 = L_s = 3$ nH, $L3 = 1.66$ nH, $L_4 = 1.08$ nH, $L_5 = 0.904$ nH, $L_6 = 0.709$ nH, $C_1 = 0.60$ pF, $C_2 = 0.30$ pF, $C_3 = C_5 = 0.24$ pF, $C_5 = C_6 = 0.27$ and $Cs = 0.35$ pF.

To validate the proposed equivalent circuit model, it has also been simulated on SERENIDE SV 8.5 circuit simulator as shown in Fig. 8. Fig. 9 compares the input impedance simulated by CST to

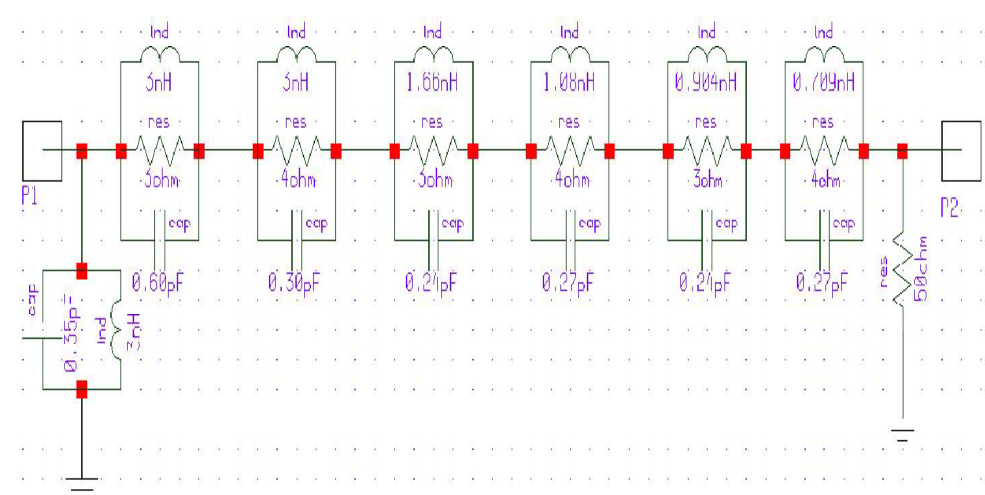

Figure 8. Equivalent circuit model of the proposed antenna is simulated by SERENIDE SV 8.5 circuit simulator.

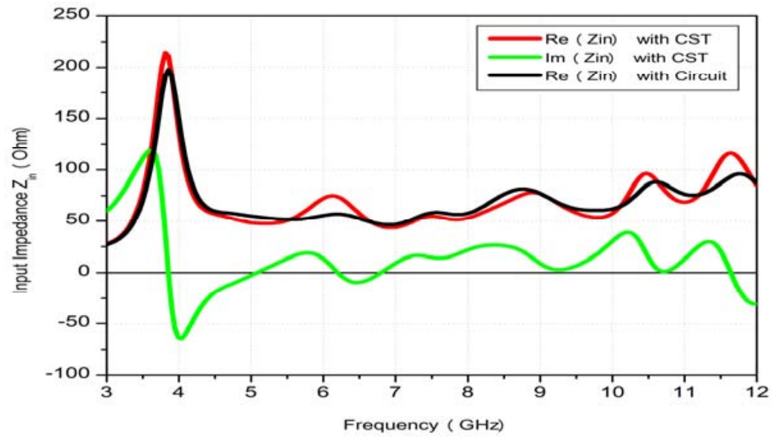

Figure 9. Comparative input impedance plot of the proposed antenna by CST and circuit simulator.

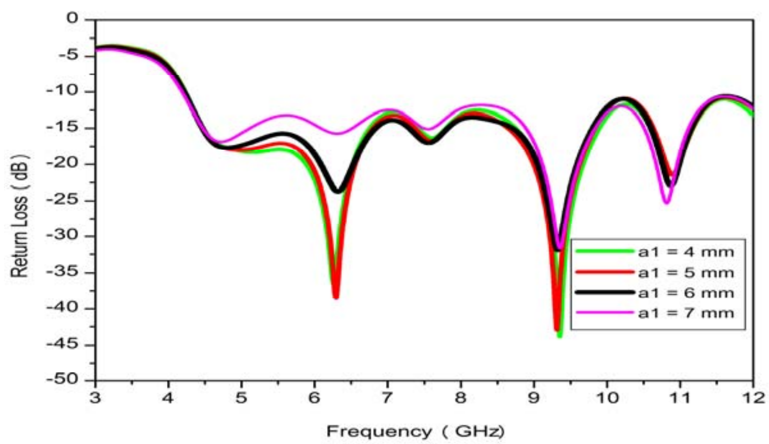

Figure 10. Effect of major axis length (a_1) of elliptical slotted patch on return loss (dB) of the proposed antenna.

that of the simulated by circuit simulator. It can be observed that the calculated parameters validate the equivalent circuit model.

5. EXPERIMENTAL AND PARAMETRIC ANALYSIS

In performance of the proposed antenna, location of the elliptical slot axis plays an important role. The effects of return loss variations with resonance frequency for different elliptical slot axis location on the ground as well as in circular patch are shown in Figs. 5–6 and Figs. 10–11, respectively. The comprehensive parametric studies about the ground slot with simple circular patch have already been discussed in Section 4.1. Here, only the discussions about the performance of the elliptical slot in circular patch have been given. It can be seen in Fig. 10 that by varying the length (a_1) of elliptical slot major axis of the circular patch from $a_1 = 4$ to 7 mm, the impedance matching improves on the lower resonance side near 4.5 GHz. It is further observed that the return loss performance also improves at $a_1 = 4$ mm and 5 mm, but impedance bandwidth slightly increases at $a_1 = 6$ mm. Therefore, the optimum value of length of elliptical slot in circular patch is taken as 6 mm in fabricated prototype.

Figure 11 shows the effect of return loss variation with change in minor axis slot length (b_1). It can be observed that by increasing the slot length (b_1), the lower resonance frequency shifts towards the lower resonance side, whereas upper resonance frequencies are more or less stable. Better impedance matching

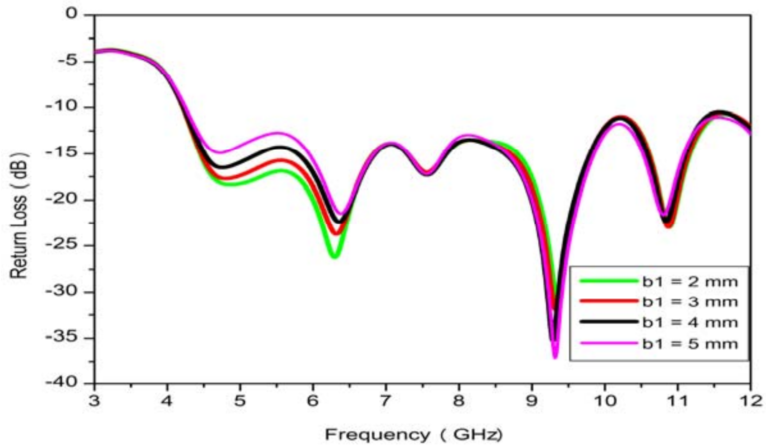

Figure 11. Effect of minor axis length (b_1) of elliptical slotted patch on return loss (dB) of the proposed antenna.

(a) (b) (c)

Figure 12. Images of the fabricated antenna and measurement setup (a) Front view; (b) Back view; (c) Proposed antenna measurement setup.

performance can be achieved between 4–6.5 GHz. As can be seen in Figs. 10–11, 95% impedance bandwidth can be achieved in the UWB band of 4.1–11.5 GHz at the best possible values of $a_1 = 6$ mm and $b_1 = 3$ mm.

The proposed directional UWB antenna has been fabricated with the optimized dimensions as given in Table 1, and measurements are carried out on the E5071C (ENA series Agilent Technologies) vector network analyzer (VNA) setup, as shown in Fig. 12. The measured results show a good agreement with equivalent circuit and CST simulation, which can be seen in Fig. 13. It has also been observed that a better return loss performance can be achieved at resonance frequencies 6.3 GHz and 9.3 GHz. The impedance bandwidth is 96% (4.2–12 GHz) by circuit simulator, 95% (4.1–11.5 GHz) under CST simulation as well as by the measurement. The designed antenna offers equal impedance bandwidth and operating frequency band by simulation as well as measurement. The calculated impedance bandwidth and variation of return loss among different resonance frequencies with elliptical axis locations are given in Table 2.

Figure 14 shows comparison of the measured and simulated gains of the proposed antenna with the reference antenna without patch slot as shown in Fig. 2(b). It can be seen in Fig. 14 that the gain of the proposed antenna improves 5.3–8.4 dBi because of better impedance matching between 4.1–10 GHz. Further, the gain also improves at higher resonance frequencies, i.e., above 5.6 GHz. The measured peak gains of 5.8, 7.5, 7.7, 7.5 and 7 dBi are observed at 5, 7, 8, 8.5 and 11.5 GHz, respectively, for C- and X-band applications.

Similarly, Fig. 15 shows the variation of the simulated directivity for different values of length of patch slot. The directivity of the proposed antenna has also been compared with the antenna without

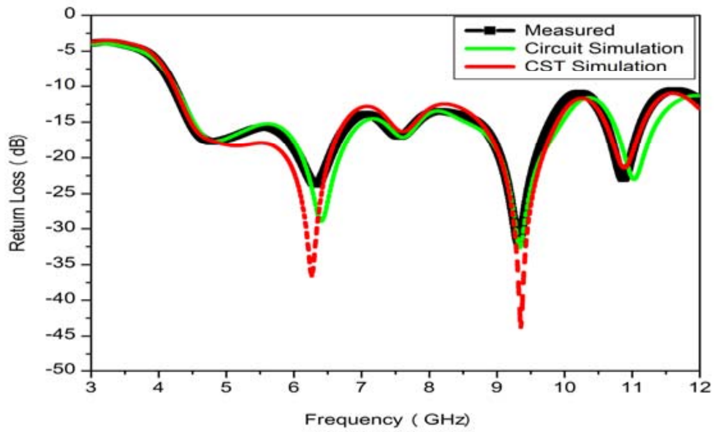

Figure 13. Comparison of measured return loss of the designed antenna with CST simulation and Circuit simulator.

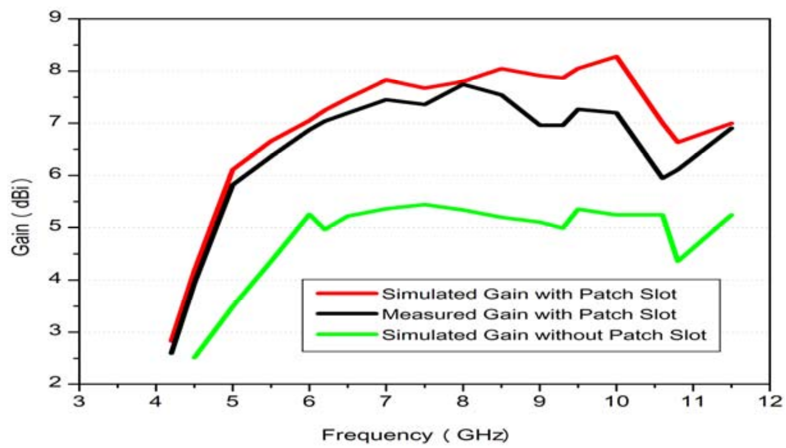

Figure 14. Comparison of measured and simulated gain of the proposed directional UWB antenna with the antenna without patch slot.

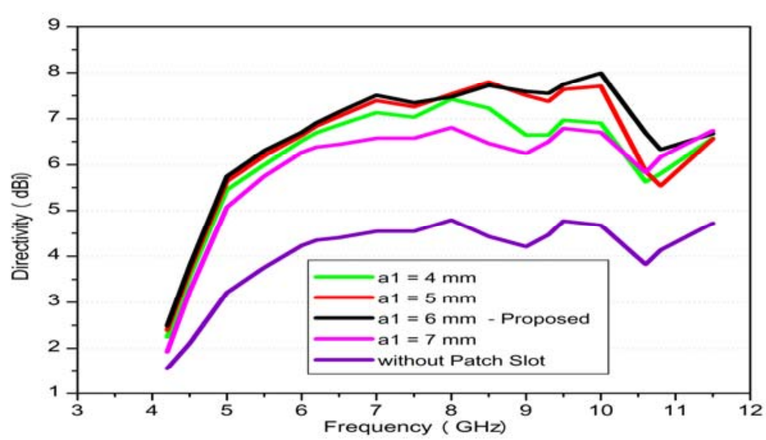

Figure 15. Variation of directivity versus frequency for different length of elliptical slotted circular patch too compare by the antenna without patch slot.

Table 2. Calculated impedance bandwidth and return loss performance with the variation of a, b, a_1, and b_1.

Elliptical Ground slot/patch slot	Parameters variation (mm)	Resonance frequencies (GHz)	Return loss (dB)	Frequency band (GHz)	Impedance bandwidth (%)
Major axis length of elliptical ground slot	$a = 23$	4.7/6.4/7.5/9.4/11	−17.5/ − 29/ − 17/ − 32.5/ − 23	4.2–12.0	96
	$\mathbf{a = 24}$	4.5/6.3/7.5/ 9.3/10.8	−17.5/ − 23/ − 17/ − 31/ − 23	4.2–11.5	93
	$a = 25$	4.6/6.2/7.4/9.3/10.6	−16/ − 22.5/ − 17/ − 38/ − 23	4.2–11.4	94
Minor axis length of elliptical ground slot	$b = 19$	6.7/7.7/9.5/11.4	−26/ − 20/ − 23/ − 50	6.0–12.0	67
	$\mathbf{b = 20}$	4.5/6.3/7.5/9.3/10.8	−18/ − 24/ − 17.5/ − 32/ − 22.5	4.2–11.5	93
	$b = 21$	5.8/7.5/9.5/10.7	−32.5/ − 12.5/ − 14/ − 13	4.1–07.0	52
Major axis length of patch slot	$a_1 = 4$	4.5/6.2/7.5/9.3/10.8	−18/ − 36.5/ − 17/ − 44/ − 22	4.2–11.6	94
	$a_1 = 5$	4.5/6.3/7.5/9.3/10.8	−18/ − 38/ − 17/ − 43.5/ − 22	4.2–11.5	93
	$\mathbf{a_1 = 6}$	4.5/6.3/7.5/9.3/10.8	−18/ − 24/ − 17/ − 32.5/ − 23	4.1–11.5	95
	$a_1 = 7$	4.4/6.4/7.5/9.3/10.6	−17/ − 16/ − 15/ − 32/ − 25	4.1–11.5	95
Minor axis length of patch slot	$b_1 = 2$	4.6/6.2/7.5/9.3/10.8	−17/ − 26/ − 17.5/ − 30/ − 22	4.1–11.5	95
	$\mathbf{b_1 = 3}$	4.5/6.3/7.5/9.3/10.8	−17.5/ − 24/ − 17.5/ − 32/ − 23	4.1–11.5	95
	$b_1 = 4$	4.4/6.4/7.5/9.3/10.8	−16/ − 22.5/ − 17.5/ − 35/ − 22.5	4.1–11.5	95
	$b_1 = 5$	4.4/6.4/7.5/9.3/10.8	−15/ − 21.5/ − 17.5/ − 37/ − 22	4.2–11.5	93

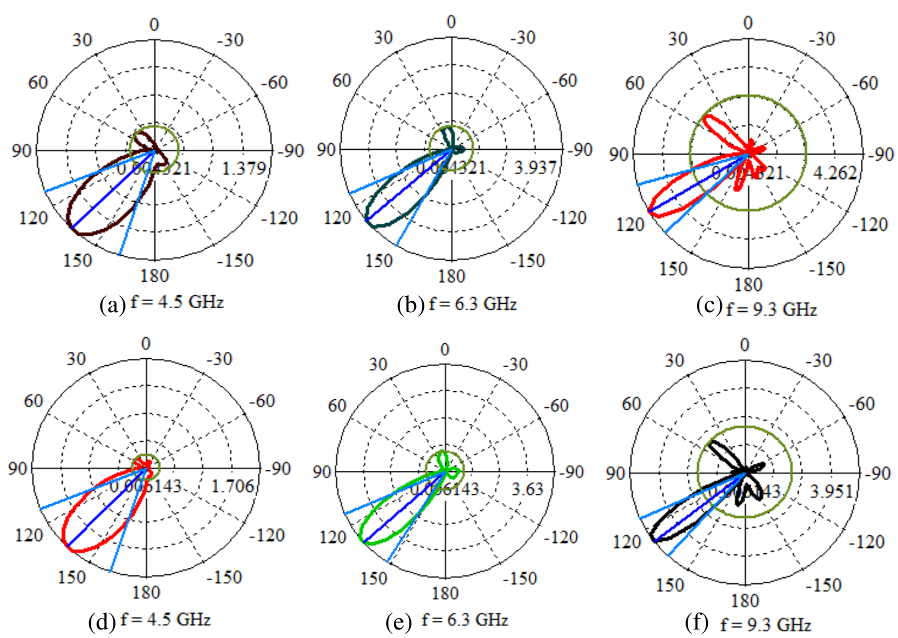

Figure 16. Simulated radiation patterns for antenna in linear scale: (a), (b), (c) without elliptical slot circular patch and (d), (e), (f) with elliptical slotted circular patch at different frequencies and $\Theta = 90$, in x-y plane.

slotted circular patch. It can be observed that the directivity of the designed antenna increases by 4.9–8 dBi.

Also, the simulated radiation patterns (in linear scale) of the proposed antenna at different frequencies are shown in Fig. 16. The 3-dB angular width or HPBW of the elliptical slotted circular

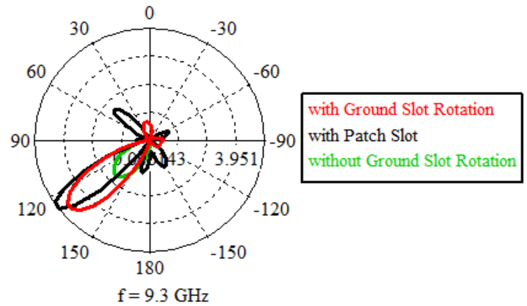

Figure 17. Comparative simulated radiation pattern of the antenna in linear scale: (a) without ground slot rotation; (b) with ground slot rotation; (c) with elliptical slotted circular patch antenna at frequency of 9.3 GHz and $\Theta = 90$, in x-y plane.

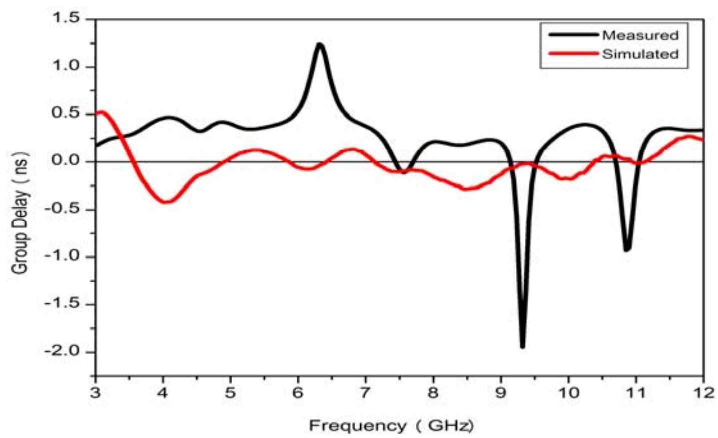

Figure 18. Measured and simulated group delay of the proposed directional UWB antenna.

patch antenna is 22° at 9.3 GHz frequency whereas the simulated HPBW is 26° for the antenna without elliptical slotted patch (with ground slot rotation at $\Theta = 45°$). Therefore, the half power beam width (HPBW) increases to 34% compared to the earlier antenna designed in [21]. Thus, the designed antenna is appropriate for C- and X-bands as well as for radar imaging systems.

Figure 17 shows the comparative radiation pattern of the antenna with and without ground slot rotation and for elliptical slotted circular patch antenna at the frequency of 9.3 GHz at $\Theta = 90$, in x-y plane. The HPBW of the elliptical slotted circular patch antenna moves between 49° and 22° degrees in the x-y plane in 4.1–11.5 GHz frequency band, which means that the main lobes of the elliptical slotted circular patch antenna offers more directional pattern than the antenna with and without ground slot rotation, as shown in Fig. 17. The calculated half power beam width (HPBW), gain and directivity of the proposed antenna are given in Table 3.

Figure 18 shows measured and simulated group delay response of the proposed directional UWB antenna. It can be observed that the variation of measured and simulated group delays of the antenna is less than 2 ns throughout the UWB band of 3–12 GHz. Therefore, the group delay performance of proposed UWB antenna demonstrates linear phase response at the desired ultra-wideband frequencies.

6. RESULTS AND DISCUSSIONS

The simulation analysis of the designed antenna has been carried out on Computer Simulation Technology and fabricated with optimized dimensions, as given in Table 1 through Caddo-71 prototype machine. The measurement results have been taken by vector network analyzer. The designed antenna achieves below −10 dB impedance bandwidth covering up the frequency range from 4.1–11.5 GHz

Table 3. Calculated and simulated parameters of the antenna with & without ground slot rotation and for elliptical slotted circular patch antenna.

Ground Structure/ Antenna Patch	Resonance frequency (GHz)	HPBW (°)	−10 dB Bandwidth (GHz)	Impedance bandwidth (%)	Gain (dBi)	Directivity (dBi)
Without Ground Slot Rotation	5.4 7.3 9.8 11	74 58 67 62	3.9–9.0	79	NA	NA
With Ground Slot Rotation ($\Theta = 45$)	4.5 6.3 7.5 9.3 10.8	51 37 30 26 24	4.2–11.5	93	4.8	4.9
With Elliptical Slotted Circular Patch	4.5 6.3 7.5 9.3 10.8	49 34 28 22 23	4.1–11.5	95	8.4	8

Table 4. Comparative performance analysis of the designed antenna with existing antennas.

Reference	−10 dB Bandwidth (GHz)	Impedance bandwidth (%)	HPBW moves between (°)	Gain (dBi)	Applications
[21] 2012	4.0–9.0	77	56°–26°	8	Radar
[29] 2013	9.3–10.5	12	NA	8.7	Partially X-band
[30] 2014	4.0–7.2	57	NA	3	Partially C-band
[31] 2014	6.8–7.3	07	NA	5.5	Partially C-band
[32] 2014	8.6–9.1	06	NA	4.4	Partially X-band
[33] 2015	6.4–9.5	39	NA	8.2	Partially C- and X-bands
Proposed Antenna	**4.1–11.5**	**95**	**49°–22°**	**8.4**	**Microwave Imaging, C and X-band**

through simulation as well as measurement. The return losses (S_{11}) are −38 dB, −43 dB through simulation at 6.3 GHz, 9.3 GHz resonance frequencies, respectively. By measurement, the return losses (S_{11}) are also −24 dB, −32 dB at the same frequencies.

The simulated gain and half power beam width (HPBW) are 4.8–8.4 dB and 49–22 degrees among 4.1–11.5 GHz, respectively. Gain and half power beam width (HPBW) of the proposed antenna improves 1–2 dB and 5–10 degrees, respectively, compared to previously designed antennas. The measured results show good agreement with equivalent circuit model and CST simulation. The radiation pattern, impedance bandwidth, directivity and flat gain characteristics of the antenna have also been compared with the earlier suggested similar research work [21–33]. The radiation patterns of the proposed antenna at different frequencies are shown in Fig. 16. The 3-dB angular width or HPBW of the antenna rotates between 49° and 22° degrees in the x-y plane with 4.1–11.5 GHz frequency band. Therefore, the main lobes of the elliptical slotted circular patch antenna is more directional with good stability than the antenna with and without ground slot rotation as shown in Fig. 17. In Table 4, a comparative study of performance analysis of the designed antenna is given with recently suggested antennas [21, 29–33].

7. CONCLUSIONS

A modified technique to design directional ultra-wideband (UWB) antenna through slotted ground structure approach has been carried out for C- and X-band operations. To obtain whole frequency range of C- and X-bands, elliptical slot is inserted into the ground, and the axis of elliptical slot is rotated 45 degrees in direction of the substrate. Further, to get better impedance matching and directivity, the minor axis of the ellipse is optimized and located symmetrically around the circular patch. Thereafter, for the further improvement in the directivity as well as gain the elliptical slot in circular patch has also been introduced. The measured results show fine conformity with equivalent circuit model and CST simulation. The proposed antenna operates into five resonate modes of 4.5, 6.3, 7.5, 9.3 and 10.8 GHz in 4.18–11.50 GHz frequency band. The calculated return losses are −18, −24, −17, −32.5, and −23 dB by measurement at the same resonance frequencies, respectively. The half power beam width (HPBW) of the antenna improves 5–10 degrees in comparison to previously designed antennas. The radiation pattern, impedance bandwidth, directivity and flat gain characteristics of the proposed antenna have also been compared with earlier suggested antennas.

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