3.1 INTRODUCTION

Circularly polarized microstrip antennas have been widely used for wireless communication applications due to their numerous advantages including light weight, low profile and conformability to various mounting structures. Circularly polarized antenna combats multipath fading by introducing polarization diversity thus enhancing the wireless communication system capacity. These antennas are classified as single feed or dual feed, depending on the number of feeding points required for generating circularly polarized wave. A dual feed antenna has the disadvantage of requiring an external polarizer such as power divider or 90° hybrid coupler for feeding the patch. The dual feed at orthogonal positions excites two near degenerated orthogonal resonant modes of equal amplitude and 90° phase difference for achieving circular polarization. A single feed antenna has many advantages, mainly less installation space and simple circuitry making them preferable for compact portable devices. In general, a single feed patch radiates linearly polarized wave and in order to generate circular polarized wave two orthogonal modes of equal amplitude and quadrature phase difference needs to be introduced. This can be achieved by perturbing the patch with respect to the feed position [12]. Over the years, several designs for single feed circularly polarized microstrip antennas using square, circular, triangular and ring shapes have been demonstrated [17-25]. Symmetrically truncating a pair of square patch corners is the most widely used structure for circular polarization. The corner truncated square ring microstrip antenna [71], chip-resistor loaded square patch [72], annular ring slot antenna [73], circular microstrip antenna with peripheral cuts with a cross slot in the centre [74], diagonally
asymmetric slit cut microstrip antenna [75]. However, most of the circularly polarized patch involves introduction of slit, stub or chamfered corners leading complex antenna designs. In this chapter, a square microstrip patch antenna using simple coaxial feed with radiating patch loaded with L-slot is proposed. The L-slot dimensions are optimized to excite two orthogonal modes of equal amplitude and 90° phase shift for radiating a circularly polarized wave. The proposed antenna design is theoretically analyzed using modal expansion cavity model and circuit theory approach and optimization is conducted using finite element method based commercial software, Ansoft HFSS [76].

3.2 THEORETICAL CONSIDERATIONS

Figure 3.1 shows the geometry of proposed single feed circularly polarized microstrip patch antenna. The antenna consists of a square patch of length $L$.

![Figure 3.1 Geometry of proposed single-feed circularly polarized L-slot microstrip antenna](image)

Figure 3.1 Geometry of proposed single-feed circularly polarized L-slot microstrip antenna (a) cross-sectional view (b) top view
The equivalent circuit of the square microstrip patch is a combination of resistance $R_i$, inductance $L_i$ and capacitance $C_i$ calculated as [1]

$$C_i = \frac{\varepsilon_0 \varepsilon_r L_i^2}{2h} \cos^{-2} \left( \frac{\pi d}{L} \right) \quad (3.1)$$

where $h$ is the thickness of substrate, $d$ is feed point location and $\varepsilon_r$ is effective dielectric constant and is given as

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{L} \right)^{1/2} \quad (3.2)$$

where $\varepsilon_r$ is the relative dielectric constant of the substrate.

$$L_1 = \frac{1}{\omega_c^2 C_i} \quad (3.3)$$

$$R_1 = \frac{Q_r}{\omega_r C_i} \quad (3.4)$$

$$Q_r = \frac{\varepsilon \sqrt{\varepsilon_e}}{4f_e h} \quad (3.5)$$

where $c$ is the velocity of light in free space and $f_e$ is the resonance frequency of the patch.

The input impedance of the square patch is calculated as

$$Z_1 = \frac{1}{\frac{1}{R_1} + \frac{j}{\omega C_1} + \frac{1}{j \omega L_1}} \quad (3.6)$$

The considered L-slot is the grouping of a horizontal slot and a vertical slot. The impedance of the horizontal slot using equivalent circuit approach comprises of a resistance and a reactive component connected in series given by [77]

$$Z_h = R_h + jX_h \quad (3.7)$$

where

$$R_h = 60 \cos^2 \psi \left[ C + l_n (kL_h) - C_i (kL_h) + 0.5 \sin(kL_h) \{S_i (2kL_h) - 2S_i (kL_h)\} + 0.5 \cos(kL_h) \{C + l_n (0.5kL_h) + C_i (2kL_h) - 2C_i (kL_h)\} \right] \quad (3.8)$$
$C$ is Euler's constant, $\psi$ is the inclination angle of slot from the radiating edge, $k$ is propagation constant in free space defined as

$$k = \frac{2\pi}{\lambda}$$  \hspace{1cm} (3.9)

$$S_i(x) = \int_0^x \frac{\sin x}{x} \, dx$$  \hspace{1cm} (3.10)

$$C_i(x) = -\int_0^x \frac{\cos x}{x} \, dx$$  \hspace{1cm} (3.11)

and

$$X_h = 30 \cos^2 \psi \left[ 2 S_i(kL_h) + \cos(kL_h) \left( 2 S_i(kL_h) - S_i(2kL_h) - \sin(kL_h) \left( 2 C_i(kL_h) - C_i(2kL_h) - C_i(kw_h^2/2L_h) \right) \right) \right]$$  \hspace{1cm} (3.12)

where $w_h$ is the width of horizontal slot.

Similarly, the impedance of the vertical slot using equivalent circuit approach can be calculated as [77]

$$Z_v = R_v + jX_v$$  \hspace{1cm} (3.13)

where

$$R_v = 60 \cos^2 \psi \left[ C + l_n(kL_v) - C_i(kL_v) + 0.5 \sin(kL_v) \left( S_i(2kL_v) - 2 S_i(kL_v) \right) + 0.5 \cos(kL_v) \left( C + l_n(0.5kL_v) + C_i(2kL_v) - 2 C_i(kL_v) \right) \right]$$  \hspace{1cm} (3.14)

and

$$X_v = 30 \cos^2 \psi \left[ 2 S_i(kL_v) + \cos(kL_v) \left( 2 S_i(kL_v) - S_i(2kL_v) - \sin(kL_v) \left( 2 C_i(kL_v) - C_i(2kL_v) - C_i(kw_v^2/2L_v) \right) \right) \right]$$  \hspace{1cm} (3.15)

where $w_v$ is the width of vertical slot.

The impedance of L-slot is considered as the parallel combination of impedance of the horizontal slot and vertical slot and is calculated as
\[ Z_2 = \frac{Z_o + Z_h}{Z_o Z_h} \]  \hfill (3.16)

The equivalent circuit of L-slot loaded square patch antenna is shown in Figure 3.2 and is computed as

\[ Z_{in} = Z_1 + Z_2 \]  \hfill (3.17)

The reflection coefficient and VSWR can be calculated as \[78\]

\[ \Gamma = \frac{Z_o - Z_{in}}{Z_o + Z_{in}} \]  \hfill (3.18)

where \( Z_o \) is the characteristic impedance of the coaxial feed.

\[ S = \frac{1 + |\Gamma|}{1 - |\Gamma|} \]  \hfill (3.19)

\[
\begin{aligned}
&\text{Figure 3.2 Equivalent circuit of proposed circularly polarized L-slot microstrip antenna}
\end{aligned}
\]

### 3.3 ANTENNA STRUCTURE AND DESIGN

The geometry of single feed L-slot loaded circularly polarized microstrip patch antenna is shown in Figure 3.1. The asymmetrical L-slot makes possible for the excitation of two orthogonal modes of equal amplitudes and 90° phase shift for circular polarized operation. The asymmetric arms of L-slot cut along x-axis and y-axis of the conventional square patch meanders the excited patch surface current densities of the two orthogonal modes leading to a compact circularly polarized microstrip antenna configuration. A good circular polarized radiation can be achieved by adjusting the length and width of the arms of the L-slot to the optimum position along x-axis and y-axis. The top view of single layer circularly polarized square antenna with L-slot is shown in Figure 3.1(b). \( A \) is the feed point of the antenna. The probe passes through the ground plane and dielectric
substrate for feeding the L-slot patch antenna. The detailed antenna parameters are listed in Table 3.1.

Table 3.1 Dimensions of the proposed L-slot circularly polarized microstrip antenna

<table>
<thead>
<tr>
<th>Antenna Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of square patch, $L$</td>
<td>30</td>
</tr>
<tr>
<td>Length of horizontal slot, $L_h$</td>
<td>6</td>
</tr>
<tr>
<td>Length of vertical slot, $L_v$</td>
<td>11</td>
</tr>
<tr>
<td>Width of horizontal slot, $w_h$</td>
<td>2</td>
</tr>
<tr>
<td>Width of vertical slot, $w_v$</td>
<td>3</td>
</tr>
<tr>
<td>Length of ground plane</td>
<td>46</td>
</tr>
<tr>
<td>Width of ground plane</td>
<td>46</td>
</tr>
<tr>
<td>Thickness of substrate, $h$</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 3.3 Prototype of the fabricated antenna
The antenna is fabricated on FR-4 epoxy substrate of relative permittivity 4.4 and thickness 1.6 mm. Fabrication of proposed antenna is done by standard photolithography process. The electrical characteristic of the fabricated antenna is measured by Agilent vector network analyzer N5230A. Figure 3.3 shows the photograph of fabricated prototype.

3.4 RESULTS AND DISCUSSION

3.4.1 Parametric Study of the L-Slot

The effect caused by varying length and width of the L-slot in the square patch has been investigated and observed. During this parametric analysis, single factor of the integrated L-slot is varied either in length or width while keeping other factors fixed. In Figure 3.4, the variation of return loss with frequency for different values of horizontal arm length has been shown. It has been found with the increase in horizontal arm length $L_h$ there is a shift in resonance towards lower frequency.

![Figure 3.4 Variation of $S_{11}$ with frequency for different length of horizontal arm](image_url)

Figure 3.4 Variation of $S_{11}$ with frequency for different length of horizontal arm
Figure 3.5 Variation of axial ratio with frequency for different length of horizontal arm

The axial ratio variation with frequency for varying length arm is depicted in Figure 3.5. For lower arm length, $L_h$, a less amount of circular polarization is observed. The 3-dB axial ratio bandwidth is maximum when horizontal arm length, $L_h$, is 6 mm. The return loss variation with frequency for different values of vertical arm length of L-slot loaded at the centre of square patch is shown in Figure 3.6. With increasing the length of L-slot, $L_v$, resonant frequency of the antenna decreases. By integrating horizontal and vertical slot on the resonating radiating patch, path of the excited surface current is increased; thus lowering the value of resonant frequency.

The axial ratio variation with frequency for different values of vertical arm of L-slot is shown in Figure 3.7. A good amount of circular polarization is observed when vertical arm length, $L_v$, is 11 mm. It is also found that the resonance frequency of antenna is depending on length and width of the L-slot.
Figure 3.6 Variation of $S_{11}$ with frequency for different length of vertical arm

Figure 3.7 Variation of axial ratio with frequency for different length of vertical arm
Figure 3.8 Variation of $S_{11}$ with frequency for different width of horizontal arm.

Figure 3.9 Variation of axial ratio with frequency for different width of horizontal arm.
Similarly, the variation of $S_{11}$ with frequency for different values of horizontal arm width is shown in Figure 3.8. The axial ratio variation with frequency is presented in Figure 3.9. For different horizontal arm width, $w_h$ almost same amount of circular polarization is observed. The value which has the maximum impedance and axial ratio bandwidth has been optimized for the antenna fabrication.

Figure 3.10 Variation of $S_{11}$ with frequency for different width of vertical arm

Figure 3.10 and Figure 3.11 presents the return loss and axial ratio variation with frequency for different vertical arm width, respectively. It has been found that the large values of length and width of horizontal and vertical arms of the L-slot leads to a shift in resonating frequency towards lower side leading to compact antenna geometry. When the vertical arm width, $w_v$ is 3 mm, optimal amount of circular polarization and $S_{11}$ is observed. Thus, the best optimized values are considered for antenna design configuration. Figure 3.12 shows the return loss of the proposed circularly polarized L-slot antenna. The antenna operates around 2.25 GHz. The measured return loss is in good agreement with calculated and simulated results.
Figure 3.11 Variation of axial ratio with frequency for different width of vertical arm

Figure 3.12 Variation of $S_{11}$ with frequency of the proposed circularly polarized L-slot microstrip antenna
The measured and simulated axial ratio of the proposed antenna is shown in Figure 3.13. The 3-dB axial ratio bandwidth is 1.8%. A slight deviation in measured and simulated results is due to fabrication inaccuracy and soldering of SMA connector.

![Axial ratio vs. Frequency](image)

Figure 3.13 Variation of axial ratio with frequency of the proposed circularly polarized L-slot microstrip antenna

### 3.4.2 Antenna Gain Characteristics

The antenna gain measurement requires basically the same environment as the pattern measurement. To measure the gain of antennas operating above 1 GHz, generally anechoic chambers are used. The various techniques for antenna gain measurement are:

- Two-Antenna Method
- Three-Antenna Method
- Gain-Transfer (or Gain-Comparison) Method

Three-antenna gain method is used to measure the gain characteristics of the proposed fabricated antenna. The three-antenna method is used when only one sample of test antenna is fabricated. Then, any other two antennas can be used to perform three
measurements which allow the calculation of gains of all the three antennas. All three measurements are made at a fixed known distance \( R \) between the radiating and transmitting antennas. It does not matter whether an antenna is in transmitting mode or in receiving mode. What matters is that the three measurements involve all three possible pairs of antennas: antenna 1 and antenna 2; antenna 1 and antenna 3; antenna 2 and antenna 3. The calculations are based on Friis transmission equation

\[
\frac{P_r}{P_t} = \left( \frac{\lambda}{4\pi R} \right)^2 G_t G_r
\]  \hspace{1cm} (3.20)

In dB,

\[
G_{(dB)} = \frac{1}{2} \left[ 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 20 \log_{10} \left( \frac{P_r}{P_t} \right) \right]
\]  \hspace{1cm} (3.21)

where \( R, P_r, P_t \) and \( \lambda \) are the distance between two antennas, received power, transmitted power and wavelength, respectively. In the case of two different antennas (antenna \( i \) and antenna \( j \)) measured during experiment \( k \) \((k = 1, 2, 3)\) becomes

\[
G_{i(dB)} + G_{j(dB)} = \left[ 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 20 \log_{10} \left( \frac{P_r}{P_t} \right)^k \right]
\]  \hspace{1cm} (3.22)

The system of equations describing all three experiments is

\[
G_{1(dB)} + G_{2(dB)} = \left[ 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 20 \log_{10} \left( \frac{P_r}{P_t} \right)^1 \right]
\]  \hspace{1cm} (3.23)

\[
G_{1(dB)} + G_{3(dB)} = \left[ 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 20 \log_{10} \left( \frac{P_r}{P_t} \right)^2 \right]
\]  \hspace{1cm} (3.24)

\[
G_{2(dB)} + G_{3(dB)} = \left[ 20 \log_{10} \left( \frac{4\pi R}{\lambda} \right) + 20 \log_{10} \left( \frac{P_r}{P_t} \right)^3 \right]
\]  \hspace{1cm} (3.25)

The system of three equations with three unknowns is obtained as

\[
G_{1(dB)} + G_{2(dB)} = A
\]  \hspace{1cm} (3.26)

\[
G_{1(dB)} + G_{3(dB)} = B
\]  \hspace{1cm} (3.27)

\[
G_{2(dB)} + G_{3(dB)} = C
\]  \hspace{1cm} (3.28)
The solution of above equations is

\[ G_{1(dB)} = \frac{A+B-C}{2} \]  \hspace{1cm} (3.29)

\[ G_{2(dB)} = \frac{A-B+C}{2} \]  \hspace{1cm} (3.30)

\[ G_{3(dB)} = \frac{-A+B+C}{2} \]  \hspace{1cm} (3.31)

Figure 3.14 shows the measured and simulated gain at boresight with frequency of the antenna. The maximum gain measured is 4.25 dBi.

![Graph showing variation of gain with frequency](image)

**Figure 3.14 Variation of gain with frequency of the proposed circularly polarized L-slot microstrip antenna**

### 3.4.3 Radiation Pattern

Anechoic chamber is used for measuring the radiation characteristics of fabricated antenna. The chamber consists of cone shaped microwave absorbers on all the walls and floor of the room and a rotational platform. Spectrum analyzer and network analyzer are used for the measurement of designed antennas. The far-field patterns are measured on
the surface of a sphere of constant radius. Any position on the sphere is identified by the standard directional angles $\theta$ and $\phi$ of the spherical coordinate system. In general, the pattern of an antenna is 3-D. However, 3-D pattern acquisition is difficult and it involves multiple 2-D pattern measurements. The minimal number of 2-D patterns is two, and these two patterns must be in two orthogonal principal planes; i.e. E-Plane and H-Plane. A principal plane must contain the direction of maximum radiation. A simplified block diagram of a pattern measurement system is given in Figure 3.15.

![Block diagram of the setup of measurement of antenna](image)

Figure 3.15 Block diagram of the setup of measurement of antenna

The total amplitude pattern is described by the vector sum of the two orthogonally polarized radiated field components; therefore

$$|E| = \sqrt{|E_\theta|^2 + |E_\phi|^2}$$  \hspace{1cm} (3.32)

$$|E(\theta, \phi)| \approx \sqrt{\cos^2 \phi |E(\theta, 0)|^2 + \sin^2 \phi |E(\theta, 90^\circ)|^2}$$  \hspace{1cm} (3.33)

The measured radiation pattern at 2.25 GHz for both E-plane and H-plane is plotted in Figure 3.16. The antenna shows stable radiation characteristics in both the planes of radiation.
3.5 SUMMARY

Single feed circularly polarized L-slot microstrip patch antenna has been presented. The presented structure can generate two orthogonal modes of equal amplitude and 90° relative phase shift; therefore, stub, notch or chamfering at corners of the square patch are not required making antenna design relatively simple. The proposed structure is simple to fabricate and is useful for designing compact circularly polarized antennas and arrays. The antenna may also be a good choice for modern wireless applications which require miniaturized circularly polarized configuration to mitigate multipath fading in wireless communication environment.