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HIGH GAIN AND LOW CROSS-POLAR COMPACT PRINTED ELLIPTICAL MONOPOLE UWB ANTENNA LOADED WITH PARTIAL GROUND AND PARASITIC PATCHES

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Abstract—In this paper a low cost, high gain, low cross-polar and compact edge feed printed elliptical antenna with a partial ground plane and parasitic patches is proposed and investigated. The proposed antenna is fabricated on a 1.6 mm thick FR4 substrate with dielectric constant of 4.4 and loss tangent of 0.025. The total planar area of the proposed antenna ($L \times W$) is $28 \times 24\,\text{mm}^2$. Both the simulated and experimental result shows that the proposed antenna provides a frequency range compatible with the ultra-wideband (UWB) standard, i.e., 3.5 GHz–12 GHz frequency band. The radiation pattern produced by the proposed antenna is approximately omnidirectional with in-phase excitation of Surface waves resulting in less cross-polarization level (less than 20 dB) compared to its co-polar component for the entire impedance band width. The maximum measured gain for the fabricated antenna is around 6.27 dBi with an average efficiency of above 90% throughout the bandwidth. A linear phase response (phase of S_{21}) accompanied by a constant group delay of 1 ns throughout the measured bandwidth makes the proposed antenna a good candidate for UWB applications.

1. INTRODUCTION

Due to ever increasing requirement of higher data rates and multitasking, systems with ultra wide band (UWB) response have drawn a considerable interest among the researchers. With the introduction of 3.1 GHz–10.6 GHz as an unlicensed band, developing

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a system which will work for the complete UWB bandwidth is a challenging problem. For a communication system utilizing UWB it is necessary that the mounted antenna (in the system) should radiate with the return loss of less than 10 dB (magnitude, i.e., VSWR ≤ 2) for the complete impedance band width and its cross-polar response should be less by 20 dB than the co-polar response. For achieving these conditions two criteria are significant, first is proper antenna design (good impedance matching) and second is surface wave suppression or it's in phase excitation [1, 2]. Other criteria for efficient UWB antennas are compactness and good time domain response.

Recently many planar antennas have been proposed for UWB applications. The antenna proposed in [2–8, 16–22] provides a required impedance bandwidth and gain for UWB applications. In [2] the structure provides a good impedance band width but the level of cross-polarization especially at higher frequencies is considerably more in comparison to its co-polar component. In [3] the gain of the proposed antenna is high at the cost of compactness. Whereas in [5, 6] the proposed antennas have good compactness accompanied with wide bandwidth, in [5] the group delay response shows distortions over the UWB band and in [6] the cross-polar component is high especially at higher frequencies. The reason for the increment of cross-polarization level especially in compact planar antenna is the destructive interference caused by surface waves.

Analysis of the surface wave and its effects was first reported in [9]. The substrate thickness used in antenna design is generally less than the quarter wave length (especially for UWB planar monopole antenna), which results in 180° out of phase reflection of the surface waves (the one that impinges the substrate and get reflected back from the ground). This out of phase reflected waves when combines with the radiating waves produces a destructive interference which results in deterioration of antenna characteristic in terms of Gain, Efficiency and Return loss. Further, the surface waves which travels through the ground get diffracted at edges of the ground (as finite grounds are used) which also contributes to destructive interference [10]. In order to overcome above mentioned deficiency the thickness of the substrate should be more then quarter wave length. Though by increasing the substrate thickness the destructive interference will reduce but because of Perfect Electric Conductor (PEC) ground some of the waves will continue to propagate along the PEC ground and get radiated through substrate-ground discontinuity which in turn gives rise to surface wave problems as mentioned in [10, 14].

Various techniques as reported in [10–15] are proposed for either suppression or providing an in phase excitation of the surface waves.

But these techniques are limited to narrow band and involve fabrication difficulties. In this paper the surface waves are provided with an in phase excitation resulting in increment of gain and reduction in cross-polarization level. Another feature of the proposed structure is its compact size as compared with the antennas proposed in [17–22].

2. ANTENNA CONFIGURATION

We have chosen a simple elliptical edge feed patch for designing an UWB antenna. The structural dimensions of the antenna are based on the design equations given in [1, 4, 10, 16]. Since the patch antenna provides a narrow band response, we have used a partial ground structure so that the field will not be confined between the patch and ground plane. The structure of proposed antenna is shown in Fig. 1. The antenna structure was designed and optimized using CST Microwave Studio 2012 simulation software.

2.1. Configuration of Elliptical Patch

The dimensions of major axis (b) and minor axis (a) (Fig. 2) are the diameters of two circular patches which are calculated by splitting the UWB bands in two halves. The first half corresponds to the 3 GHz–7.5 GHz band with center frequency of 5.5 GHz and the second half corresponds to the 7.5 GHz–12 GHz band with center frequency

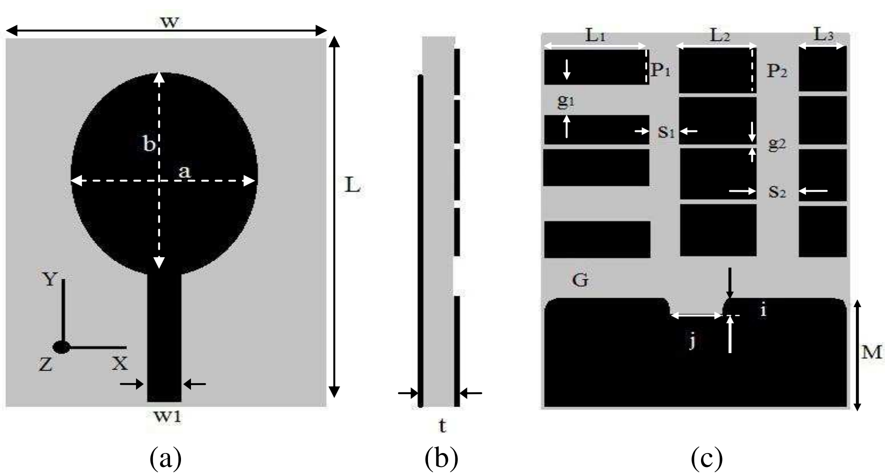


Figure 1. Proposed antenna geometry. (a) Front view, (b) side view, (c) back view.

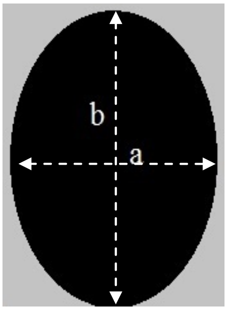


Figure 2. Geometry of elliptical patch.

of 9.5 GHz. The design equation for a circular microstrip antenna is modified and the dimensions of ellipse are calculated as follows [1]:

$$b_1 = \frac{A_{nm} \cdot C}{2\pi f_{c1}\sqrt{\varepsilon_r}} \tag{1}$$

$$a_1 = \frac{A_{nm} \cdot C}{2\pi f_{c2}\sqrt{\varepsilon_r}} \tag{2}$$

where b_1 and a_1 are the effective radius (required for calculating major and minor axis of the proposed ellipse), A_{nm} is the mth zero of the derivative of Bessel function of order n, C is the speed of light in free space, f_{c1} (equal to 5.5 GHz) is the resonant frequency which corresponds to the center frequency of the first half of the UWB band and f_{c2} (is equal to 9.5 GHz) corresponds to the center frequency of the second half of the UWB band. Major axis (b) is calculated (using Eq. (1)) as '$b = 2b_1$' and similarly value for minor axis (a) is calculated (using Eq. (2)) as '$a = 2a_1$'. The feed for the radiator is a simple edge feed using a 50 Ω microstrip transmission line with length of 9 mm and width $W_1 = 3$ mm as shown in Fig. 1(a).

2.2. Configuration of Partial Ground and Parasitic Patches

For analyzing the surface wave effects, first a planar elliptical antenna with partial ground was designed. The dimension of this conventional partial ground antenna is same as the final fabricated antenna with one difference, i.e., the absence of parasitic patches on the partial ground as shown in Fig. 3. The substrate for conventional antenna in Fig. 3 is FR4 material with ε_r= 4.4 and thickness of 1.6 mm. We have used a partial ground plane so that the electromagnetic field should not confine between the patch and ground [4]. It is known that bandwidth

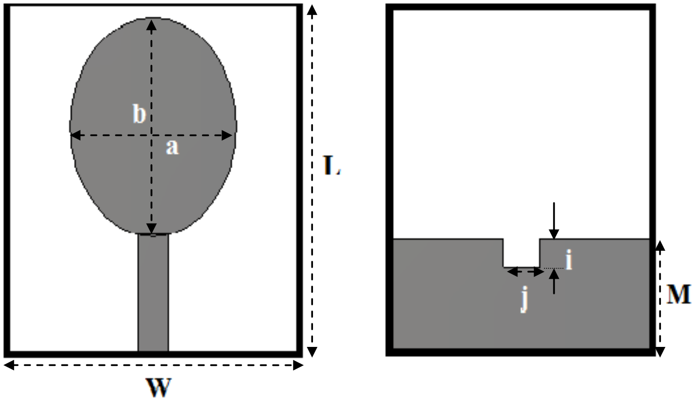


Figure 3. Conventional elliptical planar monopole antenna: $a = 12\,\mathrm{mm}$, $b = 14\,\mathrm{mm}$, $M = 9\,\mathrm{mm}$, $i = 2\,\mathrm{mm}$, $j = 3\,\mathrm{mm}$, $W = 24\,\mathrm{mm}$, $L = 28\,\mathrm{mm}$. (a) Front view, (b) back view.

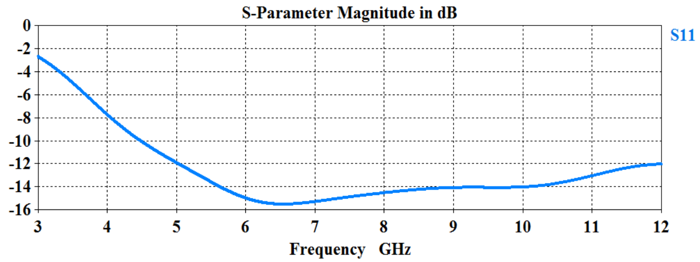


Figure 4. Return loss graph for elliptical monopole antenna.

is inversely proportional to the Q (quality) factor,

$$BW = \frac{\mathrm{VSWR} - 1}{Q_t\sqrt{\mathrm{VSWR}}} \tag{3}$$

And in turn Q_t depends upon the gap capacitance between the patch and ground. Thus to reduce the quality factor the energy stored in the capacitance between ground and radiator has to be reduced and truncating the ground will serve this purpose. Fig. 3 shows the conventional elliptical planar antenna with partial ground. The return loss graph in Fig. 4 indicates the wide band nature of the antenna. However due to the presence of partial ground structure, surface waves will get excited. The phase (phase of S_{21}) and group delay response are simulated by keeping identical pair of antenna at a distance of 1 m apart and the graph in Fig. 5 shows a non linearity in phase variation

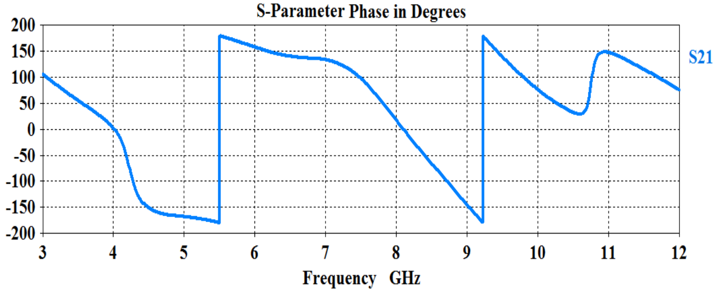


Figure 5. Phase response (phase of S_{21}) of elliptical monopole antenna.

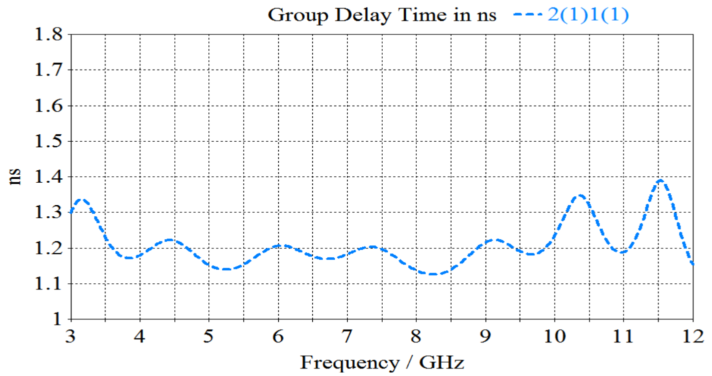


Figure 6. Group delay response of elliptical monopole antenna.

which indicates generation and an out of phase excitation of surface waves, whereas the simulated group delay response (Fig. 6) clearly shows a nonlinear group delay for complete UWB bandwidth. These surface waves will radiate in opposite phase to that of main radiating waves, which in turn generate high cross-polarization level especially at higher frequencies [10]. Fig. 7 shows the radiation pattern of the Elliptical Planar antenna with partial ground.

Simulated radiation pattern in Fig. 7 clearly indicates that the magnitude of the cross-polar component exceeds its difference limit of 20 dB (magnitude) from co-polar component and due to increase in cross polarization level, the gain of the antenna is also very less as it can be seen in Fig. 8. The gain at lower half of UWB band, i.e., 3 GHz–7 GHz varies between 1.5 dBi to 2.9 dBi where as from 7 GHz to 12 GHz the gain variation is between 3 dBi to 5 dBi.

Gain can be improved or maximized by either increasing the

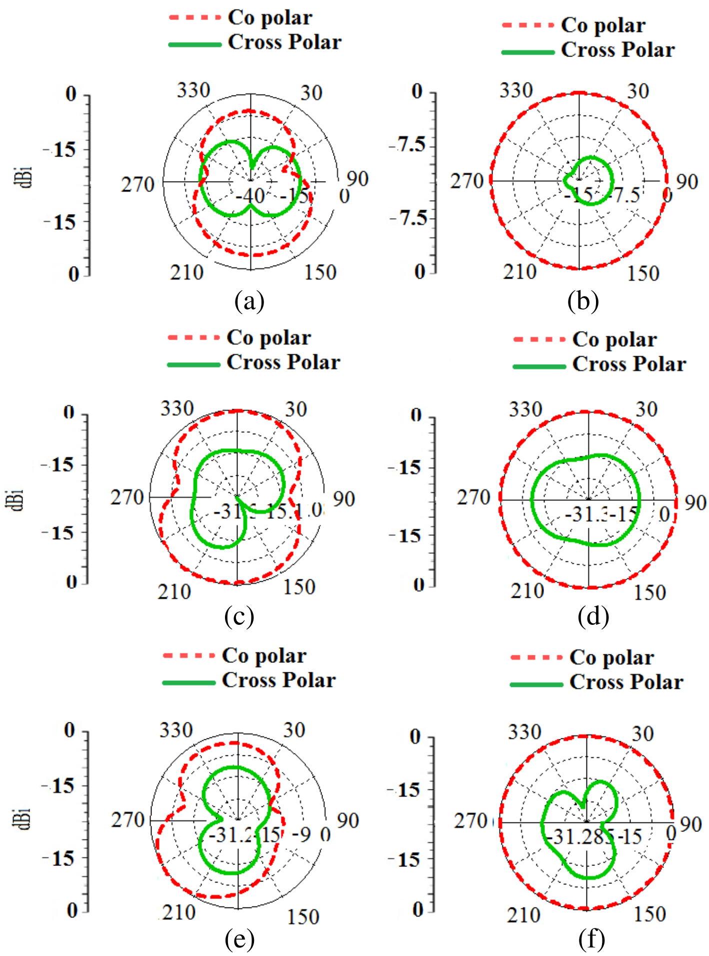


Figure 7. Simulated co and cross polar responses of conventional elliptical planar monopole antenna at (a), (b) 4.5 GHz, (c), (d) 7.5 GHz, (e), (f) 10.5 GHz. (a), (c), (e) E plane, (b), (d), (f) H plane.

antenna size or techniques like introducing Electromagnetic Band Gap (EBG) structures [13], Frequency selective structures (FSS) [14] etc.. These techniques are complex and antenna with these techniques will have integration problems in PCB's. In order to overcome these limitations it is necessary that the surface wave should be suppressed or provided with an in phase excitation while maintaining a planar structure for the antenna.

In literatures [10–15] several methods have been discussed for the suppression or cancellation of surface waves like high impedance ground

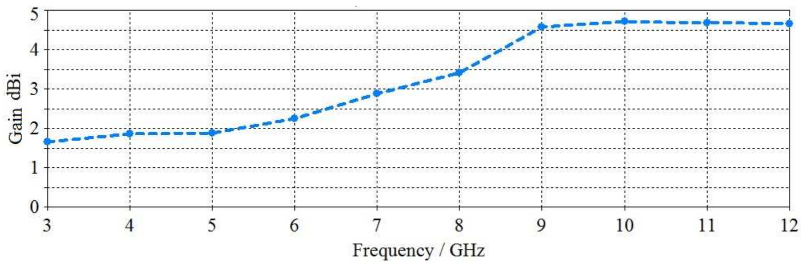


Figure 8. Simulated gain of conventional elliptical monopole antenna.

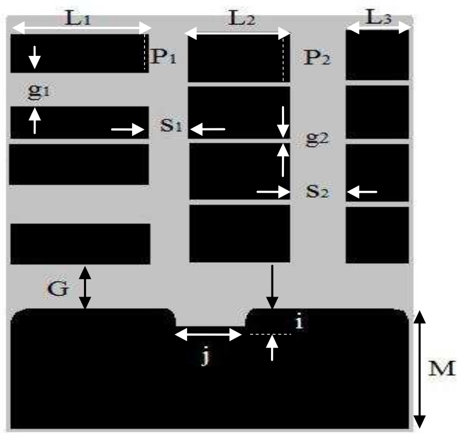


Figure 9. Partial ground with parasitic patches.

structures, defected ground techniques etc.. In this paper instead of suppressing or cancelling the surface waves, they are provided with an in phase excitation by introducing parasitic patches (as shown in Fig. 9) at the partial ground plane [15]. In order to determine dimensions of these parasitic patches the whole UWB band is divided in to 3 sub bands, i.e., 3 GHz–6 GHz, 6 GHz–9 GHz and 9 GHz–12 GHz. The lengths L_1, L_2, L_3 are equal to $\lambda/8$ ([14, 15]) where λ corresponds to the frequencies 4.5 GHz, 7.5 GHz, 10.5 GHz respectively. The parasitic patches are needed to obtain an in phase excitation of surface wave in the direction of the main radiating waves. The notch in the ground plane, i.e., $i \times j$ is for impedance matching purpose.

The dimension of the elliptical patch and partial ground with parasitic patches were optimized for obtaining a complete UWB response.

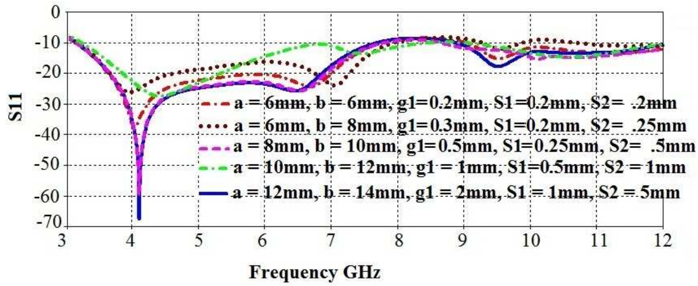


Figure 10. Analysis of return loss graph with respect to variation in the dimensions of the proposed structure (Figs. 1(a) and (c)).

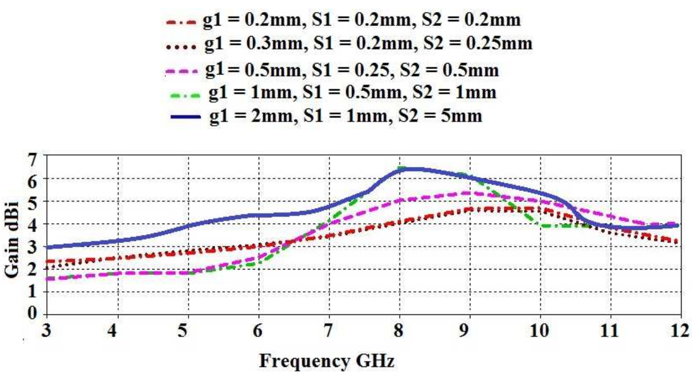


Figure 11. Analysis of gain with respect to variation in the dimensions of the proposed structure (Fig. 6).

3. MEASUREMENT AND ANALYSIS

3.1. Optimization of Proposed Structure for Obtaining UWB Band

The dimensions of the patch radiator and the gap between the parasitic patches are varied in order to achieve better bandwidth response as shown in Fig. 10. The variations in the gain with respect to variations in the gap dimension (gap between parasitic patches) are shown in Fig. 11.

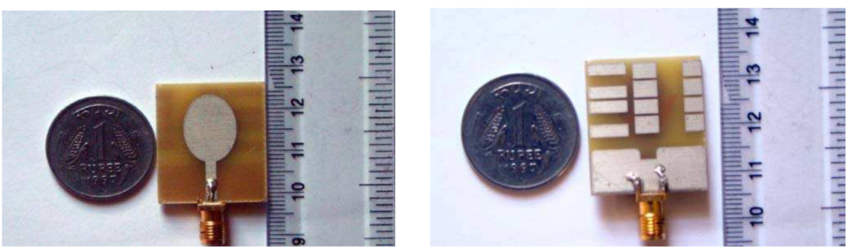
After optimizing the bandwidth response the dimensions of the major (b) and minor (a) axis were fixed at 14 mm and 12 mm respectively. With these fixed dimensions (major and minor axis of ellipse) the gap dimension (between parasitic patches) were again varied. The variations in the dimensions for optimizing gain were similar to the variations in dimensions done for bandwidth optimization.

3.2. Measurement of Fabricated Prototype

After optimization the antenna was fabricated and tested for its return loss characteristic, radiation pattern, phase response and time Domain (Group Delay) Response.

The photograph of the fabricated antenna is shown in Fig. 12. The antenna is fabricated on FR4 substrate (Dielectric constant = 4.4, thickness $t = 1.6\,\text{mm}$). Thin tin plating was done on the metallic surface of the fabricated antenna to make it corrosion resistant. The fabricated antenna was tested for its return loss, radiation pattern characteristics, time domain response and transmission phase response using Vector Network Analyzer and Anechoic chamber.

The final dimensions of the fabricated antenna (referring Fig. 1) are: $a = 12\,\text{mm}$, $b = 14\,\text{mm}$, $L_1 = 9\,\text{mm}$, $L_2 = 4\,\text{mm}$, $L_3 = 4\,\text{mm}$, $g_1 = 2\,\text{mm}$, $g_2 = 0.5\,\text{mm}$, $S_1 = 1\,\text{mm}$, $S_2 = 5\,\text{mm}$, $M = 9\,\text{mm}$, $P_1 = 2\,\text{mm}$, $P_2 = 3.5\,\text{mm}$, $i = 2\,\text{mm}$, $j = 3\,\text{mm}$, $W = 24\,\text{mm}$, $L = 28\,\text{mm}$. Fig. 13 shows the measured return loss graph of the proposed structure. The S_{11} graph clearly indicates that the proposed structure is exhibiting an UWB response by covering a bandwidth of 8.5 GHz, i.e., 3.5 GHz–12 GHz.



(a) (b)

Figure 12. Fabricated prototype antenna. (a) Front view, (b) back view.

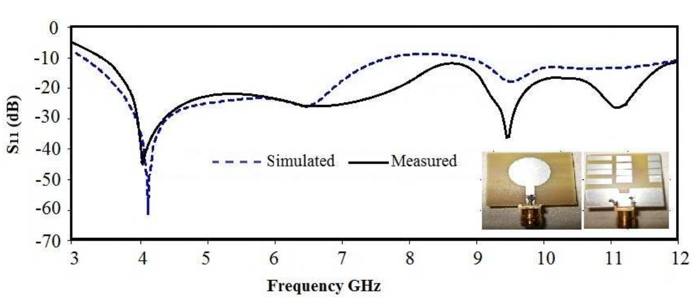


Figure 13. Return loss characteristics of fabricated antenna.

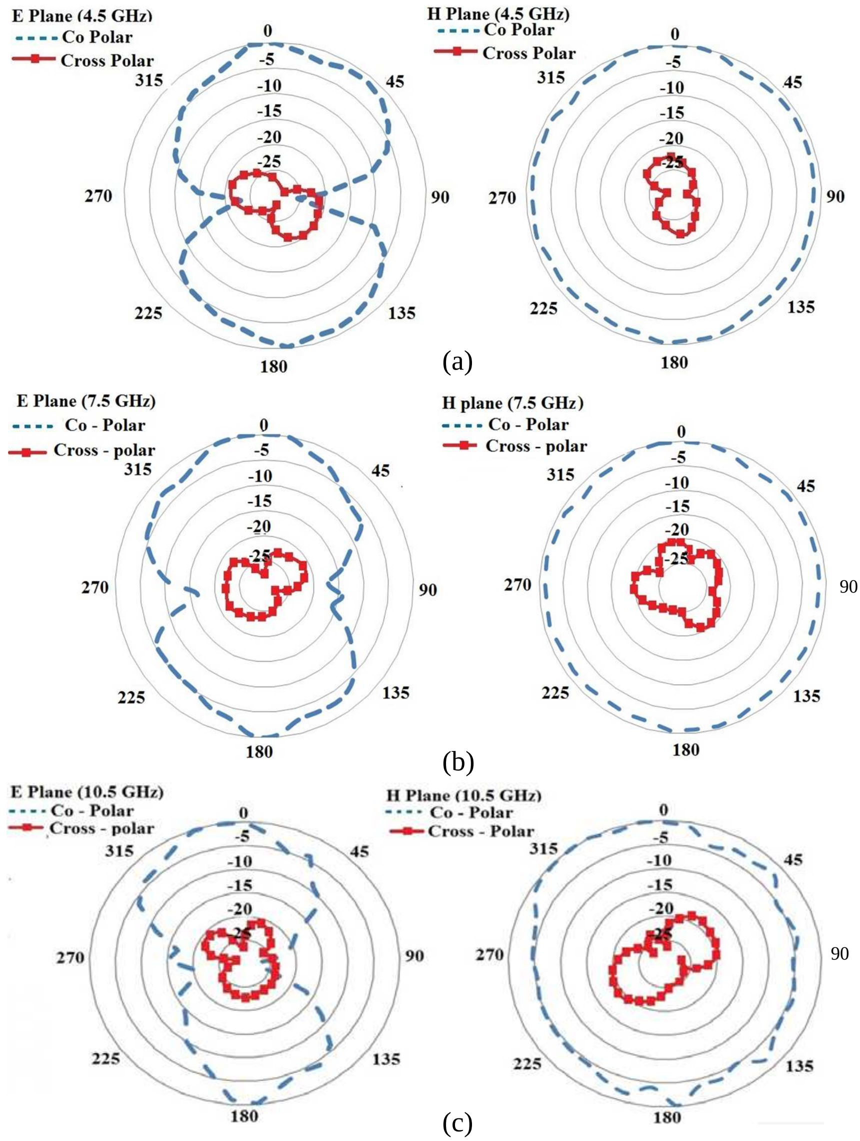


Figure 14. Measured (normalized) radiation pattern characteristic at (a) 4.5 GHz, (b) 7.5 GHz, (c) 10.5 GHz.

The measured radiation characteristics of the proposed antenna are shown in Fig. 14.

The radiation pattern measurements were carried out at 4.5 GHz, 7.5 GHz and 10.5 GHz. These frequencies were chosen in order to

Table 1. Broad side magnitude (normalized) comparison of co and cross polar response.

	4.5 GHz	7.5 GHz	10.5 GHz
Polarization (dB)	Co Cross	Co Cross	Co Cross
E 0°	0 −26	0 −28	0 −25
H 0°	0 −23	0 −20	0 −27
E 180°	0 −26	0 −24	0 −23
H 180°	0 −22	0 −25	0 −25
E 360°	0 −26	0 −28	0 −25
H 360°	0 −23	0 −20	0 −27

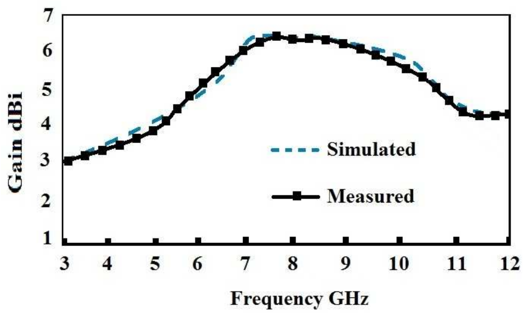


Figure 15. Gain of fabricated antenna.

approximate the radiation characteristic of the proposed antenna for complete bandwidth. In Fig. 14 the measured radiation pattern indicates an omnidirectional response for all the chosen frequencies. The magnitude comparisons between the co and cross polar component (broad side) at all three frequencies are tabulated in Table 1.

Other than tabulated angles the magnitude of cross-polarization is less than −20 dB compare to the co-polar component for both E and H plane. An approximate constant magnitude of H plane for all the radiation angles also proves the omnidirectional nature of the proposed antenna. Fig. 15 shows the measured gain of the antenna with a maximum of 6.27 dBi at 8 GHz and an average value of 4.5 dBi for the complete bandwidth except for lower frequency band, i.e., at 3 GHz–5 GHz where the gain is 3.1 dBi–4 dBi, though it fulfills the needs for the UWB application.

Figure 16 shows the simulated antenna efficiency. This Efficiency

Figure 16. Efficiency (with final dimensions).

is with respect to the dimensions of fabricated prototype. In can be seen that at 4.5 GHz the efficiency is around 95% where as at 7.5 and 10.5 it is 96% and 95% respectively. For the complete bandwidth the average efficiency is above 90% except for 3.5 GHz where the efficiency is 66% but then it increases to 97% at 4 GHz and then remains above 90% for rest of the band width.

4. TRANSMISSION PHASE AND TIME DOMAIN RESPONSE

For ensuring the effective data transmission and efficient utilization of the UWB band it is necessary that a UWB antenna possesses a linear transmission phase response. So for analyzing the phase response of the fabricated antenna, two identical antennas (fabricated prototypes) were kept at a distance of 1 m (face to face) where one of the antennas is acting as transmitter while another is receiver. Fig. 17 shows the measured phase (Phase S_{21}) response.

It is clear from Fig. 17 that the fabricated antenna provides a linear phase response for complete bandwidth which ensures in phase surface wave excitation and less distortion in signal transmission.

Since the transmission in UWB band is in the pulse form thus, it is necessary that there should be a near constant group delay (delay among the received pulse) throughout the band width. The group delay response for the fabricated antenna (face to face orientation of the fabricated prototype) is measured using Agilent E8364b PNA Network Analyzer. Fig. 18 shows the measured group delay which is nearly constant and less than (1 ns) throughout the UWB band.

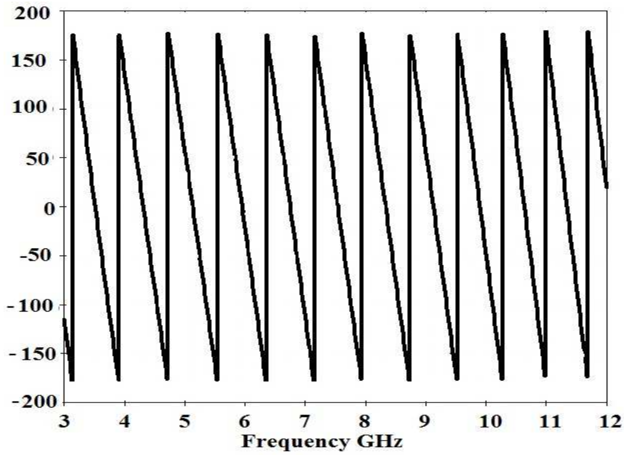


Figure 17. Phase (S_{21}) response of fabricated antenna.

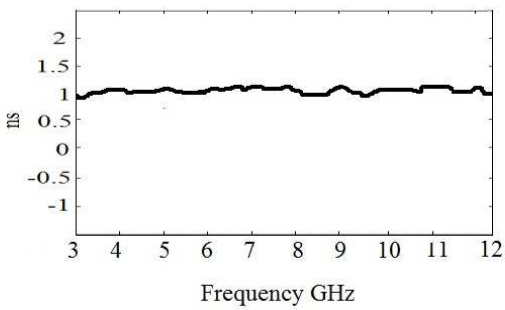


Figure 18. Measured group delay response of the proposed antenna.

5. COMPARISON OF PROPOSED ANTENNA WITH AVAILABLE PUBLISHED STRUCTURES

It is expected that for a UWB antenna the nature of the structure should be planar and compact in size so that it can be integrated with the UWB system. In [7] the reported antenna provides all essential characteristic required for UWB communication, but due to its non planar nature its integration with printed circuit boards or printed transreceiver kit will be difficult. A comparison between existing published work and the proposed antenna with respect to antenna size and gain is shown in Table 2.

It can be seen in Table 2 that at higher frequency the proposed structure is providing a better gain compare to existing published

Table 2. Size and gain (dBi) comparison.

	Antenna Size ($L \times W$) in mm	4.5 GHz	7.5 GHz	10 GHz
Ref. [2]	24×22	1.5	4	5
Ref. [3]	70×42	6.4	5.5	3.9
Ref. [6]	29×29	4	5.4	3.9
Ref. [20]	34×24	3	4.7	3.7
Ref. [21]	28.5×26	1.7	1.5	0
Proposed Antenna	28×24	3.5	6	5.7

antenna structures. As reported in [2] the magnitude of the cross polarization at 7.5 GHz for E plane is -15 dB (normalized Broad Side) and at H Plane it is near -10 dB and these cross-polar values are higher at 9.8 GHz. The antenna reported in [3] provides an excellent gain characteristics but it lacks in compactness. In the proposed structure the magnitude of cross polarization of E Plane at 7.5 GHz is less than 21 dB (normalized broad side) and for H plane it is less than 20 dB. At higher frequencies also (around 10.5 GHz) the proposed antenna shows a stable omnidirectional radiation pattern with a cross-polarization level less than 20 dB. The compactness of the proposed structure is comparable with other reported antenna mentioned in Table 2.

6. CONCLUSION

A compact, low cost printed elliptical antenna loaded with parasitic patches is presented. The proposed antenna covers the entire UWB band of 3.5 GHz–12 GHz and it can be easily integrated with PCBs of various systems. The proposed antenna provides a stable omnidirectional radiation pattern with reduced cross-polarization level throughout the UWB frequency range. The gain of the fabricated antenna varies between 3 dBi–4.5 dBi with a maximum of 6.27 dBi at 8 GHz and an average efficiency of 90% throughout the bandwidth. The linearity of the phase of S_{21} and constant group delay ensures that the proposed antenna is a good candidate for UWB application.

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