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Design And Analysis of Tri-Band Antenna with Folded Strip Resonator and Directional UWB Characteristics for Microwave Imaging, GSM and Military Applications



Abstract

In this article, a compact design of a circular radiating patch antenna with a folded strip resonator (FSR) is proposed for ultra-wideband (UWB) integrated with GSM & Military applications. The overall dimension of the proposed antenna is 30×30 mm², which is suitable for portable wireless devices. The proposed antenna consists of a circular radiating patch with a partial ground plane. Further, to enhance the impedance bandwidth of the antenna, defected ground structure (DGS) approach is used and three identical rectangular slots have been inserted in the ground plane just below the stepped quarter wave transformer feed line. To realize lower wireless band applications, a folded strip resonator is integrated with the partial ground plane. The antenna has around 90% ($S_{11} < -10$ dB) fractional bandwidth in the UWB band ranging from 6.8-17.9 GHz and resonates at 7.7/9.75/16.25GHz frequencies along with one more resonant frequency at 4.5GHz(3.6-5.4GHz) with 40% ($S_{11} < -10$ dB) fractional bandwidth for military communication. It provides an additional lower frequency band of 1.9GHz(1.7-2.2GHz) for applications of the GSM 1900 band due to addition of FSR in the ground plane which introduces additional capacitance. Furthermore, the half-power-beam-width (HPBW) is obtained from 40° - 20° in UWB band. The simulation of antenna structure has been performed on Computer Simulation Technology (CST) software on an FR-4 substrate having a dielectric constant of 4.3 with a thickness of 1.6mm. Simulated results are validated with measured results and good agreement has been observed. The applications of proposed antenna in 1.9 GHz resonating frequency also includes digital enhanced cordless telecommunications, wireless audio devices, healthcare applications and mobile network operations while 4.5 GHz resonating frequency also includes applications in 5G, radar systems, fixed wireless access and cognitive radio network etc.

Keywords: Defected Ground Structure (DGS), Folded Strip Resonator (FSR) Fractional Bandwidth (FBW), Ultra-wideband (UWB),

1. INTRODUCTION

As per current demands of modern wireless communication, compact and highly directional UWB antennas integrated with multiband are required to support various contemporary applications. Directional characteristics are an essential requirement for microwave imaging applications. Further, the integration of GSM band and military communication makes this design suitable for wireless communication applications, it also helps in reducing the size of wireless devices and makes them more versatile. The challenges faced in designing directional UWB antenna integrated with lower wireless band applications are compact size, electromagnetic interference

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problems, impedance matching along with highly stable and directional radiation characteristics. Radar-based microwave imaging is popular nowadays for the early detection of breast cancer [1-2] highly directional antennas are required for this application. From the available literature, it can be seen that the introduction of a partial ground plane and slots enhances bandwidth, directional characteristics and gain of the antenna [3-6], further use of Defected Ground Structure (DGS), slots in the radiating patch and ground plane enhance directivity, gain and bandwidth [7-11]. Hau Zing, Djamel Sayad et. al. proposed a reconfigurable notch antenna for UWB applications but it suffers from the disadvantage of omni-directional pattern [12-13].

Karthika et.al. proposed an UWB antenna for wireless applications but having a large size of 50x50 mm² [14], Further, Ankush Kapoor, Alka Khade, Pierre Maukala Mpele et. al proposed a wideband antenna which covers sub-6 GHz applications, 2G/3G/4G Wi-Fi, LTE, Bluetooth, WLAN & Wi-Max applications but it does not cover UWB [15-17]. Reshama Lakshmanan and Shinoj K. Sukumaran presented a flexible UWB antenna for WBAN application using natural rubber as a substrate but it covers only UWB [18].

Venkata et. al proposed a novel lamp-slotted antenna for the UWB band integrated with Ku band but does not cover the lower frequency band [19]. Further, Galav K, Sunanda Roy, Mehdi Rahanandeh, Kunal Srivastava et al. proposed the design of multiband antennas having size of 160×160 mm² and operating frequency in the range of 5-5.5 GHz but these antennas are suitable for the lower wireless band only without covering UWB band [20-24].

It is evident from the available literature that most of the antenna design approach aims towards designing either a multiband antenna or directional UWB antenna but it does not cover UWB band or integration of UWB with lower wireless band applications. The major limitations of these antennas are having low fractional bandwidth and large antenna size. Integration of multiband along with directional UWB characteristics is always challenging due to robust coupling between elements of the patch antenna and ground plane, other constraints are poor impedance matching and narrow bandwidth. To overcome these limitations, a partial ground plane with rectangular slots has been used and a folded strip resonator (FSR) is added to the ground plane.

The devices used in modern wireless communication systems require small-size antennas as well as integration of wireless services along with UWB applications. Therefore, the motivation of this work is to design a miniaturized directional UWB antenna integrated with multiband applications. The proposed structure contains a circular patch radiator and one folded strip resonator (FSR) has been added on the top corner of the rectangle partial ground plane to excite one more resonance at a lower frequency. To improve impedance bandwidth rectangular slots have been introduced in the ground plane. The proposed design achieves 90%, 40% and 25% fractional bandwidth (FBW) in the UWB band, military application band and GSM1900 band respectively. The gain of the proposed structure ranges from 3.9-6.7dBi, and HPBW moves between 40°-20° in the UWB band of 6.8-17.9 GHz. The proposed antenna resonates at 7.7, 9.75 and 16.25 GHz in the UWB band of 6.8-17.9GHz, 4.5 GHz (3.6-5.4GHz) for military communication band and 1.9GHz (1.7-2.2 GHz) for GSM1900 band. Further, various parameters of the antenna such as gain, bandwidth, fractional bandwidth, half power beam-width and dimensions are compared with earlier reported antennas [2, 4, 7, 8, 9, 11, 13, 15, 27-30]. in the available literature. The optimized dimensions are simulated, fabricated and validated by experimental results.

The proposed work is presented in five Sections; Section 2, elaborates proposed geometry of the antenna, design method, return loss, input impedance and gain vs. frequency plots along with parametric variation. In Section 3, measured results and discussions are reported. Section 4, represents antenna application and comparative analysis. Finally, conclusions are reported in Section 5.

2. GEOMETRY OF THE PROPOSED ANTENNA

The proposed directional UWB antenna with all the dimensions is shown in figure 1. It has a compact size of 30×30×1.6mm³; it consists of a circular radiator which is fed with 50Ω micro-strip line integrated with quarter-wave-transformer. It is fabricated on FR-4 substrate with loss tangent 0.02; thickness 1.5 mm and dielectric constant of 4.3. Three symmetrical rectangular slots have been introduced in partial ground plane to provide good impedance matching. Further, a folded strip resonator is added to excite one more resonance at lower frequency. Optimized parameters of the proposed antenna configuration are given in table 1 and subsequent to simulation on EM simulator (CST- Microwave Studio).

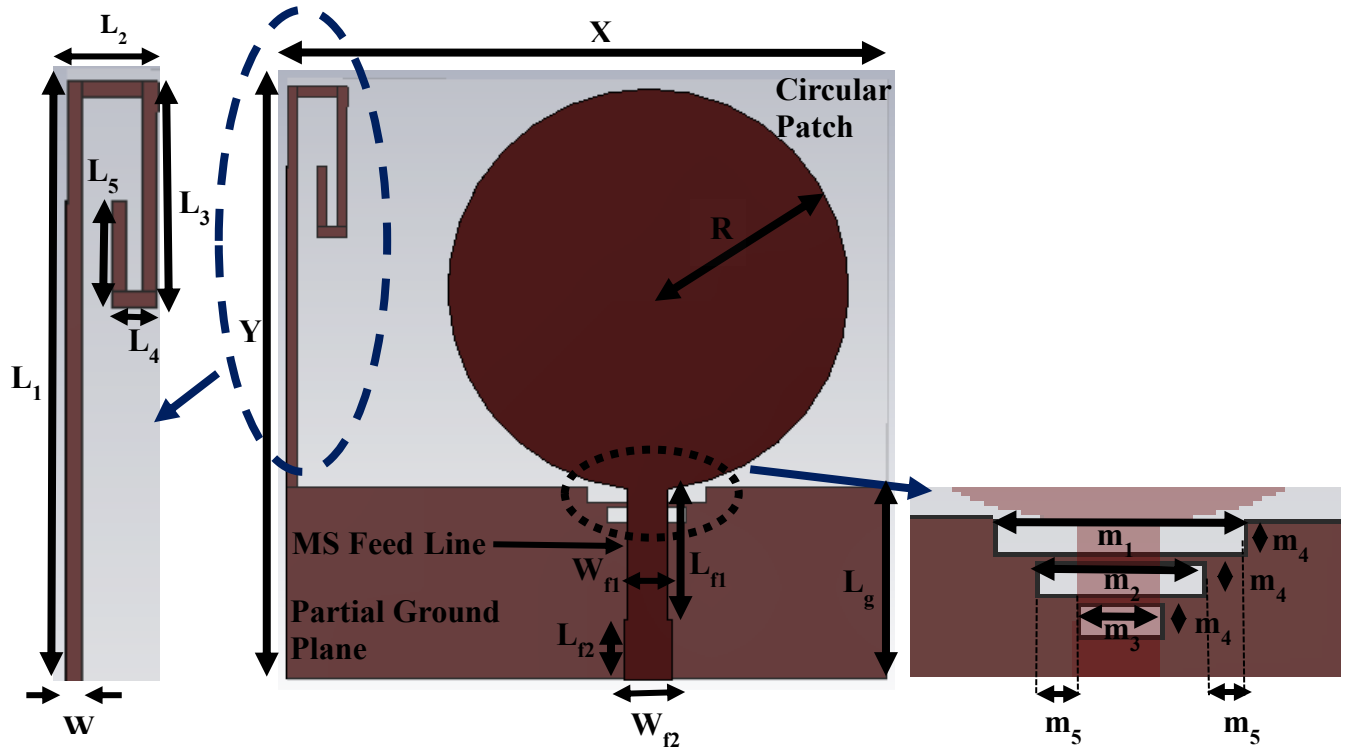


Figure 1: Design of the proposed antenna with all dimensions

The width and length of the substrate is given by ‘X’ and ‘Y’, respectively. The width and length of the partial plane has been taken as ‘X’ and ‘L_g’, respectively. Optimized separation and width of each ground slot is ‘g₁’ and ‘m₄’, respectively. Further, optimized length of the slot-1 is ‘m₁’, slot-2 is ‘m₂’ and slot-3 is ‘m₃’. One folded strip resonator has been added to the top corner of the ground plane. This proposed antenna resonates at 1.9GHz, 4.5GHz and covers UWB band from 6.8 to 17.9GHz.

2.1 DESIGN METHOD OF THE PROPOSED STRUCTURE

Design process of antenna involves two stages given in figure 2, in step 1 circular patch with radius R is designed.

Effective dielectric constant (ε_{eff}) can be calculated by the help of Equations (1) and (2) [9], [26].

$$\epsilon_{eff} = \frac{(\epsilon_r + 1)}{2} + \frac{(\epsilon_r - 1)}{2} \left[1 + 12 \frac{h}{W} \right]^{-1/2} \quad (1)$$

Approximate value of (ε_{eff}) can be calculated by

$$\epsilon_{eff} \sim \frac{(\epsilon_r + 1)}{2} \quad (2)$$

Radius of circular patch (R) is calculated by Equations (3) and (4) [9], [26].

$$R = \frac{a}{\sqrt{\left\{ 1 + \frac{2h}{\pi \epsilon_r a} \left[\ln \left(\frac{\pi a}{2h} \right) + 1.7726 \right] \right\}}} \quad (3)$$

Where, $a = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}}$

Approximate value of (R) can be calculated by

$$R = \frac{92 \times 10^9}{f_r \sqrt{(\epsilon_{eff})}} \quad (4)$$

Further, for lowest resonant frequency of 4.5 GHz, the calculated value of radius R is approximately 10.2 mm, whereas simulated value is 10mm, both the values are very close to each other.

In next step the length of folded strip resonator (FSR) (L_s) for corresponding resonating frequency (f_{r1} = 1.4 GHz) can be calculated by the equation (5), [26].

$$L_s = \frac{c}{4f_r \sqrt{\epsilon_{eff}}} \quad (5)$$

Where, ‘h’, ‘W’, ‘f_r’, ‘ε_{eff}’, ‘c’ and ‘λ_g’ are height of substrate, width of patch, lowest resonant frequency, effective dielectric constant, speed of light and guided wavelength, respectively.

From equation (5) we can calculate the length of FSR $L_s = 33.5$ mm for $f_{r1} = 1.4$ GHz (simulated resonance occurs at 1.9 GHz),

In the proposed structure total length of strip resonator is given by

$$L_s = L_1 + L_2 + L_3 + L_4 + L_5 \approx \lambda_g / 4 \quad (6)$$

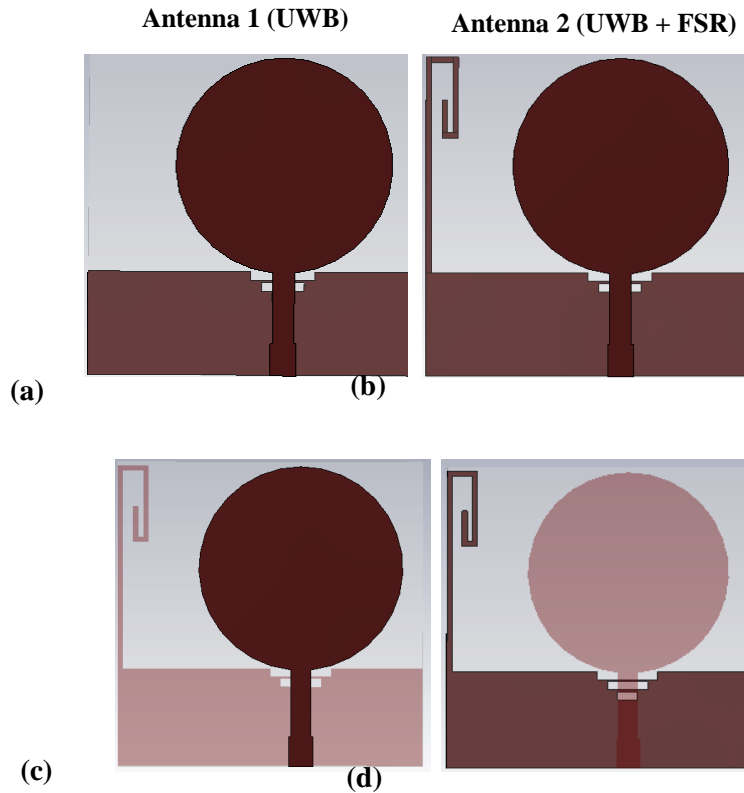


Figure 2: Design stages of the proposed antenna (a) Antenna-1 (b) Antenna-2 (c) Front view (Antenna-2) (d) Back view (Antenna-2)

From Table 1, $L_s = 33.5$ mm and from equation (2) $\epsilon_{eff} = 2.65$. The calculated value of first resonant frequency is $f_r = 1.4$ GHz and simulated value is 1.9 GHz, which are very close to each other.

Antenna-1 is designed without any FSR. It is excited by 50Ω micro-strip line and its lowest resonant frequency is 4 GHz and it also covers the UWB band (3.35-17.5GHz) with five resonating frequencies 4/7.8/10.9/13.6/16.4 GHz.

It can be observed from figure 3 that lowest resonating frequency of Antenna-1 is 4 GHz along with the UWB band (3.35-17.5GHz) due to circular patch radiator only. Further, multiband antenna with the UWB antenna is designed by adding one FSR in the ground which results to proposed antenna structure shown in figure 2 [Antenna -2]. This proposed antenna structure gives resonating frequencies at 1.9 GHz, 4.5 GHz and UWB band from 6.8 to 17.9 GHz.

Table 1: Optimized parameters of the proposed antenna configuration

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
X = Y	30	L _{f1}	6.6
R	10	W _{f2}	2.4
L ₁	20	W _{f1} = m ₃ = L ₂	2
L ₃	7	m ₂	4
m ₁	6	m ₅	1
L ₅	3	m ₄	0.8
L _g	9.6	g ₁	0.2
L _{f2}	3	W ₁	0.5
L ₄	1.5		

2.2 RETURN LOSS, GAIN & INPUT IMPEDANCE vs. FREQUENCY PLOT OF THE PROPOSED ANTENNA

The plots for Return loss ($|S_{11}|$ dB) and Gain vs. Frequency plots are as shown in figure 3 and figure 4 respectively.

It can be observed from figure 3 that proposed antenna resonates at 1.9 GHz due to FSR, and 4.5 GHz along with UWB band from 6.8-17.9 GHz due to circular patch. Further, it can be observed from figure 4 that the gain has nearly constant value in UWB band. To investigate different modes of resonance, real and imaginary part of input impedance vs. frequency has been plotted as shown in figure 5. It can be observed from the plot that real part of input impedance

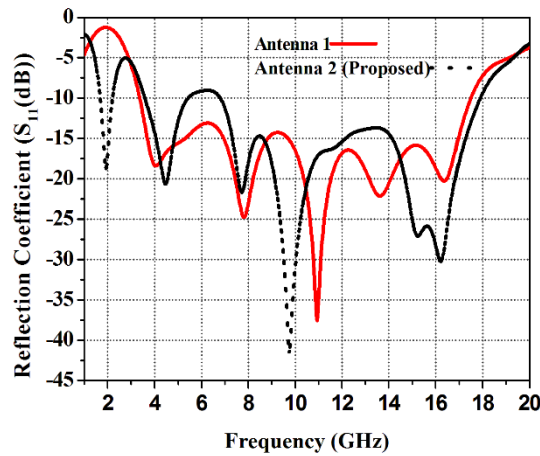
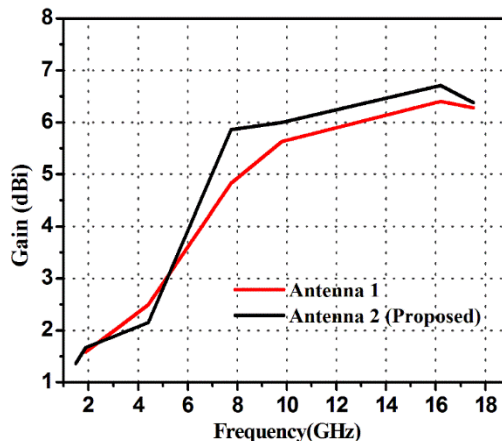


Figure 3: Return Loss vs. frequency plot for antenna (1 & 2)



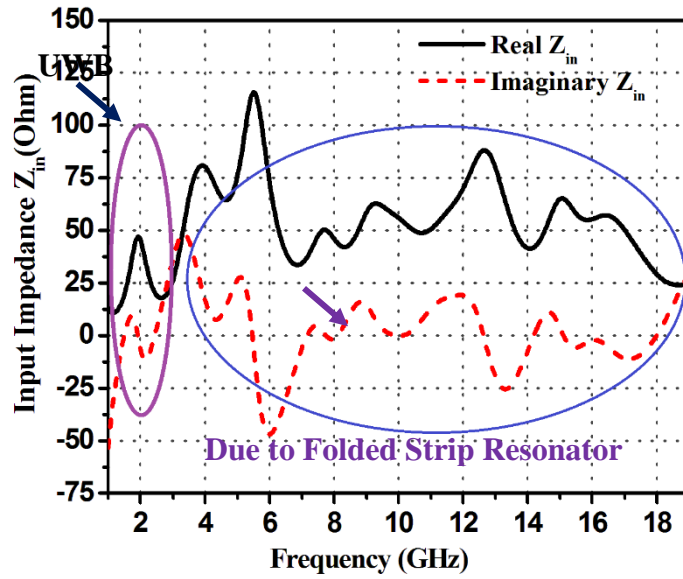


Figure 5: Input impedance vs. frequency plot for proposed antenna configuration

(resistance) has a value 50Ω and imaginary part (reactance) having very small value nearly equal to zero at resonating frequencies and resonant modes are at 1.9, 4.5, 7.7, 9.75 and 16.25 GHz respectively.

Different simulation results such as bandwidth, gain and fractional bandwidth for different antenna configurations are given in table 2.

Figure 4: Gain (dBi) vs. frequency plot for antenna (1 & 2)

Table 2: Details of Gain, bandwidth and applications of the proposed antenna configurations

Antenna Configuration	Strip Resonator	Resonant Frequency (GHz)	Bandwidth (-10 dB) GHz	Fractional Bandwidth (%)	Gain Variation (dBi)	Applications
Antenna 1	No	4/7.8/10.9/13.6/16.4	3.35-17.5	136	1.2-6.3	UWB
Antenna 2 (Proposed)	One	1.9	1.7-2.2	25	1.5-6.7	GSM
		4.5	3.6-5.4	40		Military Applications
		7.7/9.75/16.25	6.8-17.9	90		UWB

2.2 PARAMETRIC ANALYSIS

To optimize the parameters of the proposed antenna, parametric analysis has been carried out; the effect of variation of radius ‘R’ of patch on impedance characteristics of antenna is given in figure 6. This helps to optimize the performance of antenna impedance characteristics. Therefore, the variation of radius ‘R’ effects all the resonances present in UWB band as shown in figure 6. A shift of 0.5GHz can be observed in the first/operating resonance frequency as radius R varies from 9-11 mm. Hence; we can define the value of operating resonant frequency by the variation of radius ‘R’. It can be observed from the analysis that we can achieve the required operating frequency value with an optimized value of radius $R = 10\text{mm}$.

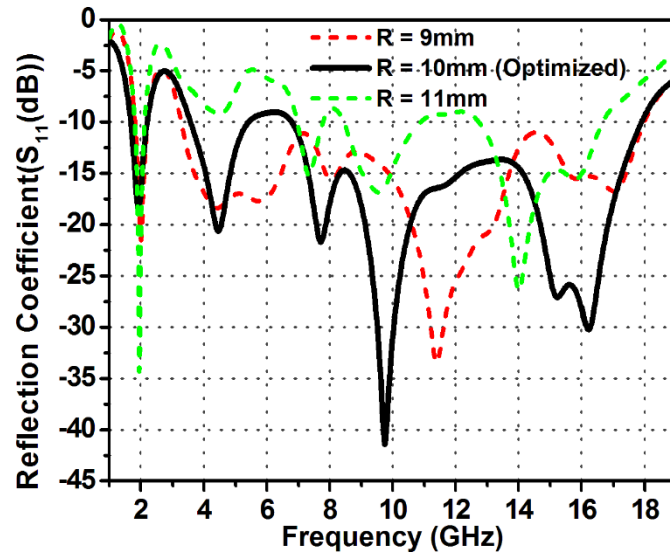


Figure 6: Return loss vs. frequency plot of proposed antenna for radius variation

Further, effect of variation of length of folded strip resonator is studied. On varying the length of strip resonator from 32.5 mm to 34.5 mm there is a shift on lowest resonating frequency from 1.8 to 2 GHz, so we can choose optimized value as 33.5 mm for 1.9GHz resonating frequency, there is no effect is observed due to strip length variation in UWB band as shown in figure 7. The first resonance is obtained due to FSR-1 is at 1.9GHz and first resonance of UWB band is at 7.7 GHz with the surface current as observed in figure 8 and figure 9.

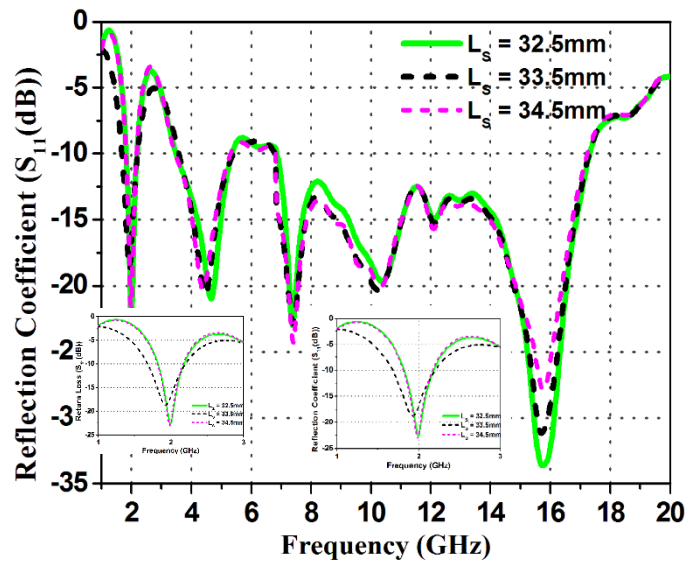


Figure 7: Return loss vs. frequency plot of proposed antenna for strip length variation

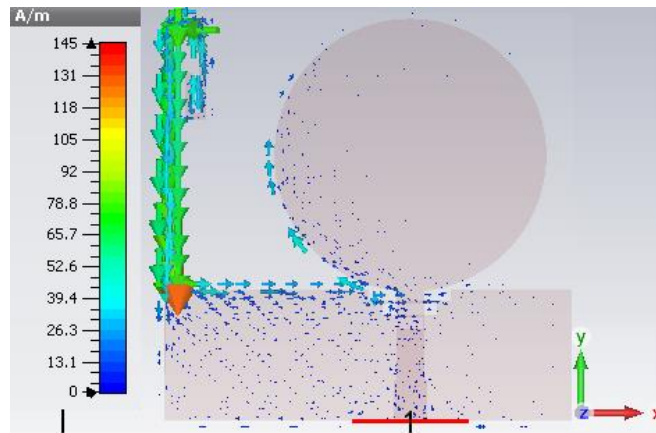


Figure 8: Surface current distribution plot of the proposed antenna at resonating frequency 1.9 GHz

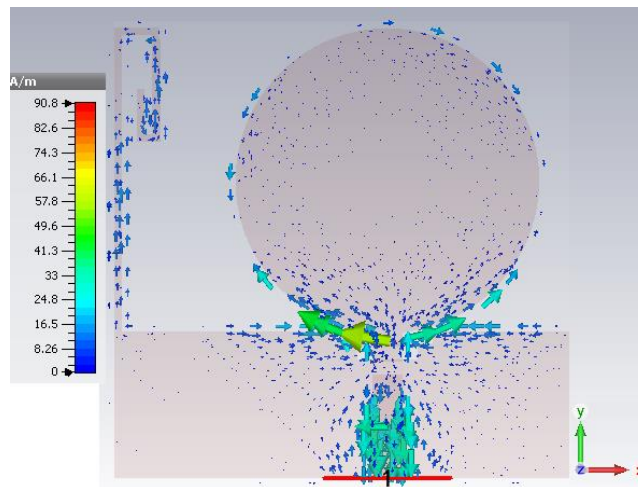


Figure 9: Surface current distribution plot of the proposed antenna at resonating frequency 7.7 GHz

3. RESULTS AND DISCUSSIONS

The simulation and performance optimization analysis of the antenna structure has been carried out with the help of Computer Simulation Technology (CST) software. The proposed structure is fabricated with the help of caddo-71 prototype machine on FR-4 substrate having thickness 1.6mm and all the dimensions as given in table 1. To measure return loss ENA series vector analyzer (VNA) is used as shown in figure 10 & figure 11.



Figure 10: The images of fabricated antenna front view and back view

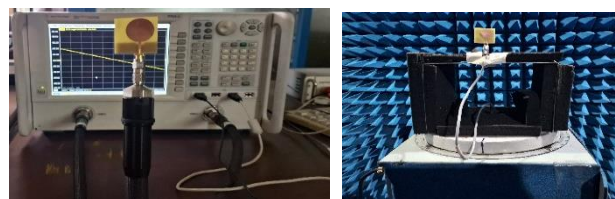


Figure 11: The images of fabricated antenna with measurement setup

The measured results show a very good agreement with simulated results as shown in figure 12 and figure 13. It can be observed that the proposed antenna structure resonates at 1.9, 4.5, 7.7, 9.7 and 16.25 GHz resonating frequencies and covers 1900MHz (1.7-2.2 GHz), 4500MHz (3.6-4 GHz) and UWB band (6.8-17.9GHz) with fractional bandwidth 25%, 40% and 90% respectively. It shows a better performance as compared to previously reported antennas. Further, measurement of gain and directivity of the proposed structure has been carried out with the help of broadband horn antenna as reference antenna. The variation of simulated gain, measured gain and directivity vs. frequency is as shown in Figure 13. Directivity varies from 1.3-7.44dBi in the entire frequency band and maximum value 7.44dBi is obtained at 16.2 GHz. Furthermore, the measured gain varies from 3.9-6.7dBi in UWB band with gain discrepancy less than ± 0.5 dBi.

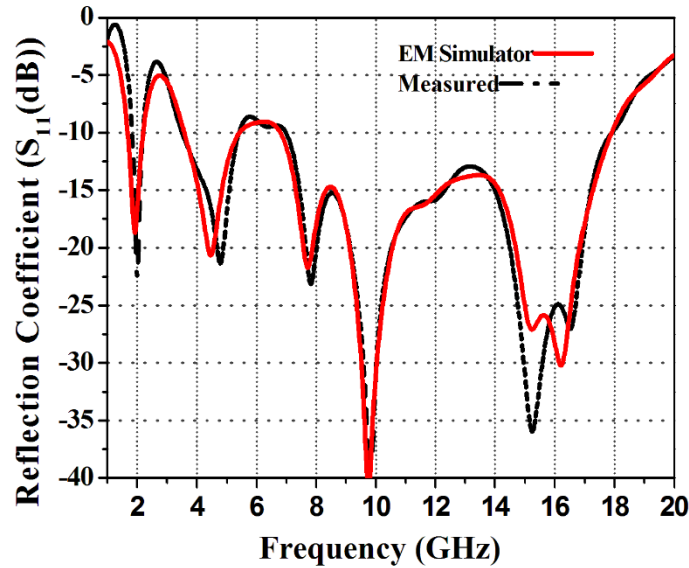


Figure 12: Simulated and measured return loss plot of the proposed antenna

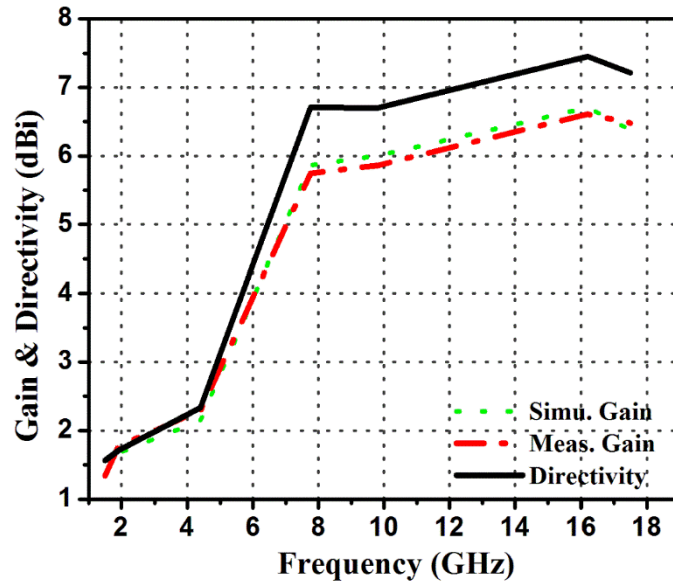


Figure 13: Simulated gain, measured gain and directivity vs. frequency plot of the proposed antenna

Radiation efficiency in the neighbourhood of 1.9 GHz frequency can be calculated using the following method

$$\text{Radiation Efficiency (E)} = \text{Gain (G)} / \text{Directivity (D)}$$

Resonating Frequency (GHz)	Radiation Efficiency (E) = (G)/(D)
1.5	0.83
4.4	0.85
7.7	0.89
9.8	0.82
16.2	0.90

The dielectric loss tangent ($\tan \delta$) used to simulate FR-4 substrate is 0.025.

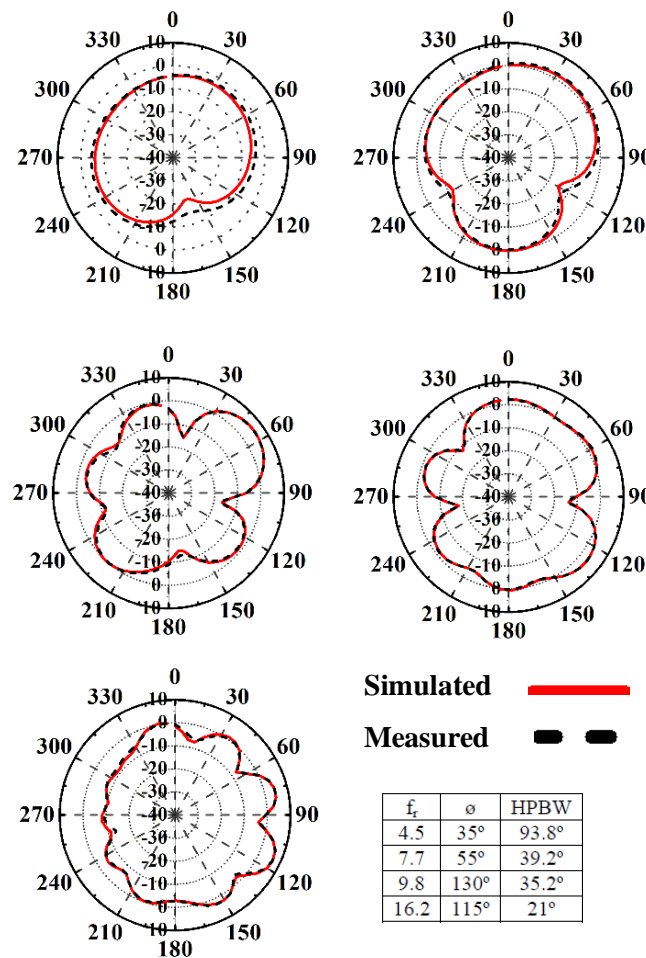


Figure 14: Simulated and measured radiation patterns of proposed antenna at different frequencies: (a) 1.9GHz (b) 4.5 GHz; (c) 7.7GHz; (d) 9.75 GHz; (e) 16.25GHz in $\theta = 90^\circ$ plane.

The simulated and measured radiation pattern of the proposed antenna at 1.9, 4.5, 7.7, 9.7 and 16.25 GHz resonating frequencies at $\theta = 90^\circ$ and x-y plane are as given in figure 14, it gives omni-directional radiation pattern at lower frequency bands 1.9 & 4.5GHz and directional characteristics are obtained in UWB band at 7.7, 9.75 and 16.25 GHz resonating frequencies. Further, a good agreement has been observed between simulated and measured radiation pattern with minute disparity. Furthermore, half power beam-width (HPBW) moves from x-axis $\Phi = 35^\circ$ to $\Phi = 115^\circ$ in x-y plane. Therefore, least HPBW from 93° - 21° degrees is obtained as compared with previously reported antennas [2, 4, 7, 8, 9, 11, 13, 15, 27-30]. The corresponding three dimensional radiation patterns are as shown in figure 15, it can be observed from figure 15 (a) & (b) that omni-directional radiation

pattern is obtained at 1.9 and 4.5 GHz resonating frequencies as analogous to figure 14(a) & (b). The maximum radiation intensity in a particular direction can be obtained at 7.7 GHz resonating frequency as shown in figure 15(c).

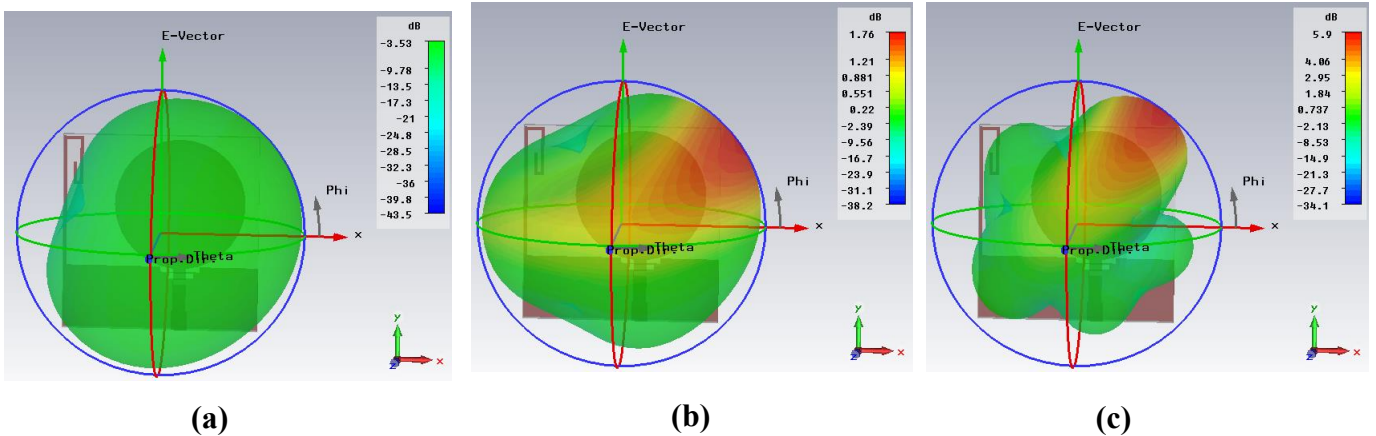


Figure 16: 3D simulated radiation pattern of proposed antenna:(a) 1.9GHz, (b) 4.5GHz, (c) 7.7GHz, respectively

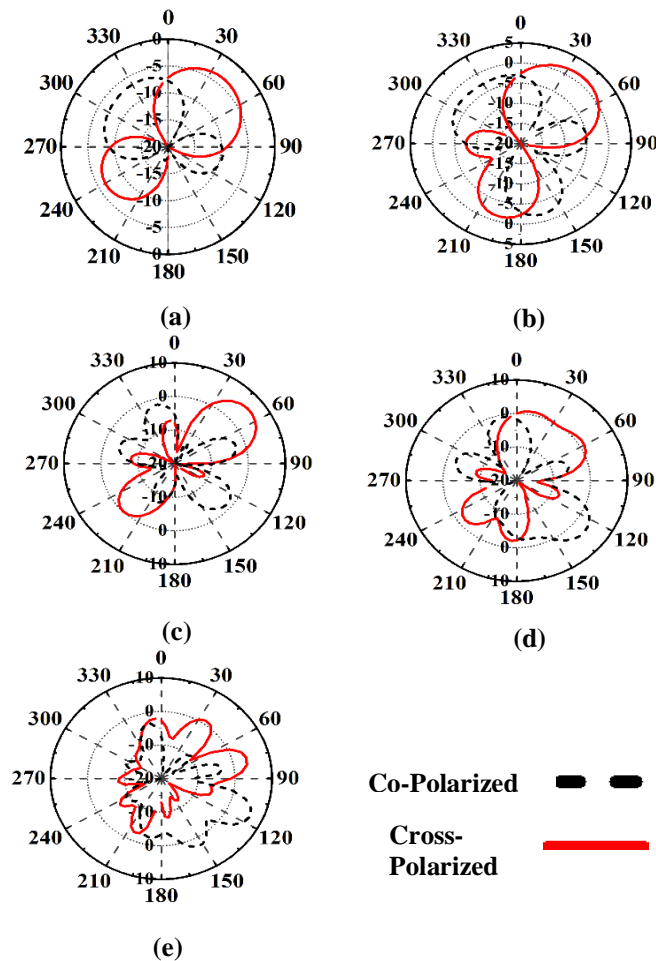


Figure 15: Simulated radiation patterns (Co-Polarized and cross-polarized) of proposed antenna at different frequencies: (a) 1.9GHz (b) 4.5 GHz; (c) 7.7GHz; (d) 9.75 GHz; (e) 16.25GHz in $\theta = 90^\circ$ plane.

Table 3: Comparative performance analysis of proposed antenna with previously reported antennas

Reference Antenna	Antenna Size [mm ²]	Bandwidth (GHz)	FBW (%)	Antenna Response	HPBW moves between(°)	Gain (dBi)	Directivity (dBi)	Radiation Efficiency
[2]	55×40	3.0-10	108	UWB	56-30	6.0-8.4	6.2-9.4	0.89
[4]	40×40	4.4-10.6	83	UWB	44-29	6.1-9.1	-	-
[7]	42×50	2.4-10.4	125	UWB	-	6.5	-	-
[8]	50×50	4.1-11.5	95	UWB	49-22	8.4	-	-
[9]	30×30	4-18	127	UWB	52-30	3.0-9.3	3-10	0.93
[11]	18×28	3.4-10	98	UWB	-	3.95	-	-
[13]	15×20	3.1-18.1	141	UWB	-	5.4	-	-
[15]	23×23	3.2-5.34	50	Sub-6 GHz	-	2.76	2.98	0.92
[27]	28×28	3-12	120	UWB with triple band rejection	-	-	-	-
[28]	20×20	3-13.6	127	UWB with dual band rejection	-	-	-	-
[29]	13.5×14.8	3.08-14	127	UWB	-	3	-	-
[30]	45×40	2.79-16.6	140	UWB	-	4.77	5.84	0.81
Proposed Antenna	30×30	1.7-2.2	25	GSM, Military Applications, UWB	40-20	1.36	1.70	0.80
		3.6-5.4	40			2.16	2.33	0.92
		6.8-17.9	90			6.7	7.44	0.90

4. APPLICATION IN MICROWAVE IMAGING

Microwave imaging technique has certain advantages such as non-ionizing radiations, noninvasive medical imaging modality, thorough inspection of tissues, less harm to body tissues as compared to traditional imaging techniques such as computed tomography imaging (CT) and magnetic resonance imaging (MRI). To generate medical images, the map of electromagnetic properties of the tissue obtained from microwave imaging is used [25]. Dielectric properties of normal and cancerous tissues are different so contrast between these can be used for reconstruction of image in microwave imaging technique.

The designed antenna has wide operating bandwidth from 6.8 GHz to 17.9 GHz with 90% fractional bandwidth which provides good resolution and high value of gain around 6.7dBi and directivity 7.4dBi; it helps in constructing high resolution images. This antenna can be used for microwave imaging as shown in figure 16, individual antenna can be used for phantom scan as shown in figure 16 (a), phantom under test is as given in figure 16 (b) and this system can create image by antenna operating from 6.8 to 17.9GHz frequency and it has a narrow pencil beam radiation patterns shown in figure 16(c), Therefore, the designed antenna has been appropriate for microwave imaging.

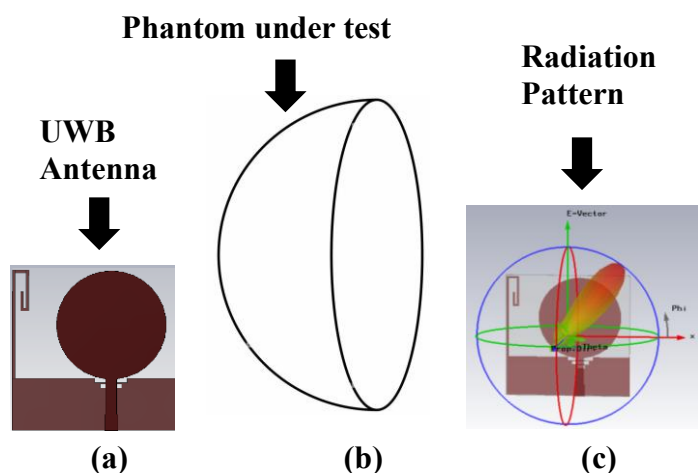


Figure 17: (a) UWB antenna for microwave imaging (b) Phantom under Test (c) Radiation pattern of the proposed antenna

5. CONCLUSIONS

A directional UWB antenna with folded strip resonator is described in this article. Proposed antenna is designed, simulated, fabricated and experimentally validated.

The proposed structure resonates at five resonating frequencies at 1.9, 4.5, 7.7, 9.75 and 16.25 GHz. It gives wide impedance bandwidth of 11.1GHz (6.8-17.9GHz) with a significant value of gain as 6.7dBi for UWB applications along with two additional lower bands with impedance bandwidth 0.5 GHz (1.7-2.2GHz) and 1.8 GHz (3.6-5.4GHz) for GSM1900 and Military applications respectively.

Antenna resonates at 1.9 GHz frequency due to insertion of FSR and impedance bandwidth is improved due to insertion of slots in the ground plane. Overall size of the antenna is $30 \times 30 \text{ mm}^2$ which is suitable for portable wireless devices.

Further, HPBW of the proposed structure is obtained between 40° - 20° . The main lobes of antenna have directional characteristic with high gain, Hence, it can be used for microwave imaging applications as described in section 4. Furthermore, the antenna size, bandwidth, fractional bandwidth, half power beam-width, gain and directivity of proposed antenna is compared with existing antenna reported in literature as mentioned in Table 3. Proposed structure is compact in size with dimensions $30 \times 30 \times 1.6 \text{ mm}^3$ and it has good fractional bandwidth of 25% (1.7-2.2 GHz) and 40% (3.6-5.4 GHz) at lower frequency bands. It has omnidirectional characteristics at lower frequency band and directional characteristics in UWB band.

Further, the applications of the proposed antenna include cordless phones, industrial and home automation, medical devices, next generation mobile networks, radar systems and high resolution imaging systems along with application in UWB band.

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