INVESTIGATIONS ON CAVITY BACKED WIDEBAND MICROSTRIP
PATCH ANTENNAS WITH ENHANCED PERFORMANCE FOR
WIRELESS COMMUNICATION APPLICATIONS

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Investigations on Cavity Backed Wideband Microstrip Patch Antennas with Enhanced Performance for Wireless Communication Applications

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DEDICATION

My Family and Almighty
ABSTRACT OF THE THESIS

Investigations on Cavity Backed Wideband Microstrip Patch Antennas with Enhanced Performance for Wireless Communication Applications
by
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Microstrip patch antennas have been extensively explored in the last few decades. Since their inception they have been widely implemented in wireless communication applications but few disadvantages have been a limitation to the performance characteristics of the microstrip patch antennas.

As part of literature survey, a novel $\Psi$-shape microstrip patch antenna (MPA) has been studied which achieved a very wide impedance bandwidth of 55% with decent radiation performance but suffered from degrading broadside gain towards higher frequencies. The wireless communication industry applications demand for smaller and compact antennas which can provide wide impedance bandwidth and good radiation performance occupying less space when installed. This thesis initially presents remedies for problems encountered with the full $\Psi$-shape MPA which include adding layer on top and also designing metallic strips onto the layer. A comparison of the performance characteristics of all three designs has been made. Then a reduced size (almost 50% than original patch size) half $\Psi$-shape MPA with optimized design dimensions is presented and the experimental verifications are performed. This antenna has provided a wide impedance bandwidth but at the cost of increased cross-polarization.

Next, a cavity backed half $\Psi$-shape MPA is presented which consists of a copper cavity placed behind the patch antenna mainly to increase the co-polarization gain and reduce the cross-polarization level. The cavity backing has proved to be effective only to a certain extent as it considerably increased the co-polarization gain by 2 dB compared to the earlier half $\Psi$-shape patch design but nevertheless proved futile in reducing the cross-polarization levels. Finally an optimized cavity backed half $\Psi$-shape MPA employing defects in the ground plane is presented along with experimental and simulation results. This design has been effective in increasing the co-polarization gain along with reduced cross-polarization while maintaining almost similar antenna performance as the earlier design. The measured results show reasonable agreement with the simulation data.
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CHAPTER 1

INTRODUCTION

Microstrip patch antennas have been extensively explored in the last few decades. Since their inception they have been widely implemented in wireless communication applications owing to their compact size, light weight, ease of design and fabrication [1-2]. Narrow impedance bandwidth and relative larger size in microwave frequency ranges have often been a limitation to the performance characteristics of the microstrip patch antennas. Researchers have made many efforts and come up with new designs to enhance the impedance bandwidth of the antenna by employing conventional methods which include: increasing the substrate thickness, implementing slots into the patch, using parasitic patches either in another layer or on the same layer [3-8]. Recently, a novel Ψ-shape microstrip patch antenna design was proposed to achieve a very wide impedance bandwidth [9]. The antenna mainly consists of a Ψ-shape patch etched on a microwave substrate and placed on a foam substrate which was essentially done for the ease of fabrication and to make it suitable for the practical wireless communication applications. The antenna design contributed a very wide impedance bandwidth of 55% with decent radiation performance but suffered from degrading broadside gain towards higher frequencies [9].

The wireless communication industry applications demand for smaller and compact antennas which can provide wide impedance bandwidth and good radiation performance occupying less space when installed. The resonant length of a microstrip patch antenna is approximately $0.5\lambda$, where $\lambda$ is electrical wavelength. One way to achieve compactness is to reduce the overall size of the antenna by approximately 50% by adding a shorting wall at the center of the patch. Investigations were performed on half U-slot and half E-shape patches where in different miniaturization techniques such as a shorting wall between the conducting patch and the ground plane, and the addition of shorting pins between the conducting patch and the ground plane were employed to achieve compactness while retaining the wideband behavior [10-15]. It has also been observed that L-shape feeding mechanism further enhances the impedance bandwidth of the antenna. The investigation results for obtaining compactness
and wideband response by implementing L-shaped feeding mechanism to a quarterwave patch antenna have been explored in [16-21]. Quarter wavelength patch antenna configurations help in achieving the compact design and ease in fabrication while retaining almost the same electrical parameters (impedance, and radiation patterns) but at the cost of increased cross-polarization level.

A comparison between cavity-backed and without cavity-backed patch antennas have been made in [22], where it was observed that the cavity backed patch antenna improves the impedance bandwidth as well as the radiation performance [22-24]. This partially open metallic resonator (cavity) effectively suppresses the surface waves thereby increasing the broadside gain but high cross-polarization has always been a limitation. A defected ground structure (DGS) was proposed in [25] to reduce the cross-polarized radiation without affecting the dominant mode and co-polarized radiation patterns of a conventional antenna. Few other designs with DGS were explored to improve the antenna performance which consisted of arc shaped slots symmetrically placed around the SMA feed in the ground plane [25-29].

### 1.1 MICROSTRIP PATCH ANTENNA

This section presents the characteristics and performance related issues of microstrip patch antennas (MPA’s). This section also includes the advantages as well as drawbacks in implementing microstrip patch antennas with different kinds of feeding mechanisms to the MPA’s.

#### 1.1.1 Microstrip Patch Antenna Geometry

A microstrip patch antenna in its basic form consists of a metallic radiating patch on one side of dielectric substrate, which has a ground plane on other side. The radiating patch can be considered as an extension of microstrip line as shown in the Figure 1.1 [30].

The radiating elements and feed lines are usually photoetched on the dielectric substrate. The radiating patch may be square, rectangular, circular, elliptical, triangular or any other configuration as shown in Figure 1.2. Square, rectangular and circular are the most common shapes of microstrip patch antennas used mainly due to the ease of fabrication of these designs. Other shapes include the triangular patch antenna which has the ability to produce dual polarization but have been limited by high cross-polarization and the circular...
ring structures limited by a very small structure resulting in low impedance bandwidth.
Linear and circular polarizations can be achieved by either a single element or an array of
elements which have beam scanning abilities as well as high directivities if a phased array
antenna is implemented [30]. Assuming a voltage input at feedline, when operating in
transmission mode, current is excited on feedline to the patch of a vertical electric field
between the patch and the ground plane. So therefore the patch element resonates at certain
wavelength and this result in radiation [31]. As discussed in earlier subsections, the
microstrip patch antennas essentially consist of a radiating patch placed directly above a ground plane. There are wide varieties of dielectric substrates that are used to design microstrip patch antennas. The choice of the dielectric material mainly relies on the kind of performance characteristics required and also varies with the antenna implementation in various wireless communication applications.

Various broadbanding techniques have to be devised to obtain wide impedance bandwidth while achieving high gain and compact sizes. In this thesis, rectangular microstrip patch antennas have been considered owing to their better performance characteristics explained above and different geometries added to the patch design to obtain wide bandwidth with decent radiation performance of the antenna.

1.1.2 Transmission Line Model

The transmission line model (TLM) of a microstrip patch antenna is shown in Figure 1.3.

![Figure 1.3. Transmission line model for microstrip patch Antennas with electric field lines. Source: C. A. Balanis, Modern Antenna Handbook, 1st ed., Danvers, MA: John Wiley & Sons, 2008.](image)

The microstrip patch antenna etched on the dielectric substrate is of finite dimensions. The patch undergoes fringing at the edges as shown in the Figure 1.3. The amount of fringing that the patch undergoes depends mainly on the dimensions of the patch as well as the substrate thickness. It is worth noting that the fringing fields influence the operating resonant frequency of the patch. The fringing lines shown in the figure are basically nonhomogeneous lines of two dielectrics, in this case the dielectric substrate and air, they mostly reside in the substrate. The fringing fields cause the patch becoming electrically larger at higher frequencies. Even patch with smaller dimensions become electrically larger due to the fringing field phenomena.
A compromise between the fields in substrate and air has resulted in the concept of effective dielectric constant which is defined as “the dielectric constant of the uniform dielectric material so that the fringing lines in Figure 1.3 (p. 4) has identical electrical characteristics, particularly propagation constant, as the actual propagating lines” [1]. The effective dielectric constant varies with the frequency such a way that an increase in the frequency results in electric field lines concentrating in the dielectric substrate which causes the microstrip line to behave as a homogeneous line. The fringing depends on the ratio of $L/h$ of the patch and the height $h$ of the substrate of dielectric constant $\varepsilon_r$. The effective dielectric constant is a function of resonant frequency. The value of $\varepsilon_{\text{reff}}$ is less then $\varepsilon_r$ mainly due to the fringing fields concentrating at the edges of patch are not confined in the substrate but also spread in the air also as shown Figure 1.3 (p. 4). The expression for $\varepsilon_{\text{reff}}$ is given as [1]:

$$
\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12}{\varepsilon_r} \right]^\frac{1}{2}
$$

where,

- $\varepsilon_{\text{reff}}$ = Effective dielectric constant
- $\varepsilon_r$ = Dielectric constant of substrate
- $h$ = Height of dielectric substrate
- $W$ = Width of the patch

### 1.1.3 Advantages and Limitations

The advantages of the microstrip patch antennas compared to the conventional antennas are listed below [1-3]:

- Light weight, occupy less space making them easy to install.
- Widely used in microwave frequency region due to their low profile, ease of design and fabrication using modern printed circuit technology.
- They are mechanically robust when mounted on rigid surfaces.
- Different kinds of polarizations can be achieved with different designs.
- Dual frequency and dual polarization can be achieved.
- Different kinds of reconfigurations can be achieved suitable for multiband operations which is essential in cellular applications.
Though the microstrip antennas are versatile and offer various advantages when compared to conventional antennas, they also have few drawbacks which are listed below [1-3]:

- The serious limitation for their implementation is narrow impedance bandwidth.
- Their performance is sometimes limited by low efficiency, poor power handling capacity, poor polarization purity and poor scan performances.
- Radiation into half-space has sometimes limited microstrip antenna performance.
- Designing arrays involve complex feed structures.
- Spurious radiation from feeds and junctions degrade the antenna performance.
- Increased cross-polarization and mutual coupling within array structure at higher frequencies in frequency band also limit antenna performance.
- Designing microstrip antennas on dielectric substrates having higher permittivity also include poor performance of the microstrip antennas.
- Poor isolation from feed and radiating element.

### 1.1.4 Radiation Mechanism of Patch Antennas

The radiation mechanism can be best explained with the help of the image theory. The patch is suspended at a short distance above the ground plane but still it radiates really well which is mainly due to the resonant cavity formed by the microstrip patch and the ground plane. The resonant cavity is associated with losses which include material (conductor and dielectric) loss and also loss due to radiation into free space. Good radiation contributes to better radiation efficiency of the patch. Radiation can also be explained in terms of the field distribution between the patch and the ground plane shown in Figure 1.4.

![Figure 1.4. Current distribution on the patch surface and below the patch. Source: R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, Microstrip Antenna Design Handbook, Boston, MA: Artech House, 2001.](image-url)
Excitation of the patch results in negative and positive charge distributions mainly because the patch is half wavelength long in dominant mode. The repulsive forces between the charges tend to push the charges in various directions and along the edges of the patch. Due to the predominance of the attractive forces, charge concentration remains below the patch while minor current flow is on the surface of the patch. The patch can be modeled as cavity with electric walls and only TM modes are possible in this cavity [2-3]. The quality factor Q is inversely proportional to the substrate thickness $h$ which implies that the bandwidth is proportional to $h$. The field distribution level inside the patch cavity at resonance is proportional to $Q$. This implies that the surface current on the patch is inversely proportional to $h$. This increase in the amplitude of the surface current at resonance as the substrate gets thinner exactly balances the image effect, causing the radiation level to be reduced by a factor proportional to $h$.

1.2 NEED FOR WIDEBANDWIDTH

Microstrip patch antennas have narrow impedance bandwidth which is a serious fundamental limitation due to the small electrical volume occupied by the element. This limitation prevents its usage in modern wireless communication applications. Also when a narrow bandwidth microstrip antenna is used in circular polarization applications, its axial ratio characteristic rapidly degrade off resonance hence we require some broadening techniques to improve the bandwidth of the microstrip antenna. Researchers have tried to improve the performance characteristics of the microstrip antenna by employing different kinds of feeding techniques and have been successful in achieving wide impedance bandwidths. But these bandwidths have been obtained at the cost of increased substrate thickness and height or volume and also accompanied by degradation in some antenna characteristics. Some effective broadening techniques have been classified below [3]:

- Bandwidth increases monotonically with thickness. Also a decrease in the dielectric constant value increases the bandwidth. This implies that using a thicker low permittivity surface like foam effectively increases the impedance bandwidth of the antenna.

- Selection of suitable patch shape is a key factor in the increase of bandwidth. The patch shapes include annular ring, rectangular or square shaped, quarter wave patch and other antenna geometries.
• Selection of suitable feeding technique also plays a major role in the process. Of the various feeding techniques like probe feeding, edge feeding, proximity coupling to microstrip line and aperture coupling, it has been observed that the aperture coupling technique has been widely employed to achieve broadband antennas.

• Broadbanding by using stacked elements include: designing a geometry such a way that patches are placed one upon other in which the upper patch sizes may vary with respect to the lower patch size. The excitation given to the lower patch excites the upper patches by electromagnetic coupling. The main advantage of this feature is that a small volume is sufficient to design more number of elements reducing the surface area it occupies.

• Broadbanding using coplanar parasitic elements consist of coplanar resonators with slightly different resonant frequencies. The geometry mainly consists of only the central patch driven by the feedline and the other patches are either gap coupled or directly coupled to the driven patch. It has been observed by many researchers that when two patches were gap coupled to the main patch along the radiating edges, a maximum bandwidth upto 5.1 times that of a single rectangular patch antenna was obtained.

• Other broadbanding techniques include loading structures like resistive loading, capacitive loading, implementing slots into the antenna design etc.

1.3 QUARTER WAVELENGTH MICROSTRIP PATCH ANTENNAS

This section mainly emphasizes on the importance of size reduction of conventional microstrip patch antennas while maintaining similar antenna performance. A conventional rectangular microstrip patch antenna is of the order of half-wavelength. In modern day world, compact wideband antennas are essentially required for various hand-held mobile antenna applications. Researchers have come up with various compact designs and development techniques for these applications but most of these designs have been associated with either degrading impedance bandwidth or radiation performance caused mainly due to increased cross-polarization. The design of compact microstrip patch antennas while maintaining wide impedance bandwidth has always been a challenge problem.

One efficient way to solve this problem is to split the half-wave patch antenna into equal halves using symmetry boundary conditions without affecting its surface field distributions. The basic geometry for a quarter wave patch antenna is shown in Figure 1.5. Figure 1.5(a) shows the half U-slot patch antenna while Figure 1.5(b) shows the full U-slot patch antenna geometries, respectively [32].
The main goal behind designing this antenna geometry is explained as follows: The electrical field distribution on a half wave patch antenna consists of maximum electrical field at one of its radiating edges and a zero field intensity in the center part of the patch and due to phase reversal, there is maximum field intensity at the other radiating edge [3]. Effectively, one half of the patch can be removed and a shorting wall can be implemented without disturbing the field distributions. This results in the resonance of the quarter wave patch at almost the same resonant frequency as the half patch antenna. The name of this
antenna has been derived from the fact that the distance between the radiating edge of the patch and the shorting wall is $\lambda/4$. The advantage of this quarter wave patch design is that similar performance characteristics of the half wave patch antenna can be derived with more effective usage in wireless communication applications.

1.4 L-SHAPE FEEDING MECHANISM

The L-shaped probe feeding mechanism for the microstrip patch antennas has been an attractive feature. The narrow bandwidth limitation of the microstrip patch antennas has limited their use in wireless communication industry. Various techniques have been explored in past to enhance the impedance bandwidth of the microstrip patches which include implementation of stacked patches. The disadvantage of this method is that addition of parasitic patches makes the structure more complex to design and fabricate. Using a thicker dielectric substrate would degrade the performance characteristics of the antenna. An effective way to enhance the impedance bandwidth of the microstrip patch antenna is to use L-shape feeding mechanism. A simple model to show the mechanism is presented in Figure 1.6 [18]. The authors in [18] have observed that bending a straight probe/strip to an L-shaped probe/strip is easy in fabrication and with the use of a rectangular patch fed by the L–probe, they were able to achieve a wide impedance bandwidth and average gain of 35% and 7.5 dBi, respectively.

The L-shape feeding mechanism is primarily associated with quarter wavelength patch antennas to obtain wide impedance bandwidth [16-20]. The authors in [18] employed finite-difference time-domain (FDTD) method to analyze L-probe proximity-fed rectangular patch antennas. Numerical results for the input impedance, co- and cross-polarization radiation patterns were presented and comparison with the measurements showed good agreement between the computed and measured results. In [20] the researchers designed an L-shape probe fed patch mounted on a metallic cylinder and were able to achieve wide impedance bandwidth which helped in the designing of cavity backed design presented in this thesis.

1.5 Simulation Tools Used

There are various sophisticated numerical techniques to design and compute performance characteristics of antennas but complex designs involve lot of computational delays and a user friendly software is very much needed to solve the issues related to design and computation. The main software implemented to investigate the performance of the antenna designs as a 3D finite structure with finite boundaries is Ansoft HFSS v.11, a Finite Element Method (FEM) based 3-D full wave analysis software. HFSS stands for High Frequency Structural Simulator and is a Maxwell equation solver [33]. The software utilizes a 3D full-wave Finite Element Method (FEM) to compute the electrical behavior of high-frequency and high-speed components. HFSS delivers fast simulation speed and the its ability to solve large scale simulations with improved meshing results in efficient, high-quality mesh generation that translates directly to reduced memory and simulation time. The software has a frequency domain solver that computes numerical techniques to find approximate solutions by solving complex partial differentials equations and integral equations [33].

In Ansoft HFSS software, the structure is modeled by specifying its geometry either by giving the coordinates for all constituents of structure or by parameterizing the structure by assigning variables for different dimensions of the antenna model. HFSS then automatically “meshes” or subdivides the structure into small tetrahedral mesh elements. The scattering parameter of the meshed structure is compared with the previous iteration, until the difference between the two most recent iterations falls below a user-specified threshold. In
this way, the user can ensure that the simulation results are converging towards a single solution. The main advantage of this software usage is that the user has the flexibility to specify a range of frequencies for which solutions will be calculated using the final mesh. The software can plot the scattering parameters, surface current distributions, near field electromagnetic densities, radiation patterns and gain as well as various other antenna parameters [33].

The simulation results have to be verified with experiments performed on the fabricated antenna designs. The AML is equipped with an Anritsu’s vector network analyzer (VNA) model # 37269D to determine the scattering parameters of the fabricated antenna. The far-field radiation pattern measurements have been performed in the anechoic chamber located at the antenna and microwave laboratory, SDSU. The radiation patterns obtained from the measurements are only raw data, while the Friis transmission equation is used to determine the antenna’s gain.

1.6 ORGANIZATION OF THESIS WORK

This thesis work is divided into the following chapters: Chapter 2 presents the $\Psi$-shape microstrip patch antenna geometry with the simulation results to show the wide impedance bandwidth performance along with the limitations in the broadside gain of the patch antenna. Next, the modified patch design which includes adding a Rogers TMM dielectric sheet on top is presented and a comparison is made for the antenna performance between the two designs in terms of return loss and broadside gain. Next, an optimized design is presented which shows considerable improvement in broadside gain when compared to the original $\Psi$-shape. Finally, simulation results along with comparison with same $\Psi$-shape patch etched on foam substrate is presented.

Chapter 3 presents a newly conceived wideband half $\Psi$-shape MPA design with one edge shorted to the ground with the aid of a partial shorting wall. The optimized design dimensions, parametric studies performed on critical patch dimensions and the experimental verifications done on the fabricated antenna prototype are also presented. This chapter also introduces the L-shape feeding mechanism to the patch antennas also supported by literature studies related to this feeding mechanism. The surface current distributions on the patch are
presented to show that the design suffers with high cross-polarization which is a serious limitation for its usage in wireless communication applications except acceptable.

Chapter 4 presents the cavity backed half $\Psi$-shape MPA. This chapter mainly concentrates on increasing the co-polarization gain while reducing the cross-polarization. An optimized cavity backed design is obtained after performing few parametric studies related to cavity dimensions and a comparison is made with respect to the half $\Psi$-shape MPA to show little improvement in antenna performance and also supported by current distributions at certain frequencies on cavity and patch.

Chapter 5 finally presents an optimized cavity backed $\Psi$-shape MPA design with defects in ground plane along with the fabricated prototype design and the supporting parametric studies performed on the cavity and slot dimensions. Also a comparison of the performance characteristics of all three designs has been made. The important parametric study results for the designs are also presented in this section.

Finally, Chapter 6 presents conclusions and areas of future study.
CHAPTER 2

FULL Ψ-SHAPE MICROSTRIP PATCH ANTENNA
(MPA)

The literature studies and design issues along with performance results for the full Ψ-shape MPA are presented in this chapter.

2.1 LITERATURE STUDY

The microstrip patch antenna suffers from narrow impedance bandwidth, which can be improved significantly by employing coupled resonator structures such as stacked microstrip antennas or U- and E-slots-loaded patches [4-6]. Both E-shape and U-slot-loaded single-layer rectangular microstrip patch antennas have shown the potential to provide 2:1 VSWR impedance bandwidths of 30%-35% on electrically thick substrate materials [7]. In addition, a dual U-slot-loaded microstrip patch antenna has shown an impedance bandwidth of approximately 44% [8] on a foam substrate alone. A novel Ψ-shape microstrip patch antenna design was designed to achieve a very wide impedance bandwidth [9]. The Ψ-shape microstrip patch antenna discussed in this thesis has provided a very wide impedance bandwidth with decent radiation performance for usage in wireless communication applications.

The antenna mainly consists of a Ψ-shape patch etched on a microwave substrate and placed on a foam substrate which was essentially done for the ease of fabrication and to make it suitable for the practical wireless communication applications. The antenna design contributed a very wide impedance bandwidth of 55% with decent radiation performance but suffered from degrading broadside gain towards higher frequencies [9]. The authors cited the electrical length of the patch becoming larger causing the excitation of an orthogonal higher order modes as the reason for the degradation of broadside gain. The simulation model for the Ψ-shape patch design along with the results with alternate design modifications to improve its performance is presented in the succeeding subsections.
2.1.1 Antenna Geometry

The novel ψ-shape patch antenna geometry (top and side views) is shown in Figure 2.1(a-b). The original rectangular patch length and width are 48.5 and 26 mm, which includes two slots of width = 6 mm and length = 19 mm symmetrically placed around the patch center and two slots of width = 6 mm and length = 23 mm cut toward the bottom of the patch. All combined modifications result in the proposed Ψ-shape patch [9]. The finite ground plane size is 75 mm x 75 mm and all the dimensions of the Ψ-shape MPA have been obtained after parametric studies done on the pivotal dimensions of the antenna. A 50 Ω SMA connector is used for feeding the patch antenna. The microwave substrate on top of the foam has been used for ease of the antenna fabrication making it compatible for various wireless communication applications.

2.1.2 Performance Results

All parametric studies have been performed on different antenna dimensions and an optimized design was obtained taking into account its performance with respect to the broadside co-polarization gain ($\theta = 0^\circ$) and the reflection coefficient magnitude. The simulated 2:1 VSWR impedance bandwidths is 55% with good directional radiation patterns in the frequency band (4.15GHz to 7.30GHz) as shown in Figure 2.2(a-b). Also the tail part of the design acts as a stub providing additional resonances thereby providing very wide-bandwidth. The simulated radiation patterns shown in Figure 2.3(a-d) clearly indicate that the cross-polarization is very high at higher frequencies in the frequency band due to the excitation of higher order modes.

2.2 \(\Psi\)-SHAPE MPA WITH DIELECTRIC SHEET

Although the novel \(\Psi\)-shape patch design provides a very wide impedance bandwidth, the unwanted high cross-polarization always causes a hindrance while implementing in wireless communication applications. An alternative design or some modifications have to be sought to reduce the cross-polarization while retaining the same antenna response. In this section, a design with modification done to the earlier patch design has been presented. The performance characteristics of the patch with supporting simulation results are presented.

2.2.1 Antenna Geometry

The simulation model for the \(\Psi\)-shape MPA with the dielectric substrate on top is shown in Figure 2.4. The modified design essentially consists of a Rogers TMM sheet ($\varepsilon_r = 9.2$, thickness = 0.8 mil) placed at a height of 9mm from the patch surface. The dielectric sheet height has been obtained after series of parametric studies were performed on the antenna. The simulation results for the optimized design along with surface current distributions are presented in the following sections. The main idea behind implementing the dielectric sheet is to prevent any radiations from scattering away from the patch and also the sheet effectively help in forming resonances in the broadside direction of the patch. These help us increase the co-polarization gain as well as reducing the cross-polarization levels.
Figure 2.2. Full $\Psi$ shape MPA (a) reflection coefficient magnitude and (b) broadside gain versus frequency.
Figure 2.3. Simulated radiation patterns at (a) 6 GHz, (b) 7 GHz, (c) 8 GHz and (d) 8 GHz.
2.2.2 Optimized Performance Results

All parametric studies have been performed on different antenna dimensions and an optimized design was obtained taking into account its performance with respect to the broadside co-polarization gain ($\theta = 0^\circ$) and the reflection coefficient magnitude. Initially nominal values were considered for the sheet dimensions along with the distance from the patch surface. Figure 2.5(a-b) plot clearly indicates that the placement of sheet has slight effect on the antenna performance. The broadside gain has considerably increased in the lower part of the frequency band when compared to the original patch design while retaining the same impedance bandwidth in the frequency band. More techniques have to be employed to reduce the cross-polarization effect. A solution has to be sought to add few modifications to the design including the dielectric layer and it has been observed that adding strips on the dielectric layer showed considerable improvement in antenna performance has been presented in the succeeding subsection.

2.3 $\Psi$-SHAPE MP WITH DIELECTRIC SHEET AND METALLIC STRIPS

The previous section has provided a modified design of the $\Psi$-shape MPA which has considerably increased the broadside gain while retaining the same impedance bandwidth. For practical wireless applications, high gain antennas with wide impedance bandwidth are always preferred. The final design with simple structures added to the previous design has been presented in this section with supporting simulation results.
Figure 2.5. Full $\Psi$-shape MPA with Rogers TMM layer on top (a) reflection coefficient magnitude and (b) broadside gain versus frequency.
2.3.1 Antenna Geometry

The simulation model for the Ψ-shape MPA with the dielectric substrate with rectangular strips on top is shown in Figure 2.6. The modified design essentially consists of a Rogers TMM sheet (ε_r = 9.2, thickness = 0.8 mil) placed at a height of 9mm from the patch surface. Two rectangular strips have been designed on the dielectric sheet separated by a distance which has been obtained after performing some parametric studies on the design. The simulation results for the optimized design along with surface current distributions are presented in the following sections. The strips effectively redirect the surface currents in the Y-axis direction where the surface currents contributing the co-polarization gain predominate. The optimized results have been presented in the following subsection.

![Figure 2.6. Top view of the simulation model of Ψ-shape patch antenna with Rogers TMM layer on top.](image)

2.3.2 Optimized Performance Results

All parametric studies have been performed on different antenna dimensions and an optimized design was obtained taking into account its performance with respect to the broadside co-polarization gain (θ= 0°) and the reflection coefficient magnitude. The simulated 2:1 VSWR impedance bandwidths is 52.7% with good directional radiation patterns in the frequency band (4.2GHz to 7.30GHz) as shown in Figure 2.7(a). Figure 2.7(b) clearly indicates a considerable increase of 3dBi gain at 7 GHz frequency. Our goal to increase the broadside gain with reduced cross-polarization level while retaining the same impedance bandwidth. The simulated radiation patterns to support the above accomplishments have been presented in Figure 2.8(a-d).
Figure 2.7. Full $\Psi$ shape MPA with Rogers TMM layer and metallic strips (a) reflection coefficient magnitude and (b) broadside gain versus frequency.
Figure 2.8. Simulated radiation patterns at (a) 6 GHz, (b) 7 GHz, (c) 8 GHz and (d) 8 GHz.
The surface current distributions on the patch and rectangular strips at 7 GHz in the frequency band for all the three designs have been presented in Figure 2.9(a-c). Figure 2.9(a) showing the current distribution for the original simple $\Psi$-patch design which clearly depicts the current cancellations at the edge of the patch and also predominating cross-polarization currents in the $X$-axis resulting in the excitation of higher order modes. This has resulted in the poor performance of the patch at higher frequencies in the frequency band. The current distribution for modified design shown in Figure 2.9(b) depicts the improvement in gain of the patch mainly due to the redirected surface currents preventing current cancellations. The surface current distribution on the patch as well as the rectangular strips for the final design is shown in Figure 2.9(c). The rectangular strips have played a pivotal role in preventing current cancellations on the patch and also redirecting high currents in the $Y$-axis which has resulted in the considerable increase in the broadside gain.

2.4 COMPARISON OF $\psi$-SHAPE PATCH WITH DIELECTRIC SHEET AND METALLIC STRIPS

In this subsection, a comparison has been made for the three designs namely $\Psi$-shape MPA, $\Psi$-shape MPA with rogers TMM dielectric layer and $\Psi$-shape MPA with dielectric layer and metallic strips in terms of reflection coefficient magnitude and broadside gain versus frequency. The simulation results have been clearly shown in the Figure 2.10(a-b).

2.5 $\Psi$-SHAPE MICROSTRIP PATCH ANTENNA ON FOAM

The previous subsections presented the antenna geometry which essentially consisted of the $\Psi$-shape microstrip patch antenna etched on a dielectric substance. This subsection mainly concentrates on the effect of replacing the dielectric sheet with foam which implies that the antenna geometry consists of the patch placed on foam. The main idea behind designing the patch antenna on foam is to make the structure simple to design and fabricate which is an essential requirement in the wireless industry. Also the use of dielectric materials makes the antenna more lossy. It has been reported in the literature studies that wide-bandwidth can be obtained by implementing microstrip patches on thick foam substrates which has low dielectric constant of 1.06.

The foam thickness has been varied with respect to the antenna performance. The optimized results have been presented in Figure 2.11(a-b). Figure 2.11(a) indicates a slight
Figure 2.9. Surface current distribution at 7 GHz for (a) Full $\Psi$ shape MPA, (b) Full $\Psi$ shape MPA with dielectric sheet and (c) Full $\Psi$ shape MPA with dielectric sheet and strips.
Figure 2.10. Comparison of (a) Reflection coefficient magnitude and (b) Broadside gain vs Frequency plots for the three designs namely (i) Only $\Psi$-shape MPA, (ii) $\Psi$-shape MPA with Rogers TMM dielectric layer and (iii) $\Psi$-shape MPA with Rogers TMM dielectric layer and metallic strips.
Figure 2.11. Comparison of (a) Reflection coefficient magnitude and (b) Broadside gain vs Frequency plots for the designs namely Ψ-shape MPA etched on dielectric substrate and Ψ-shape MPA on foam substrate.
shift in the impedance bandwidth to the higher frequencies which has been a result of the absence of the dielectric substance. The attempt to design patch on foam has proved to be futile as the Figure 2.11(b) (p. 33) clearly indicates that the low broadside gain prevails except for the shift in the frequency band for obvious reasons.

This chapter presented the simulation results for the radiation performance of the Ψ-shape microstrip patch antenna. It was initially observed that the patch antenna suffered from degrading broadside gain at higher frequencies in the frequency band (4.0 GHz – 8 GHz). A Roger’s TMM layer was investigated on top of the patch antenna and it was observed that it had minimal improvement in the broadside gain although it retained the wide impedance bandwidth of the Ψ-shape MPA. A solution to encounter the problem included designing rectangular strips on top of the Roger’s TMM layer and it was able to reduce the cross-polarization levels thereby considerably increasing the broadside gain while retaining the wide impedance bandwidth performance of the antenna.

Also a performance related comparison was made between the Ψ-shape patch etched on Roger’s material and a Ψ-shape patch etched on foam material and it was observed that patch etched on foam has caused a slight shift in the impedance bandwidth with similar radiation performance. The wireless communication applications demand for more compact wideband antennas. The following sections provide compact designs along with their designing issues including simulation and measurement results.
CHAPTER 3

HALF $\Psi$-SHAPE MICROSTRIP PATCH ANTENNA (MPA)

The literature studies and design issues along with performance results for the half $\Psi$-shape MPA are presented in this chapter.

3.1 LITERATURE SURVEY

Although the full $\Psi$-shape MPA shows enhanced performance in terms of broadside gain and reduced cross-polarization which is very much needed in the wireless communication industry applications, the demand has increased for smaller and compact antennas occupying less space during installation with almost similar response. Investigations have been done extensively and researchers have come up with various techniques to reduce the patch dimensions [11-14]. In [15] shorting pin technique was used to reduce the size of the half U-slot patch antenna and achieved an impedance bandwidth of 28.6% and also had stable radiation patterns across the matching band.

In [16] primarily investigations were performed to reduce the resonant length of two kinds of wideband patch antennas: the U-slot patch antenna, and the L-probe-fed patch antenna which include increasing the dielectric constant of the microwave substrate material, the addition of a shorting wall between the conducting patch and the ground plane, and the addition of a shorting pin between the conducting patch and the ground plane. Simulation and experimental results confirmed that the size of the antennas can be reduced by as much as 94%, while maintaining impedance bandwidths in excess of 20%.

Various other miniaturization techniques have been employed to reduce the patch dimensions while retaining the same performance characteristics of the antenna similar to half-wavelength patch antennas [17-18]. In [19] a simple technique for further reducing the size of a conventional antenna was proposed which essentially required folding a patch from middle giving quarter-wavelength length with shorted wall.
Reduction in patch size might result in increased cross-polarization and a shift in the frequency band to the higher frequencies. Some techniques have to be devised to obtain the half $\Psi$-shape MPA which has a reduced antenna size with wide impedance bandwidth.

### 3.2 Antenna Geometry

The top and side views of the half $\psi$-shape patch antenna geometry are shown in Figure 3.1(a-b). A photograph of the fabricated antenna is shown in Figure 3.2(b). The half $\Psi$-shape MPA was obtained as a result of splitting the full $\Psi$-shape MPA reported in [4] into two equal parts and some modifications to the original patch antenna dimensions. The width and length of slot around the center of the patch antenna are denoted as $P_{SW}$ and $P_{SL}$, respectively. The width and length of one end of patch are denoted as $P_{W1}$ and $P_{L1}$ while the width and length of the other end of the patch are denoted as $P_{W2}$ and $P_{L2}$, respectively. The patch is placed at a height of 4.8mm from the ground plane of dimensions $L \times W$. A rectangular strip of length $F_L$ and width $F_W$ is placed on a Cuming foam substrate ($\varepsilon_r = 1.06$, $\tan\delta = 0.002$, thickness = 3.2mm) with dimensions 30mm x 30mm. The rectangular strip is excited by a 50$\Omega$ co-axial connector forming a L-shape feeding to the half $\Psi$-shape patch which is placed on the 1.6mm foam substrate from the ground plane. The center edge of the half $\Psi$-shape MPA is shorted to the ground with the help of a partial shorting wall of length $L_{SH}$. All the dimensions of the half $\Psi$-shape MPA have been obtained after parametric studies done on the pivotal dimensions of the antenna. The dimensions of the proposed antenna are listed in the Table 3.1.

### 3.3 Parametric Study Results

A series of parametric studies are performed on the dimensions of the half $\Psi$-shape patch. Initially nominal values have been considered for all dimensions and then varied individually to see the effect of the change in dimensions with respect to the impedance bandwidth of the antenna. Following are the important observations.

1. The ground plane size has been varied along with the size of the foam substrate. It was observed that large reflection coefficient magnitude was obtained for smaller values of $L$ and $W$. The optimized dimensions for $L$ and $W$ obtained are 30mm x 30mm. The width of the $\Psi$-shape patch $P_{W2}$ has been reduced by 3mm from the original full $\psi$-shape patch to obtain wide impedance matching bandwidth and broadside co-polarization gain ($\theta = 0^\circ$) 3dB gain bandwidth.
Figure 3.1. The proposed half $\Psi$-shape patch antenna simulation model (a) top view and (b) side view.
Figure 3.2. The proposed half Ψ-shape patch antenna photograph of the fabricated prototype.

Table 3.1. Half Ψ-Shape Patch Antenna Design Parameters in mm Unit

<table>
<thead>
<tr>
<th>Parameters</th>
<th>L</th>
<th>W</th>
<th>P₁₁</th>
<th>P₁₂</th>
<th>P₂₁</th>
<th>P₂₂</th>
<th>Pₛ₁</th>
<th>Pₛ₂</th>
<th>F₁</th>
<th>F₂</th>
<th>F₃</th>
<th>Lₛₐ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>35</td>
<td>35</td>
<td>26</td>
<td>3</td>
<td>17</td>
<td>13.5</td>
<td>16</td>
<td>7.25</td>
<td>15</td>
<td>4</td>
<td>9</td>
<td>18</td>
</tr>
</tbody>
</table>
2. The dimensions of the L-shape feeding strip plays a critical role in the antenna performance. The strip coupled with the SMA connector provides L-shape feeding to the patch antenna. Figure 3.3(a) shows the variation in the feed length (FL) with respect to the impedance matching of the patch antenna. It can be clearly observed from the plot that larger the length of the feed, better is the impedance matching of the antenna. Also increase in the feed length improves the matching but in contrast it causes a shift in the impedance bandwidth to higher end of the frequency band. The optimum feed length FL =15mm provides a very well matched antenna with wide bandwidth of 48.7% in the frequency band.

3. Similarly, the effect of change in feed width (FW) with respect to reflection coefficient magnitude is shown in Figure 3.3(b). It is evident from the plot that a very wide strip worsens the impedance matching of the antenna. A 4mm wide strip provides a well matched antenna retaining the same matching bandwidth of 48.7% in the frequency band (6.2GHz-10.2GHz).

4. The feed distance (FD) also plays a vital role in the improvement of reflection coefficient magnitude of the antenna. Figure 3.3(c) shows the parametric studies performed on the feed distance with respect to the reflection coefficient magnitude of the antenna. It can be inferred from the plot that increasing the feed distance has reduced the impedance matching bandwidth of the antenna. An optimum feed distance FD of 5mm has contributed same impedance bandwidth obtained with the feed length and width.

5. The length of the partial shorting wall (LSH) joining the radiating edge of the patch antenna to the ground plays a pivotal role in the impedance matching performance of the antenna. The parametric study result for this parameter is provided in Figure 3.3(d). It can be observed that an increase in shorting wall length has a significant improvement on the antenna impedance matching bandwidth. The best result of 48.7% bandwidth from (6.2GHz to 10.2GHz) was obtained for the length of the shorting wall LSH = 18mm.

### 3.4 Optimized Performance Results

All parametric studies have been performed on different antenna dimensions and an optimized design was obtained taking into account its performance with respect to the broadside co-polarization gain (θ= 0°) and the reflection coefficient magnitude. The half Ψ-shape microstrip patch antenna provides a simulated 3dB gain bandwidth of 38.50% and a measured impedance matching bandwidth of 53.59% with good directional radiation patterns within the frequency band (5.0GHz to 11.0GHz) as shown in Figure 3.4(a-b).

The broadside radiation performance of the antenna is better explained with the surface current distributions plotted at different frequencies in the frequency band as shown in Figure 3.5(a-c). The cross-polarization is very high with low co-polarization gain at 6.6 GHz frequency which is mainly caused due to the current cancellations at the tail part of
Figure 3.3. Parametric study results for critical patch dimensions (a) FL = 13mm to 16mm, (b) FW from 3mm to 6mm, (c) FD from 3mm to 7mm, (d) $L_{SH}$ from 15mm to 20mm showing the reflection coefficient magnitude (S11, dB) versus frequency (GHz).
(c)

(d)
Figure 3.4. Half $\Psi$-shape MPA (a) reflection coefficient magnitude versus frequency and (b) broadside gain versus frequency.
Figure 3.5. Surface current distribution at (a) 6.6 GHz (b) 9 GHz (c) 10 GHz of the half $\Psi$ shape MPA.
the patch and also the presence of high currents in the X-axis have contributed to the poor performance as shown in Figure 3.5(a) (p. 45).

The improved antenna performance at 9 GHz frequency has been result of fewer current cancellations as evident from Figure 3.5(b) (p. 45). Finally, the surface current distribution at 10 GHz frequency plotted in Figure 3.5(c) (p. 46) indicates that cross-polarization has been considerably increased with a decrease in co-polarization gain which has been mainly caused due to the excitation of orthogonal higher modes resulting in considerable performance of the antenna.

### 3.5 Experimental Verifications

The impedance and radiation pattern measurements for the fabricated prototype (Figure 3.2, p. 38) were performed at the Antenna and Microwave Laboratory (AML) in San Diego State University which is fully equipped with an Anritsu 37269D Vector Network Analyzer (VNA) shown in Figure 3.6 and an anechoic chamber with an antenna measurement system from Orbit/FR shown in Figure 3.7. Figure 3.8 shows a comparison between the measured reflection coefficient obtained from VNA and the simulated results which show considerable agreement. The measured impedance bandwidth of the antenna obtained (w.r.t $S_{11} < -10$ dB) is 53.59% while the simulated impedance bandwidth is 48.78% showing considerable improvement in the impedance matching bandwidth with the measured data. This is attributed to the dielectric and conductor losses associated with the patch conductor and substrate in practical fabrication than the simulated case which basically changes the Q factor slightly thereby offering wider matching bandwidth. More bandwidth in contrast to a half E-shape patch can be attributed to the tail part of the patch antenna which acted as a tuning stub, thereby, introducing a third resonance in addition to the two lower resonances present with the E-shape patch resulting in wide bandwidth [1]. The variance in simulated and measured impedance bandwidth is mainly due to the errors arising when the antenna prototype was fabricated by hand. The fabrication errors which include uneven foam thickness and imperfect soldering resulted in the shift of bandwidth to lower frequency band of the antenna which is evident from the Figure 3.8.

The fabricated antenna was then mounted in the anechoic chamber for radiation pattern measurements. The measured normalized patterns when compared with the simulated
Figure 3.6. The half $\Psi$-shape patch antenna connected to the VNA.

Figure 3.7. The half $\Psi$-shape patch antenna mounted in the anechoic chamber.
patterns show reasonable agreement as shown in Figure 3.9(a-f). The gain patterns were plotted for three frequencies within bandwidth namely 6GHz, 7GHz and 8GHz for the $\phi = 0^\circ$ and $\phi = 90^\circ$ cut planes. It is clearly visible from Figure 3.9(a-f) that the cross-polarization is higher for simulated results in both planes compared to the measured results. Also the measured gain patterns appear slightly different from the simulated gain patterns which can be attributed to errors caused while aligning the antenna in chamber and hand fabrication of the antenna induces errors in measured results.

This section presented a newly conceived wideband half $\Psi$-shape MPA design with one edge shorted to the ground with the aid of a partial shorting wall. The main idea behind this model was to achieve compactness in designing antenna for the ease of installation and also providing wideband response. The experimental verifications done on the fabricated antenna prototype have been presented. The half $\Psi$-shape patch antenna provided a simulated 3dB gain bandwidth of 38.50% and a measured impedance matching bandwidth of 53.59% with good directional radiation patterns within the frequency band (5.0GHz to 11.0GHz).

This chapter also introduced the L-shape feeding mechanism to the patch antennas also supported by literature studies related to this feeding mechanism in Chapter 2. The surface current distributions on the patch were presented to show that the design suffered from high cross-polarization which is a serious limitation for its usage in wireless industrial
Figure 3.9. Measured and simulated normalized radiation patterns at (a) 6 GHz at $\phi = 0^\circ$ plane, (b) 6 GHz at $\phi = 90^\circ$ plane, (c) 7 GHz at $\phi = 0^\circ$ plane, (d) 7 GHz at $\phi = 90^\circ$ plane, (e) 8 GHz at $\phi = 0^\circ$ plane, (f) 8 GHz at $\phi = 90^\circ$ plane.
(a) 6 GHz at $\phi = 0^\circ$ plane

(b) 6 GHz at $\phi = 90^\circ$ plane
(c) 7 GHz at $\phi = 0^\circ$ plane

(d) 7 GHz at $\phi = 90^\circ$ plane
(e) 8 GHz at \( \phi = 0^\circ \) plane,

(f) 8 GHz at \( \phi = 90^\circ \) plane.
applications. The following chapters present modified geometries mainly concentrating on increasing the co-polarization gain while reducing the cross-polarization and retain the wide impedance bandwidth response of the antenna.
CHAPTER 4

CAVITY BACKED HALF $\Psi$-SHAPE MICROSTRIP PATCH ANTENNA

The literature studies and design issues along with performance results for the cavity backed half $\Psi$-shape MPA are presented in this chapter.

4.1 LITERATURE SURVEY

Although the half-$\Psi$-shape patch antenna offers compactness in design and fabrication, the wireless communication industry applications, such as base station antenna systems, demand for small size antennas with relatively higher gain which provide wide impedance bandwidth as well as high gain with minimal cross-polarization for their effective usage. The feeding techniques for the patch antenna are associated with a large amount of leakage radiation from the probe which deteriorates the radiation performance of the antenna mainly caused by the vertical portion of the feeding probe being very long for a thick patch antenna [22].

Also while practically implementing patch antennas in wireless communications, patch antennas are generally used with a finite ground plane, which usually causes degradation (such as increased cross-polarization and backward characteristics, thereby leading to decreased antenna gain. To overcome this problem, patch antennas with cavity backing have been demonstrated [23-25]. In the above papers, authors have presented a wideband cavity-backed capacitive probe-fed patch antenna with a parasitic patch also used for bandwidth enhancement. The proposed antenna was simulated using numerical technology based on the FIT (finite integration technique) and the prototype of the antenna was constructed and tested. Various experimental studies were performed on cavity backed designs to suppress cross-polarization and increase the co-polarization gain while retaining the wide impedance bandwidth of the antenna [22-25].

This chapter present a cavity backed half $\Psi$-shape MPA which essentially consists of a copper cavity placed behind the original half $\Psi$-shape patch shown in the preceding
chapter. The antenna design geometry and the parametric studies performed on the design as well as the optimized results with simulated radiation patterns at different frequencies are presented in this chapter.

4.2 ANTENNA GEOMETRY

This section presents a cavity backed half $\Psi$-shape MPA designed to improve the broadside co-polarization gain with almost similar antenna response. The proposed cavity backed design is shown in Figure 4.1(a-b). A copper cavity with radius 32.254mm and height 12mm is placed symmetrically behind the half $\Psi$-shape MPA. The cavity plays a pivotal role in redirecting the surface currents in the broadside direction and also preventing any backside radiation thereby increasing the co-polarization gain and also controlling the front-to-back (F/B) ratio. The best cavity radius and height have been obtained after extensive parametric studies performed individually with dimensions of the antenna, one at a time while other parameters were kept invariant. The parametric results are supported by surface current distributions as well as simulated radiation patterns at different frequencies which depict the improved performance of the antenna.

4.3 PARAMETRIC STUDY RESULTS

The parametric study was performed on the critical dimensions of the cavity backed design namely cavity height and cavity radius. Initially nominal values have been considered for each dimension before they were varied individually to see their effect on the antenna performance. The main parametric study results for the cavity radius and height are presented in Figure 4.2(a-d). The goal of implementing the cavity behind the patch has been explained in the preceding chapters. The reflection coefficient magnitude and broadside gain versus frequency have been plotted for the simulation results.

(i) A critical parameter as part of our parametric results includes the cavity height. It is evident from the Figure 4.2(a) that impedance matching improves with increase in cavity height upto an extent and the matching deteriorates with large cavity height. Also it can be inferred from Figure 4.2(b) that the broadside gain increases with increase in cavity height. An optimum cavity height of 14 mm provides better impedance matching with improved gain of the antenna.
Figure 4.1. The proposed cavity backed half $\Psi$-shape MPA simulation model (a) top view and (b) side view.
Figure 4.2. Parametric study results for the cavity backed design: Reflection coefficient magnitude and broadside gain vs frequency for (a-b) Cavity height varied from 11 mm to 15 mm and (c-d) Cavity radius varied from 33 mm to 36 mm.
(ii) The diameter of the cavity plays a pivotal role in improving the performance characteristics of the antenna. It can be observed from the Figure 4.2(c) (p. 60) that the impedance matching shows improvement with the increase in the cavity radius but in contrast there is a drop in the broadside gain within the frequency band (5 GHz-11 GHz). A cavity with very large radius provides an almost well impedance matched design but a cavity radius around 33 mm provides a compromise between the impedance matching and broadside gain of the antenna

4.4 Optimized Performance Results

All parametric studies have been performed on different antenna dimensions and an optimized design was obtained taking into account its performance with respect to the broadside co-polarization gain ($\theta = 0^\circ$) and the reflection coefficient magnitude. The cavity backed half $\Psi$-shape microstrip patch antenna provides a simulated 3dB gain bandwidth of 38.50% with good directional radiation patterns within the frequency band (5.0GHz to 11.0GHz) as shown in Figure 4.3(a-b). The comparison of the cavity backed the simulation results for half $\Psi$-shape MPA and antenna designs are presented in Figure 4.4(a-d). It can be observed from Figure 4.4(a) that implementing a cavity behind the half $\Psi$-shape MPA has caused a shift in the impedance bandwidth to the lower frequency band.

The main advantage behind using a cavity can be inferred from Figure 4.4(b). The broadside co-polarization gain for the half $\Psi$-shape MPA is around 6 dBi allover the frequency band except for an increase in gain at around 9GHz. The plot also clearly shows a considerable improvement of 2 dB gain over the frequency band. The cavity backed antenna has helped in increasing the co-polarization gain shown in Figure 4.4(c) but nevertheless it has failed to show considerable reduction in cross-polarization level. Also the peak gain shows a considerable improvement with the cavity backed design by 3dB for most of the band as shown in Figure 4.4(d).

Also the surface current distribution on the cavity at various frequencies show a clear picture and help in explaining our simulation results Figure 4.5(a-d). The literature survey has educated us about work previously done by various researchers earlier and they have come up with various designs. One effective way to reduce the cross-polarization is to
Figure 4.3. (a) Reflection coefficient magnitude and (b) Broadside gain Vs Frequency plots.
Figure 4.4. Comparison of (a) Reflection coefficient magnitude (b) Co-polarization gain, (c) Cross-polarization gain, and (d) Peak realized gain Vs Frequency plots for the antenna designs namely half Ψ-shape MPA and cavity backed Ψ-shape MPA.
Figure 4.5. Surface current distribution at (a) 5.9 GHz (b) 6.8 GHz (c) 8.7 GHz and (d) 9.8 GHz of the cavity backed half $\Psi$-shape MPA.
implement slots in ground plane. The designs and the theory behind their implementation have been explained in preceding chapters and succeeding chapter as well.

The simulated radiation patterns at different frequencies in the frequency band have been presented in Figure 4.6(a-d). The radiation patterns indicate that the antenna has a decent amount of broadside radiation performance throughout the frequency band except for increased cross-polarization level at some frequencies in the frequency band.

This chapter presented the cavity backed half $\Psi$-shape MPA. This chapter mainly concentrated on increasing the co-polarization gain while reducing the cross-polarization which it proved to be less effective. An optimized cavity backed design was obtained after performing few parametric studies related to cavity dimensions and a comparison was made with respect to the half $\Psi$-shape MPA to show little improvement in antenna performance and also supported by current distributions at certain frequencies on cavity and patch.

A modified cavity backed half $\Psi$-shape MPA with defects in ground plane has been finally presented in the following chapter along with the fabricated prototype design and the supporting parametric studies performed on the cavity and slot dimensions. The slots helped in redirecting the surface currents in broadside direction thereby reducing cross-polarization and increasing the co-polarization gain. The supporting simulation results are also presented in the following chapter.
Figure 4.6. Simulated radiation patterns at (a) 6 GHz, (b) 7 GHz, (c) 8 GHz and (d) 8 GHz.
CHAPTER 5

DEFECTED CAVITY BACKED HALF Ψ-SHAPE PATCH ANTENNA

The literature studies and design issues along with performance results for the cavity backed half Ψ-shape MPA with ground plane defects are presented in this chapter.

5.1 DEFECTED CAVITY BACKED PATCH

The cavity backed design offers an improvement in impedance matching bandwidth and broadside gain compared to the half Ψ-shape MPA but at the cost of increased cross-polarization. One effective way to reduce the unwanted cross-polarization while retaining the same antenna response is to add defects in the ground plane i.e., to design and implement slots into the ground plane. The slots have been mainly designed to redirect the surface currents thereby preventing current cancellations and increasing the broadside gain. In recent years, there has been lots of interest in studying microstrip patches with defected ground structures (DGS) and researchers have come up with different kinds of slots which include concentrated circular rings, annular rings, rectangular slots, arc shaped and other geometries [25-27], [28-29]. The authors in [27] have proposed a DGS consisting of arc shaped slots symmetrically placed around the SMA feed in the ground plane to reduce the cross-polarized radiation without affecting the dominant mode and co-polarized radiation patterns of a conventional antenna. The parametric studies for the cavity and slot dimensions to achieve the optimized design have been presented in this section.

5.2 ANTENNA GEOMETRY

This section presents a cavity backed half Ψ-shape MPA designed to improve the broadside co-polarization gain which was lacking in the cavity backed Ψ-shape antenna design presented in the earlier sections. Also this antenna design considerably reduces the cross-polarization level at all frequencies throughout the frequency band. The proposed cavity backed design with defects in ground plane is shown in Figure 5.1(a-b). A photograph of the fabricated antenna is shown in Figure 5.2(a). A copper cavity with radius 36.254mm
Figure 5.1. The proposed cavity backed half $\Psi$-shape MPA with defects in ground plane (a) simulation model (top view) and (b) simulation model (side view).
and height 12mm is placed symmetrically behind the half $\Psi$-shape MPA. The cavity plays a pivotal role in redirecting the surface currents in the broadside direction and also preventing any backside radiation thereby increasing the co-polarization gain and also controlling the front-to-back (F/B) ratio. A defected ground plane consisting of two rectangular slots of dimensions 12mm x 3mm were designed to reduce the effect of higher order modes on the antenna performance. The initial design consisted of two arc shaped slots placed symmetrically around the SMA feed as shown in Figure 5.3(a-b), but for the ease of fabrication they have been replaced by rectangular slots. The final cavity and slot dimensions have been obtained after extensive parametric studies performed individually with each dimension with respect to antenna performance.

5.3 PARAMETRIC STUDY RESULTS

A parametric study was performed on the dimensions of the cavity and slots in the ground plane. Initially nominal values have been considered for each dimension before they were varied individually to see their effect on the antenna performance. The main parametric study results for the cavity radius and height along with the slot design is presented in Figure 5.4(a-b). Primarily, the defected ground plane consisted of two arc shaped slots placed
Figure 5.3. (a) Arc shaped and rectangular slot defects based antenna geometries, and its comparison (b) of reflection coefficient magnitudes, and (c) broadside gain.
(a)

(b)
Figure 5.4. Parametric study results for cavity and ground plane slot (defect) design parameters (a) Cavity radius varied from 32.254 mm to 37.254 mm and (b) Cavity height varied from 9 mm to 13 mm.
symmetrically around the SMA feeding but for the ease of fabrication, they have been replaced by rectangular slots as shown in Figure 5.4(a) (p. 79).

(i) The diameter of the cavity plays a pivotal role in improving the performance characteristics of the antenna. It can be observed from the Figure 5.4(a) (p. 79) that the impedance matching shows improvement with the increase in the cavity radius with maximum impedance bandwidth of 58.67% obtained with the cavity radius = 36.254mm in the frequency band (5.6GHz-10.25GHz). A cavity with very large radius induces a slight mismatch at the lower frequencies and impedance matching close to -10 dB line which is prone to mismatch with hand fabricated antenna designs.

(ii) Another critical parameter as part of our parametric results includes the cavity height. It is evident from the Figure 5.4(b) (p. 79) that the best reflection coefficient magnitude of 57.77% was achieved with a cavity height = 12mm. It has to be noted that smaller cavity heights provide similar impedance matching but with reduced broadside co-polarization gain.

(iii) Figure 5.5(b-c) shows the comparison of reflection coefficient and broadside co-polarization gain vs frequency for the slot designs. The plots clearly indicate that both antenna designs of slot show negligible difference in impedance matching and gain of the antenna. Both the designs clearly show close agreement in impedance matching, co-polarization and cross-polarization vs frequency.

5.4 Optimized Performance Results

The optimized simulation results for all the three designs are presented in Figure 5.5(a-d). These optimized results have been obtained after performing detailed parametric studies on dimensions of the antennas. It can be observed from Figure 5.5(a) that implementing a cavity behind the half-Ψ-shape MPA has caused a shift in the impedance bandwidth to the lower frequency band. The main advantage behind using a cavity with defects in ground plane and the advantages with the modified design can be inferred from Figure 5.5(b). The broadside co-polarization gain for the half-Ψ-shape MPA is around 6 dBi throughout the frequency band except for an increase in gain at around 9GHz. The plot also clearly shows a considerable improvement of 2 dB gain over the frequency band. The cavity backed antenna with ground plane defects provides the reduced cross-polarization than
Figure 5.5. (a) Reflection coefficient magnitude (b) Co-polarization gain, (c) Cross-polarization gain, and (d) Peak realized gain Vs Frequency plots for all the antenna designs.
without defects which is clearly evident in Figure 5.5(c) (p. 83). Also the peak gain shows a considerable improvement with the cavity backed design by 3dB for most of the band as shown in Figure 5.5(d) (p. 83).

The surface current distributions plots at different frequencies in the frequency band shown in Figure 5.6(a-d) provide a better insight into the antenna performance which include current cancellations and redirection of currents responsible for the variation in broadside gain of the antenna prototype. The slots play a pivotal role in redirecting surface currents on the patch which contribute to the co-polarization gain of the antenna. The surface current distributions provided in Figure 5.6(a-d) have clearly shown that the slots have redirected the surface currents into the broadside direction as well as suppressing the higher order modes and also reducing the current cancellation which has resulted in our optimized design providing decent amount of broadside gain with suppressed cross-polarization throughout the frequency band.

5.5 EXPERIMENTAL VERIFICATIONS

The impedance and radiation pattern measurement results for the fabricated prototype antenna shown in Figure 5.2 (p. 75) were performed in the Antenna and Microwave Laboratory (AML) in San Diego State University which is fully equipped with an Anritsu 37269D Vector Network Analyzer (VNA) shown in Figure 5.7 and an anechoic chamber with an antenna measurement system from Orbit/FR shown in Figure 5.8. Figure 5.9 shows a comparison between the measured impedance bandwidth of the antenna (w.r.t $S_{11}<-10$ dB) which is 56.94% and the simulated bandwidth which is 56.57% showing close agreement. The defects in ground plane wherein two slots have been implemented help in redirecting currents preventing current cancellations thereby significantly improving the broadside co-polarization gain. Also from Figure 5.9, it is clearly evident that there is a slight shift in impedance bandwidth for the measured prototype which has been caused due to errors arising while fabricating the cavity and improper soldering resulted in differing results.

The fabricated prototype antenna was then mounted in the anechoic chamber for radiation pattern measurements. The measured normalized patterns when compared with the simulated patterns show reasonable agreement which are presented in the Figure 5.10(a-f). The gain patterns were plotted for three main frequencies namely 6GHz, 7GHz and 8 GHz in
Figure 5.6. Surface current distribution at (a) 6 GHz (b) 7 GHz (c) 8 GHz and (d) 9 GHz of the cavity backed half $Ψ$ shape MPA with defects in the ground plane.
Figure 5.7. The antenna prototype connected to the VNA.

Figure 5.8. The half Ψ-shape patch antenna mounted in the anechoic chamber.
Figure 5.9. Simulated and measured reflection coefficient magnitude versus frequency for the cavity backed half Ψ-shape MPA with rectangular defects as shown in Figure 5.1 (p. 74).
Figure 5.10. Measured and simulated normalized radiation patterns at (a) 6 GHz at $\phi = 0^\circ$ plane, (b) 6 GHz at $\phi = 90^\circ$ plane, (c) 7 GHz at $\phi = 0^\circ$ plane, (d) 7 GHz at $\phi = 90^\circ$ plane, (e) 8 GHz at $\phi = 0^\circ$ plane, and (f) 8 GHz at $\phi = 90^\circ$ plane.
the frequency band for $\phi = 0^\circ$ and $\phi = 90^\circ$ planes. The patterns clearly depict higher cross-
polarization for the measured data which can be attributed to errors caused due to
misalignment of the antenna in the chamber in addition to the hand fabrication of the antenna
which itself induces errors in the measured results. The cavity backed antenna with defects
show improved broadside co-polarization gain over the frequency band.

This chapter presented an optimized cavity backed $\Psi$-shape MPA design with defects
in ground plane along with the fabricated prototype design and the supporting parametric
studies performed on the cavity and slot dimensions. Also a comparison of the performance
characteristics of all three designs was made. The cavity backed design with slots into the
ground plane achieved a simulated 3dB gain bandwidth of 36.36% and a measured
impedance matching bandwidth of 56.57%. Next chapter presents conclusion and future
study.
CHAPTER 6

CONCLUSIONS AND FUTURE STUDY

The goal of this thesis was to design a small and compact microstrip patch antenna which provides wide impedance bandwidth with decent radiation performance which finds applications in wireless communications industry. A literature survey has been done on different types of microstrip patch antennas and it has been observed that the $\Psi$-shape MPA has provided a very wide impedance bandwidth very much required for modern day wireless applications. The antenna suffered from degrading broadside gain at higher frequencies with increased cross-polarization. The remedies to overcome this problem have been discussed in chapter 2 where different methods were employed to reduce cross-polarization while maintaining the same impedance bandwidth have been presented.

Chapter 3 presented a newly conceived wideband half $\Psi$-shape MPA design with one edge shorted to the ground with the aid of a shorting wall. The main aim of designing this model was to design a small compact antenna which occupies less space during installation and has wideband response. The experimental verifications done on the fabricated antenna prototype have been presented. The half $\Psi$-shape patch antenna provided a simulated 3dB gain bandwidth of 38.50% and a measured impedance matching bandwidth of 53.59% with good directional radiation patterns within the frequency band (5.0GHz to 11.0GHz). This chapter also introduced the L-shape feeding mechanism to the patch antennas also supported by literature studies related to this feeding mechanism. The surface current distributions on the patch were presented to show that the design suffered from high cross-polarization which is a serious limitation for its usage in wireless industrial applications.

Chapter 4 presented the cavity backed half $\Psi$-shape MPA. This chapter mainly concentrated on increasing the co-polarization gain while reducing the cross-polarization which it proved to be less effective. An optimized cavity backed design was obtained after performing few parametric studies related to cavity dimensions and a comparison was made with respect to the half $\Psi$-shape MPA to show little improvement in antenna performance and also supported by current distributions at certain frequencies on cavity and patch.
Chapter 5 finally presented an optimized cavity backed $\Psi$-shape MPA design with defects in ground plane along with the fabricated prototype design and the supporting parametric studies performed on the cavity and slot dimensions. Also a comparison of the performance characteristics of all three designs was made. The cavity backed design with slots into the ground plane achieved a simulated 3dB gain bandwidth of 36.36% and a measured impedance matching bandwidth of 56.57%.

For future study, the cavity could be replaced by other models to achieve miniaturization for effective usage in wireless industry which require more compact designs. Also switches could be implemented to achieve frequency reconfiguration. A stacked layer consisting of half $\Psi$-shape patches can be designed to see their response for different applications. For achieving higher gain, array antenna can be implemented.
REFERENCES


