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Simulation and Experimental Studies on Printed Ultra Wide Band Antennas

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Abstract
Printed patch antennas are generally planar, low mass and low profile radiating elements. Due to their possible conformity and simple manufacturing, printed antennas are interesting techniques for wide variety of applications like GPRs and See-through-the wall radars. Major disadvantages associated with this printed antennas are low gain and narrow bandwidth. However many broad banding techniques are in the literature such as aperture coupling using multi layer substrates, using parasitic elements etc... by its nature, for defense applications which challenges us to improve the bandwidth of the antenna without increasing the thickness of the substrate. One such method that facilitates our need is insertion of wide slots in the ground plane, steps in the planar patch and partial ground plane technique in order to make it to radiate bidirectionally.

Index Terms: Coplanar Waveguide (CPW), Impedance Bandwidth, Micro Strip Antenna (MSA), Radiation Pattern, Ultra Wide Band (UWB), VNA Return Loss Plot.

I. Introduction

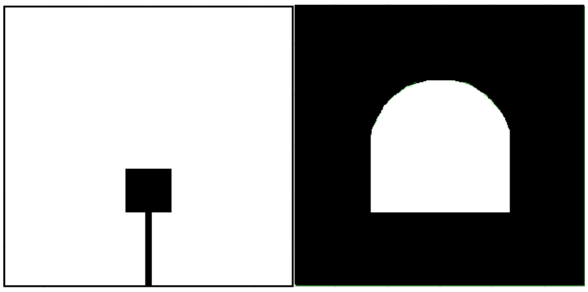
MSAs are attractive due to their light weight, conformability and low cost [5]. These can be integrated with printed strip-line feed networks and active devices. A major contributing factor for recent advances is the current revolution in electronic circuit miniaturization brought about by developments in large scale integration. MSA based on photolithographic technology [8] are seen as an engineering breakthrough.

In its most fundamental form, a MSA consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side. For a rectangular patch [7], the length L of the patch is usually $0.33\lambda_0 < L < 0.5\lambda_0$, where λ_0 is the free-space wavelength. The patch [6] is selected to be very thin such that $t << \lambda_0$ (where *t* is patch thickness). The height *h* of dielectric substrate is usually $0.003\lambda_0 \leq h \leq 0.05\lambda_0$.The dielectric constant of the substrate ε_r is typically in the range $2.2 \leq \varepsilon_r \leq 12$. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation. However, such a configuration leads to a larger antenna size. In order to design a compact MSA [8], substrates with higher ε_r must be used which are less efficient and result in narrower bandwidth. Hence a trade-off must be realized between the antenna dimensions and antenna performance. Here we use different Ultra wide band techniques to achieve greater bandwidth. The Simulator tool is CST studio (Finite Difference Time Domain) and HFSS (Finite Element Method).

II. Planar Antenna(with slot in ground plane)

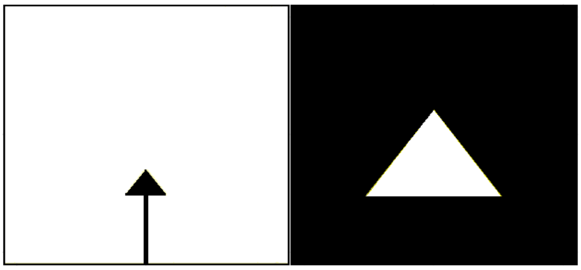
II.A Printed Wide Slot Antennas

Wide-Slot antenna [1] is superior in its wide-band characteristics. Together with its narrow slot counterpart, they form the two major members of the slot antenna family. Although many coplanar waveguide (CPW) - fed and microstrip-fed wide-slot antennas have been proposed for wide-band applications, studies on the effect of the interaction between feed and slot on impedance bandwidth and radiation patterns are rare. It was found that by choosing suitable combinations of feed and slot shapes and tuning their sizes, an optimum impedance bandwidth can be obtained, and more importantly, stable radiation patterns across the whole band can be achieved. The photo plots depicting the fabricated and engineered designs of Square patch antenna with wide slot and Triangle patch antenna with triangular slot are presented in Figures 1 and 2, respectively.



(a) Front View (b) Back View

Figure 1: Square patch antenna with Wide slot (Photo Plot).



(a) Front View (b) Back View

Figure 2: Triangle patch antenna with Triangular slot (Photo Plot).

II.A.1 Antenna design

The geometries of the two proposed antennas [1] were fabricated on the Rogers TMM4 (ε_r=4.4) and FR4 (ε_r=4.4) substrate. Design 1(Figure 3) has an Arc-Shaped slot (Semicircle Arc, radius 26.85mm) and a square-patch feed with edge length of 15mm; Design 2 (Figure 8) has a triangular-shape slot and an equilateral triangular-patch feed with an edge length W_p of 14mm. The widths W_f and lengths for both feeds are about one third of the slot size and their lengths are close to but less than the quarter wavelength measured at the lower frequency edge. The lengths are shorter than a printed monopole at the same frequency, because the slot edge acts as a capacitive load to the monopole.

II.A.2 Square Patch with Wide Slot

The design view, simulation and experimental results of square patch with wide slot antenna are presented in this section.

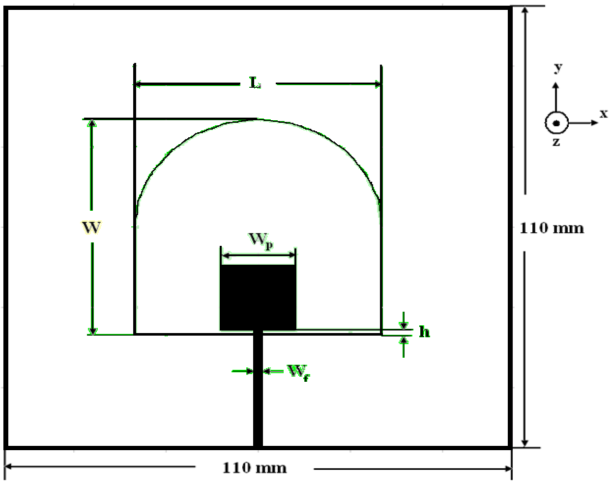


Figure 3: Top-View of the Square patch antenna with Wide slot (Design 1).

II.A.3 Simulation Results

Figure 4 shows the simulated return loss curve. It can be seen that the antenna can be operated from 1 to 12 GHz with a return loss better than 10dB. The simulated radiation patterns are shown in Figures 5 and 6. The antenna offers maximum gain of 6.5dBi.

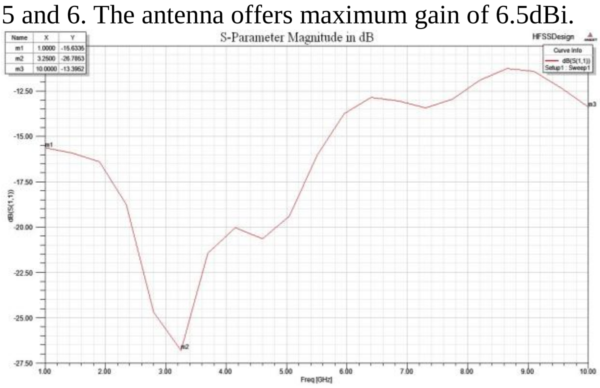


Figure 4: Simulated Return loss plot for Square patch antenna with Wide slot.

II.A.4 Experimental Results

The measured plot shows that Design 1 has very wide impedance bandwidths ($S_{11} \leq$ -10 dB), which is 120% (1.9 GHz to 7.7 GHz). The antenna was fabricated on two different substrates; Rogers TMM4 and FR-4. The return loss plots taken from VNA are shown in Figure 7. The antenna fabricated on TMM4 substrate has an operating band from 1.9 GHz to 7.7GHz for $S_{11} \leq$ -10 dB (Figure 7 a). On FR-4 the antenna has lesser bandwidth 2GHz to 6.4GHz. Therefore it is clear that antennas fabricated on Rogers have good impedance bandwidth with good return loss response when fabricated on FR-4 at higher frequencies.

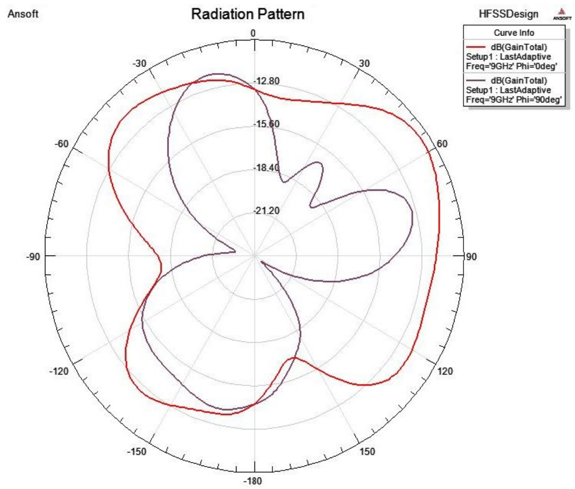
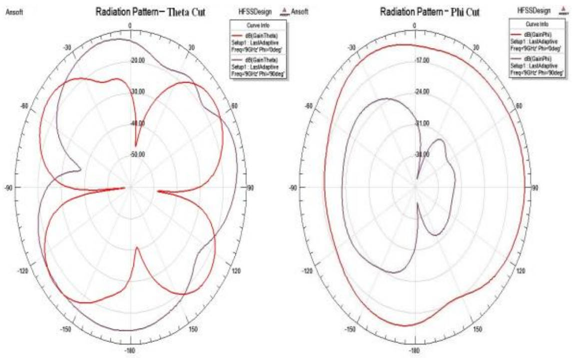
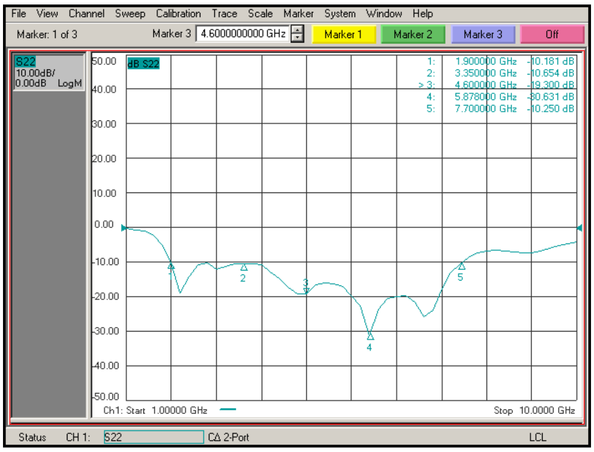


Figure 5: Two-dimensional Radiation plot.

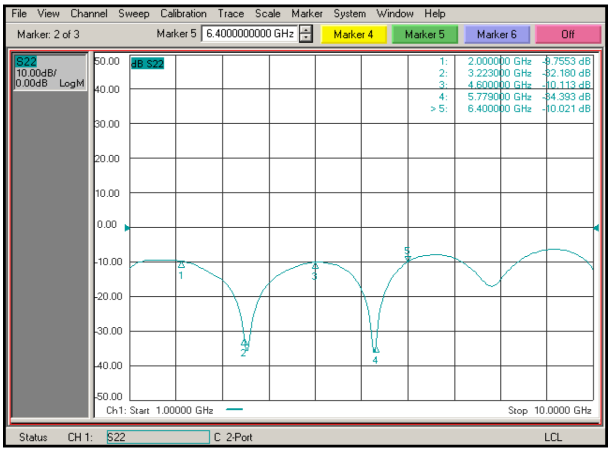


(a) Theta Cut Pattern. (b) Phi Cut Pattern.

Figure 6: Radiation Patterns of □ and □ planes.



(a) On Rogers TMM4 Substrate.



(b) On FR4 Substrate.

Figure 7: Measured VNA Return loss plot for Square patch antenna with Wide slot.

II.B.1 Triangle Patch with Triangular Slot

The design view [1] (Figure 8), simulation and experimental results of triangle patch with triangular slot antenna are presented in this section.

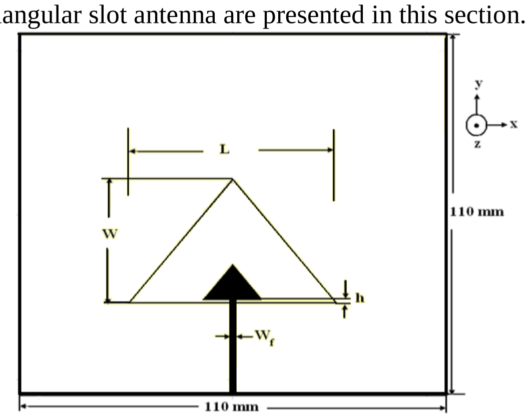


Figure 8: Top-View of the Triangle patch antenna with Triangular slot (Design 2).

II.B.2 Simulation Results

The simulated return loss curve (Figure 9) shows an operating band from 4.1GHz – 8.2GHz. Figures 10 and 11 depict the simulated radiation patterns. At the beam peak, the antenna has a gain of 2.5dBi within the operating bandwidths.

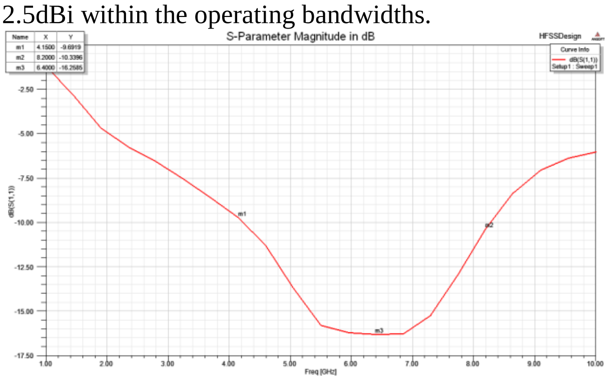


Figure 9: Simulated Return loss plot for Triangle patch antenna with Triangular slot.

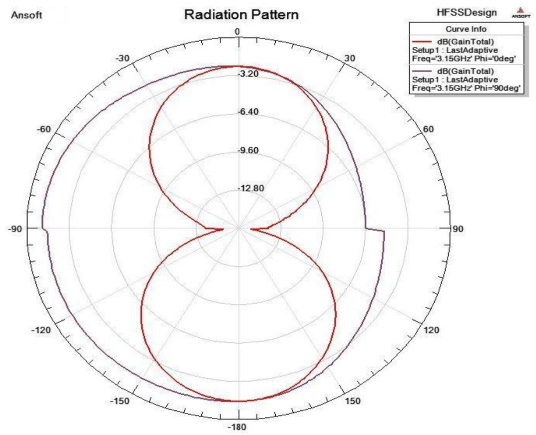
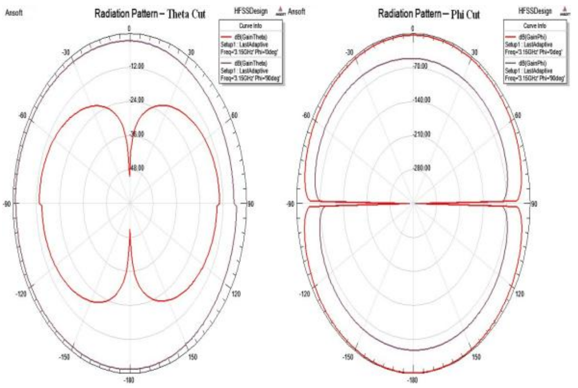


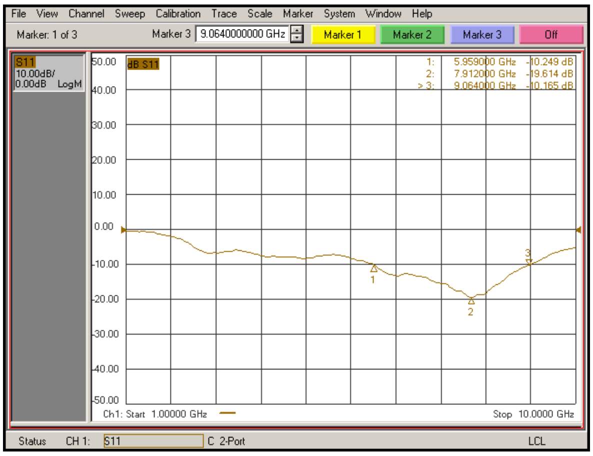
Figure 10: Two-dimensional Radiation plot.



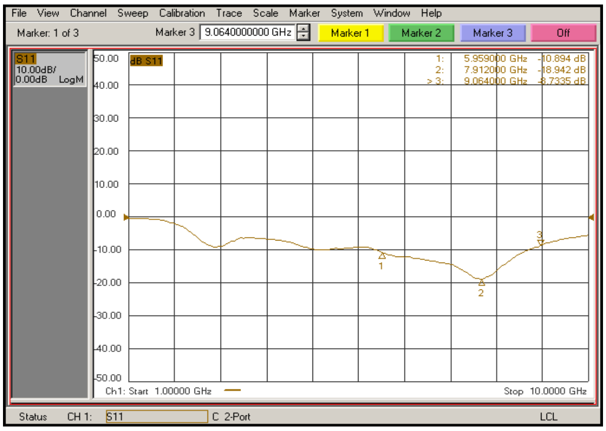
(a) Theta Cut Pattern. (b) Phi Cut Pattern.
Figure 11: Radiation Patterns of □ and □ planes.

II.B.3 Experimental Results

The measured return loss (Figure 12) shows that Design 2 has very wide impedance bandwidth, which is 67% (5.95 to 9GHz) $S_{11} \leq -10$ dB. From Figure 12 it is clear that Rogers has good impedance BW with good RL when compared with FR4. The design was expected to get impedance BW >70%. This inaccuracy was due to the fabrication error and connector mismatch.



(a) On Rogers TMM4 Substrate



(b) On FR4 Substrate
Figure 12: Measured VNA Return loss plot for Triangle patch antenna with Triangular slot.

II.B.4 Key Design Parameters

Slot & Feed Shapes:

Wide-slot antennas have different slot shapes such as rectangular, square, circular; and various feed shapes such as T, Cross, Fork-like, Bow-tie, Radial stub, Pi, Double-T, Circular and Rectangular. The antennas used in the study employ Square and Triangular- patch feeds to excite the Arc and Triangular- shape slots, respectively. These two combinations are chosen because of their wide impedance bandwidths and good radiation characteristics.

Since a large slot is used in wide-slot antenna, a high level of the electromagnetic coupling to feed line results in very large bandwidth. Therefore, varying the feed shape or slot shape will change the coupling property and thus control the impedance matching. It is noticed that the two designs proposed share the same design rules. First, the feed and slot shapes should be similar. Thus, a square patch or fork-like feed works well for a square-shape slot but not for a triangular-shape slot. Secondly, the feed should occupy an area of about one third of half of the slot size. This implies that the distance between the edge of the feed and the slot is very crucial for wide-band matching; in fact, it should be gradually changed or kept constant.

Wide-slot antenna is known to have wide impedance bandwidth but generally its operating bandwidth is limited due to the degradation of the radiation patterns at the upper edge of the impedance bandwidth. Through the study on different slot shapes, it is found that currents flowing on the edge of the slot will increase the Cross-Polarization component in the H-Plane and cause the main beam to tilt away from the broadside direction in the E-Plane. From the simulation, a square-patch fed antenna matching with an Arc-shape slot can produce better radiation patterns than with a Square-shape slot, even though both slot shapes match well with the feed. The patterns of the antenna generated by Triangular slots, among the different slot shapes, are the most stable across the operating band.

To conclude, the antenna feed and slot should be of similar shapes for optimum impedance matching, but for better radiation patterns, a triangular shape slot should be used.

Feed Gap h

The feed gap effect on the impedance matching is investigated and it is found that good impedance matching can be obtained by enhancing the coupling between the feed and slot [6]. When the coupling is increased to a certain value, an optimum impedance bandwidth can be obtained. However, if the coupling is further increased beyond this value, the impedance matching will deteriorate; showing that over coupling can degrade the impedance matching as under Coupling. Figure 4 shows the simulated return losses of Design 1 with feed gap of 1.2mm. It can be observed that the frequency corresponding to the lower edge of the bandwidth is fairly independent of the feed gap h, but the frequency corresponding to the upper edge is heavily dependent on it. Moreover, tapering the feed gap will further increase the impedance bandwidth.

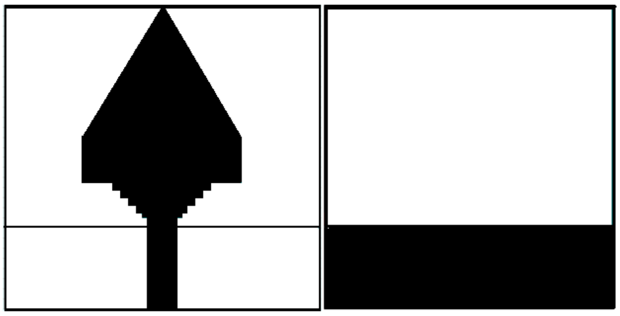
II.B.5 Outcome

Two microstrip-fed printed wide-slot antennas have been developed and both of them can offer over 100% impedance bandwidths and stable radiation patterns across the whole bands. From the investigation of various wide-slot antennas, it is found that the substrate, feed and the slot make a strong effect on the antenna's impedance bandwidth and the radiation patterns. Experimental results show that by choosing suitable combinations of feed and slot shapes and tuning their dimensions, good impedance bandwidth and stable radiation patterns can be obtained. Based on these findings, wide-slot antennas can be further improved for wide-band satellite and communications applications.

III. Planar Antenna (with partial ground plane)

III.A Diamond Shaped Ultra Wide Band Planar Antenna

This design is intended to instil more compactness in printed antenna by manifesting stepping and partial ground plane fed by a microstrip line for ultra wideband mobile applications [2]. Figure 13 shows the Photo plots of diamond shaped patch antenna for ultra wideband applications.



(a) Front View (b) Back View

Figure 13: The Diamond shaped Compact antenna (Photo Plot).

A small (30 x 30 mm^2) printed microstrip fed monopole antenna has been designed and fabricated. Antenna parameters measurement of return loss has been performed to test the validity of simulation and verify eligibility of the antenna for microwave imaging purpose.

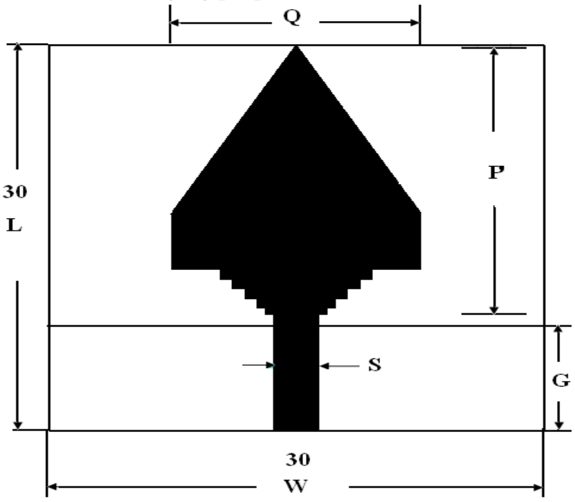


Figure 14: Top-View of the Diamond shaped Compact antenna (all dimensions are in mm).

III.A.1 Antenna Design

Figure 14 shows a diamond shaped compact antenna [2] which is printed on Rogers substrate (ε_r = 3.38) with thickness 1.6 mm and size 30 x 30 mm^2 and the antenna feeding structure is 50Ω microstrip line. Several techniques have been adopted to acquire large impedance bandwidth including a diamond like triangular radiating patch with five steps of various sizes and a partial ground plane. The physical structure of five steps with various dimensions has been adopted to increase the effective electrical length at the lower frequency band (3-4 GHz). Another theory that motivated the introduction of steps and sharp edges is that sharp corners provide current null at the edges, which leads to lower VSWR at non-resonant frequencies. Therefore, it leads to broader bandwidth. Moreover, triangular radiating patch has more constant radiation characteristics over the wide frequency range compared to some other patch shapes. The critical antenna parameters are tabulated in Table 1.

Antenna Parameters	**Dimensions (mm)**	**Antenna Parameters**	**Dimensions (mm)**
W	30.00	Step 1	0.50 x 0.50
L	30.00	Step 2	0.50 x 0.75
S	2.72	Step 3	0.75 x 0.75
G	7.90	Step 4	0.75 x 0.75
P	21.00	Step 5	0.75 x 0.75
Q	15.00		

Table 1: Critical Antenna Parameters.

III.A.2 Simulated and Experimental Results

The Return loss measurement of the fabricated antenna was performed using Vector Network Analyzer (VNA). The simulated and measured plots of the return loss (Figures 15 and 16) of the antenna show that measured impedance bandwidth is 4.5 GHz (from 2.3 to 6.8 GHz), which is equivalent to 100%. The difference in the simulated and measured return loss can be attributed to the intrinsic properties of Rogers's substrate and fabrication inaccuracies.

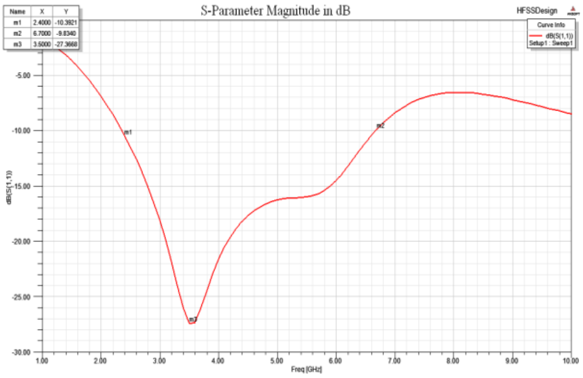


Figure 15: Simulated Return loss plot for Diamond shaped Compact antenna.

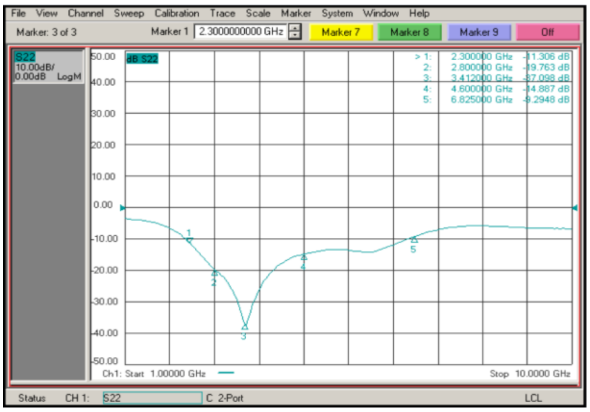


Figure 16: Measured VNA Return loss plot of Diamond shaped Compact antenna.

Figures 17 and 18 shows two dimensional radiation patterns of the proposed antenna which depict antenna's omnidirectional pattern over wide range of frequency.

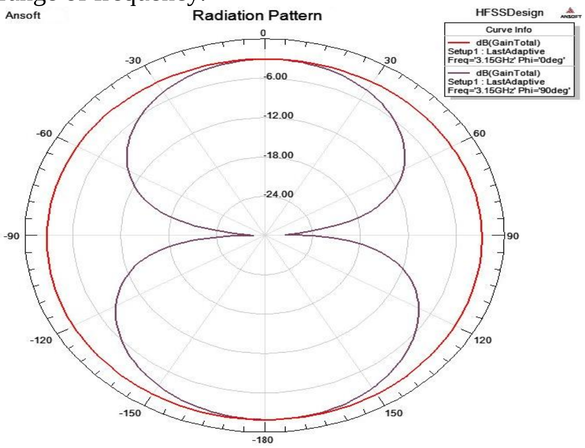
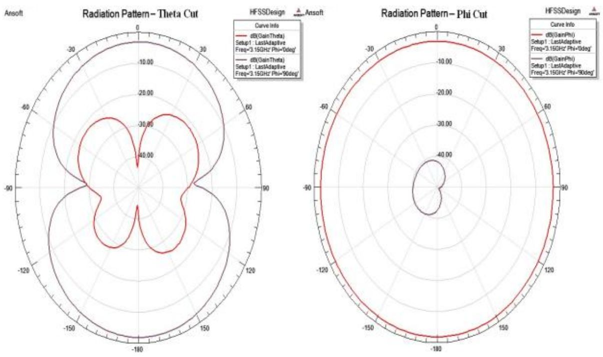


Figure 17: Two-dimensional Radiation plot.



(a) Theta Cut Pattern. (b) Phi Cut Pattern.

Figure 18: Radiation Patterns of □ and □ planes.

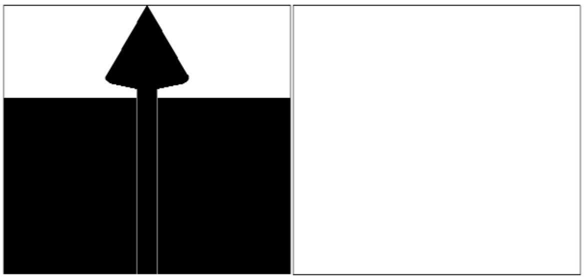
III.A.3 Outcome

A printed microstrip feed UWB antenna with good impedance bandwidth and stable radiation characteristics is proposed. The antenna is compact and useful.

IV. Coplanar Waveguide Fed Ultra Wideband Antennas

IV.A.1 Cedar Patch Antenna

In this design [3], we present a UWB patch antenna, which has advantages of smaller area, better return loss in high frequency and higher gain in normal direction of antenna plane. The proposed antenna, with small size of 23.9 × 46.5 mm^2, is designed to operate over the frequency band between 4.8 and 13.8 GHz. The photo plot of Cedar patch is shown in Figure 19. The numerical simulation and analysis for this antenna is performed using *'High Frequency Structure Simulator'* ***(HFSS),*** which is based on the finite element method.



(a) Front View (b) Back View

Figure 19: UWB Coplanar Waveguide-fed cedar patch antenna (Photo Plot).

The CPW fed cedar patch antenna has a single layer metallic structure, as shown in Figure 20.The different dimensions in the considered design are listed in Table 2. The antenna and a 50 Ω CPW are printed on the same side of a dielectric substrate. ***W2*** is the width of the metal strip and ***g*** is the gap of distance between the strip and the coplanar ground plane. ***L1*** denote the length of the ground plane, ***h*** is the feed gap between the cedar patch and the ground plane, so ***W2*** and ***g*** are fixed at 3.2 mm and 0.15 mm, respectively, in order to achieve 50Ω impedance. In this design we have used **FR4** substrate having ε_r = 4.4, h=1.6mm.

W	W1	W2	W3	L1	L3	L
46.5	21.5	3.2	5	16.9	8	1

Table 2: Dimensions of cedar patch antenna in mm.

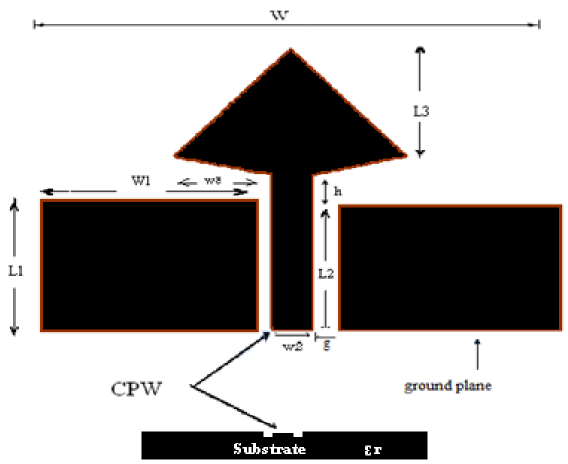


Figure 20: The Layout of Ultra Wideband Coplanar Waveguide-fed Cedar Patch antenna.

The first parameter is the feed gap ***h***. When all the parameters are fixed, the performance of the CPW fed patch antenna is quite sensitive to *h*. We are trying to find the optimal value of *h* and we observed that the -10dB return loss bandwidth of the antenna varies significantly when *h* varies. When *h* increases, the -10dB bandwidth becomes narrower due to the fact that the impedance matching of the antenna is getting worse. Looking across the whole spectrum, it seems that a bigger gap doesn't affect the first resonance very much, but has a much larger impact on the higher harmonics. This suggests that the feed gap affects more the travelling wave operation of the antenna as shown in Figure 21. **The optimal feed gap is found to be at *h*=1mm.**

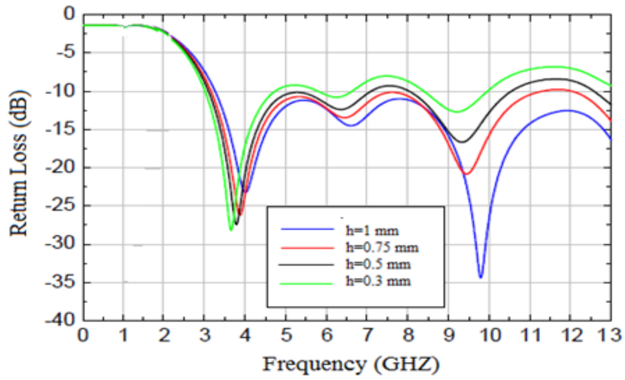


Figure 21: Return loss v/s frequency as a function of 'h'.

Another design parameter influencing the antenna operation is the width of the ground plane ***W***. The variation of the ground plane width shifts all the resonance modes across the spectrum. It is interesting to notice that the -10 dB bandwidth is reduced when the width of the ground is either too wide or too narrow. The optimal width of the ground plane is found to be at *W*=46.5mm. When the ground plane width is either reduced or increased from its optimal size, so does the current flow on the top edge of the ground plane. This corresponds to a decrease or increase of the inductance of the antenna if it is treated as a resonating circuit, which causes the first resonance mode to shift either up or down in the frequency band. Also, this change of inductance causes the frequencies of the higher harmonics to be unevenly shifted. Therefore, the change of the ground plane width makes some resonances become not so closely spaced across the spectrum and reduces the overlapping between them. Thus, the impedance matching becomes worse (RL >-10dB) in these frequency ranges. This feature is illustrated in Figure 22.

It is also noticed that the performance of the antenna is almost independent of the length *L* of the ground plane.

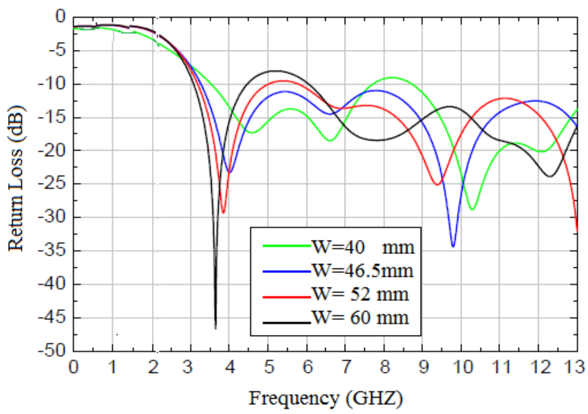


Figure 22: Return loss v/s frequency as a function of 'w'

IV.A.2 Simulated and Experimental Results

The designed antenna is fabricated using the FR4 substrate having dielectric constant ε_r=4.4 and a thickness of h= 1.6 mm. The simulated return loss plot is shown in Figure 23 and the measured return loss plot is shown in Figure 24. The measurements are done using a vector network analyzer.

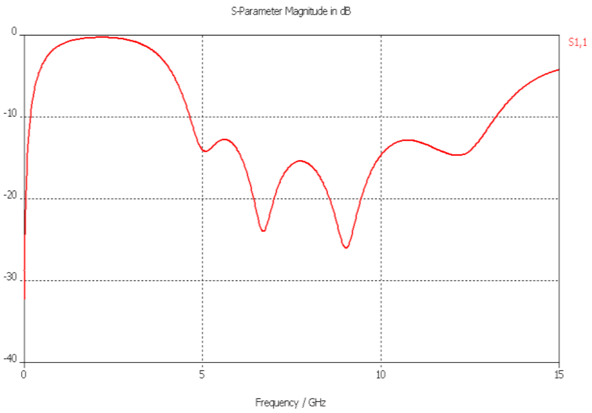


Figure 23: Simulated Return loss plot of UWB Cedar patch antenna.

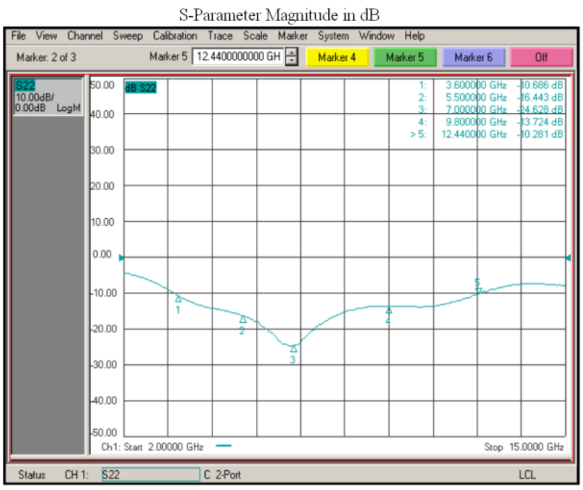


Figure 24: VNA Return Loss plot of UWB Cedar patch antenna.

IV.A.3 Radiation Pattern

The simulated radiation patterns (Figures 25 and 26) at operating frequency have a bidirectional radiation pattern with a main lobe magnitude of 4.2dBi.

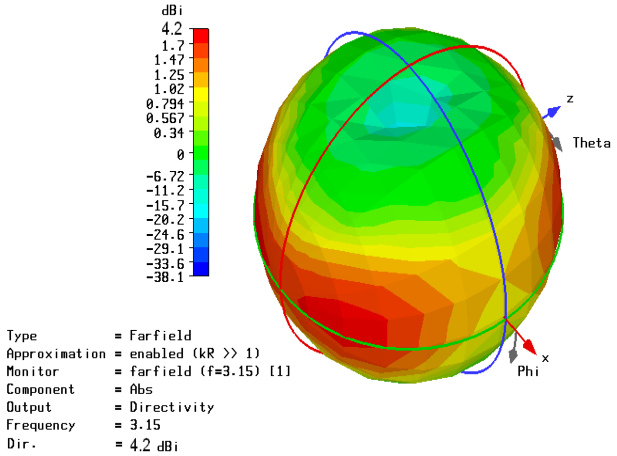


Figure 25: Bidirectional Radiation Pattern.

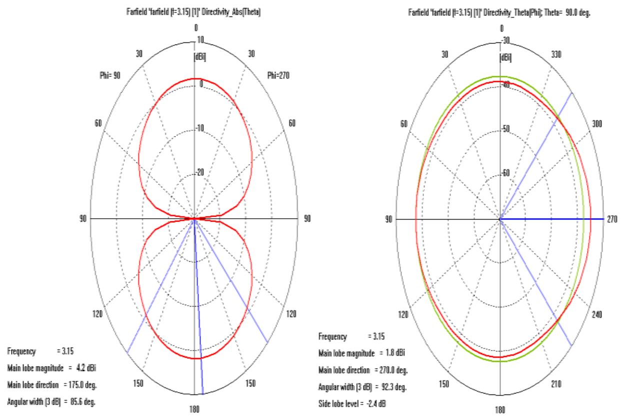


Figure 26: Simulated 2-D Radiation Patterns.

IV.B.1 Rectangular Slot Antenna with U-Shaped Tuning Stub

Coplanar waveguide (CPW) fed Ultra wide-band slot antenna is presented [4]. The rectangular slot antenna is excited by a 50Ω CPW with a U-shaped tuning stub. The impedance bandwidth, from both measurement and simulation is about 110% (S_{11} < -10dB). The antenna radiates bi-directionally. The radiation patterns obtained from the simulations are found to be stable across the matching band.

This design presents an ultra wide-band coplanar waveguide-fed rectangular slot antenna on a thin substrate. A U-shaped tuning stub is used to enhance the bandwidth of the slot antenna. Measured and simulated impedance bandwidth of 110% is achieved for this antenna. The radiation patterns are bi-directional. The patterns obtained from the simulation are stable across the matching band and at the high end of the band. An average gain of more than 2dBi is obtained. The simulation software used is CST Microwave Studio.

The slot is etched at the center (Figure 27) of a 10cm (~ 2 λ_0) x 10cm (~ 2 λ_0) ground plane. The substrate has a dielectric constant ε_r = 3.38 and thickness h=0.813 mm (0.017 λ_0), where λ_0 is the free space wavelength at the center frequency 6.14 GHz. The rectangular slot has a width W_r=32.2mm (0.65 λ_0) and length L_r=21.1mm (0.43 λ_0). A 50 Ω coplanar waveguide with slot width W_s =0.125mm and center conductor width W_f =1.88mm is used. In addition, a U-shaped tuning stub embedded within the slot terminates the CPW feed. The stub has a length of W_{stub} =16mm and width L_{stub} =10mm.

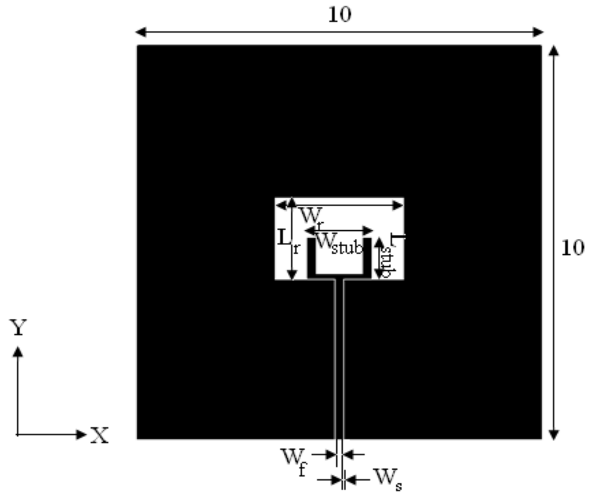


Figure 27: Layout of Ultra Wideband Coplanar Waveguide-fed Rectangular slot antenna. (All dimensions in mm)

IV.B.2 Simulated and Experimental Results

Figures 28 and 29 shows the simulated and measured return loss plots, respectively of the CPW-fed slot antenna. The resonant frequencies of the simulation and measurement results are in good agreement within the matching frequency band 2.79GHz to 9.48GHz, which corresponds to an impedance bandwidth of 110% (S_{11} < -10dB). The wide bandwidths are due to the multiple resonances introduced by the combination of the rectangular slot and the U-shaped stub. Detailed studies of the effect of the various parameters are lengthy, rigorous and are beyond the scope of this project. Note that the slot antenna radiates bi-directionally, with similar radiation level in both the directions. The 3dB beam widths at 3.15 GHz are 59.2^0 and 144.5^0 in the E-plane and H-plane, respectively. The simulation patterns are shown in Figures 30 and 31. Both the E-plane and H-plane patterns give similar beam widths and shapes. Notice the cross-polarization level increases at 6GHz because the stub arm length is close to a half wavelength around this frequency. Also, it can be seen that the beam width is wider at lower end of the frequency band. The average gain, obtained from the simulation is about 3.5dBi ± 1.6dBi across the matching band.

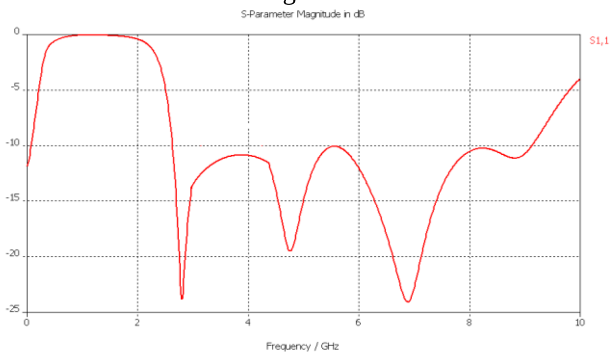


Figure 28: Simulated Return loss plot of Rectangular slot antenna with U-shaped tuning stub.

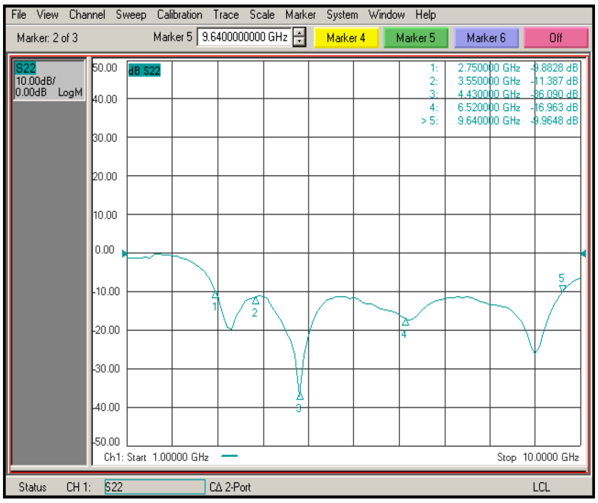


Figure 29: VNA Return Loss plot of Rectangular slot antenna with U-shaped tuning stub.

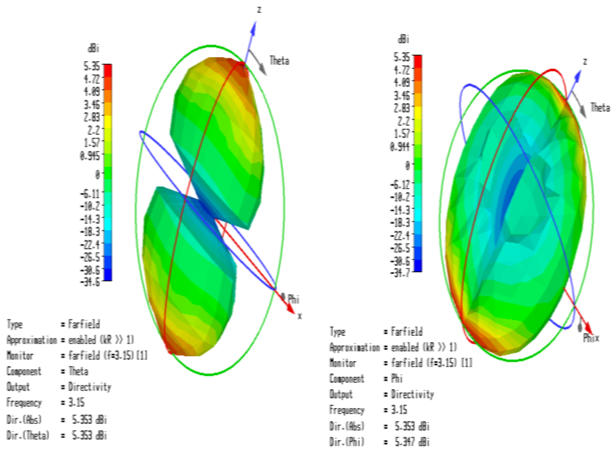


Figure 30: Three-dimensional Radiation Pattern, Theta cut and the Phi cut.

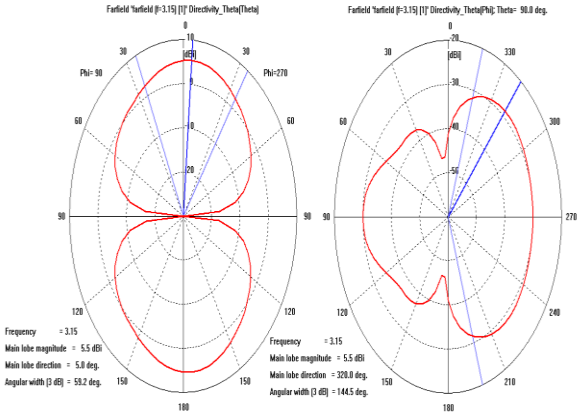


Figure 31: Polar Radiation Pattern, Theta cut and the Phi cut.

V. Outcome on Analysis of different UWB antennas

Type of Antenna	Range B.W (in Ghz)	Impedance B.W S1,1(< -10dB)	Gain (in dBi)	Applications
Square Patch with Wide Slot	1.9 – 7.7 (B.W=5.8)	120%	2.5	Wireless Communications
Triangle Patch with Triangular Slot	4.1 – 8.2 (B.W=4.1)	67%	2.5	Wireless Communications
Diamond Shaped Ultra Wide Band Planar Antenna	2.3 - 6.8 (B.W=4.5)	100%	2.5	Mobile/ Wireless Communications.
Cedar Patch Antenna	3.6 – 12.4 (B.W=8.8)	110%	4.2	Radar Systems, GPRs.
Rectangular Slot Antenna with U-Shaped Tuning Stub	2.79 - 9.48 (B.W=6.69)	110%	5.35	Defense/ Medical Imaging Applications

VI. Conclusion

In this paper, five indigenous geometric elements of Ultra Wideband printed antennas are designed, fabricated and tested. A brief summary of the simulated and experimentally observed results are presented below:

The achieved characteristics of the Ultra Wideband antennas are as follows:

- The antennas were observed to be operating at a very wideband range with an impedance bandwidth of 110% on an average. This value of impedance bandwidth corresponds to Ultra Wideband range (3.1GHz to 10.6GHz) especially for wireless communication.
- The return loss response of the fabricated antenna was found to be in good agreement with that of the simulated one over the designed frequency range.
- The designed antennas are very compact and stable, so that it can be embedded even in mobiles.

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