CHAPTER 3
ANALYSIS OF MICROSTRIP PATCH USING SLITS AND SLOTS

3.1 INTRODUCTION

Rectangular slits and circular slots on the patch antennas are analyzed in this chapter. Even though the patch antennas can be fed by several methods, microstrip feed, coaxial probe feed are considered for analysis. The following antenna configurations are given by using slits and slots. Obviously, the inclusion of slits and slots provide multiple resonant functionalities and enhanced bandwidth.

The first configuration presented here is the rectangular patch with the slots on edges of the patch. For second configuration C-shape slot over the rectangular microstrip patch is analyzed by coaxial and microstrip line fed. Third configuration includes small slot on the centre of the patch and large slit on the right side of the patch. Rectangular slit and slot on circular patch are discussed in the fourth configuration. The above antenna configuration design details, simulation, experimental results are analyzed. The fundamental properties used here include S-Parameter value, VSWR, gain, directivity, efficiency etc. [1-5].

3.2 RECTANGULAR MICROSTRIP PATCH ANTENNA

Figure 3.1 shows the model rectangular microstrip patch with coaxial probe feed [1].

![Figure 3.1: Rectangular microstrip patch antenna model](image)
Rectangular patch antenna at 2 GHz is proposed by Md. Maruf Ahamed [39] at thickness 2.8 millimeter (mm) and excited by microstrip line feed.

But, in this research work, a probe feed excitation is proposed at a thickness of 1.6 mm. The patch length determines the resonant frequency of the antenna. The patch width affects the resonant resistance of the antenna. The substrate thickness influences bandwidth and changed coupling level. Thicker dielectric material provides wider bandwidth. But it gives fewer coupling for a given aperture size. Antenna’s resonant frequency calculation is done by the following equation 3.1 [32].

The patch antenna dimensions are obtained for operating at multi band iteratively.

\[
f_r = \frac{1.152}{2} \frac{c}{\sqrt{\varepsilon_{\text{ref}}}} \frac{L}{2} \left[ \frac{(W + 2\Delta L) + (Wc + 2\Delta L)}{(W + 2\Delta L) + (L + 2\Delta L)} \right]
\]

(3.1)

Where \( f_r \) is resonant frequency
\( C \) is velocity of the Electromagnetic wave, = \( 3 \times 10^8 \) m/s
\( \Delta L \) is change in length, given in equation 1.6
\( \varepsilon_{\text{ref}} \) is effective dielectric constant, given in equation 1.7
\( L \) is Length, given in equation 1.8
\( W \) is width.

The patch antenna width is computed as follows [53].

\[
W = \frac{c}{2f_r \sqrt{\varepsilon_r + 1}}
\]

(3.2)

\( \varepsilon_r \) is the dielectric constant of the substrate material.

A rectangular shaped patch antenna is designed for 2.45 GHz resonance frequency, quarter wavelength \( \lambda/4 \) of 30.5 mm. Substrate height of 1.6 mm is selected in a FR4 material of dielectric constant, \( \varepsilon_r = 4.4 \). By
using the above length and width expressions it is synthesized as the
dimension of 38 mm wide and 29 mm length. It is designed to give resonance
frequency with 236.5 ohms input impedance. The ground size is taken as
greater than the patch dimensions by approximately six times the substrate
thickness all around the periphery, as 48 mm X 40 mm[2].

3.2.1 Working principle of rectangular MSA

When patch is fed, the ratio of E to H field is proportional to the
impedance of the feed location. Since at the end of the patch current is zero,
at the center of the patch current is maximum; At the end of the patch voltage
is maximum, at the center of the patch voltage is minimum; Fringing E-fields
between the edges of the rectangle patch and the ground plane, add up in
phase due to voltage distribution and produce the radiation.

![Figure 3.2: Rectangular patch with L= 29 mm, W=38 mm](image)

This patch antenna is fed with a coaxial probe line of radius 0.6 mm
near the center of the patch at Fp. It is shown in figure 3.2. The patch width is
computed from equation 3.2 that W=37.26; taken as 38 mm; Length is
computed from equation 1.6-1.8, that L=28.69; taken as 29 mm. Its (W/L) ratio
is calculated and it is 1.31. It gives for the frequency band of 2.40 to 2.48,
Calculated resonant frequency fr=2.45GHz, simulation gives 2.42GHz with
the bandwidth of 50 MHz.
3.2.2 Probe fed C-shaped slotted antenna

The antenna configuration is given in figure 3.3 and C shaped slot is carved on the rectangular patch of substrate thickness about 0.01\(\lambda\). This slot reduces the Q factor of the patch, which is due to less energy stored beneath the patch and higher radiation. For a 2.45 GHz resonance frequency, quarter wavelength \(\lambda/4 = 30.5\) mm, rectangular patch is designed with 1.6 mm thickness, dielectric substrate constant \(\varepsilon_r\) as 4.4. The antenna’s dimensions are computed as 38 mm wide and 29 mm long with the input impedance of 236.5 ohms. The W/L ratio is 1.31. The patch antenna is fed with coaxial probe, feed point ‘fp’ at the right center of the patch. The slot radius is 0.6 mm for inserting the connector. The ground size is taken as 48 mm X 40 mm.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch Width</td>
<td>38</td>
</tr>
<tr>
<td>Patch Length</td>
<td>29</td>
</tr>
<tr>
<td>Slot thickness</td>
<td>1</td>
</tr>
<tr>
<td>Patch thickness</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 3.1 Specifications of C-shaped slot patch1

This antenna structure is simple and showing good performance in a single band. For the purpose of comparison, it is noted as patch1.

Figure 3.3: C-shaped slot with probe fed patch1
The current distributions at the place in dark red shade show the radiation power of the C-shaped patch antenna in figure 3.4. The radiation properties of this antenna have been analyzed.

The simulation and measured VSWR display is plotted in figure 3.5. It shows the result of simulation close to 1 and measurement close to 3 of C shaped slotted on the patch with coaxial probe fed. The patch antenna is suitable for low profile wireless applications. The simulation and measurement of return loss result is plotted as S-parameter display in figure 3.6. This graph is drawn from reflection coefficient vs frequency.
Figure 3.6: S-Parameter of C-shaped slotted rectangular patch

In this figure, 10 dB return loss bandwidth $[(2.15-2)/2.075]$ of 7.2 % is obtained. The smith chart is given in the figure 3.7. In that chart, impedance variations at frequencies are displayed.

Figure 3.7: Smith chart of C-shaped slot probe fed patch

This antenna is meshed with meshing frequency 3 GHz. It is simulated and the $S_{11}$ parameter, VSWR, gain, efficiency and directivity results are tabulated in table 3.3. The return loss is better than -10 dB in $S_{11}$ display.
This plot shows the resonant frequency 2.1 GHz at -12 dB with single resonant band width.

### 3.2.3 Inset fed C-shaped slot microstrip antenna

Rectangular patch is designed with a height of 1.6 mm, $\varepsilon_r$ as 4.4 for the resonance frequency 2.45 GHz. This patch is fed by microstrip line. It is also called as inset fed. This antenna is designed with previous dimension but location and current feed point is different. It is shown in figure 3.8. For the purpose of comparison, it is named as patch2. The ground size is taken as 68 mm X 40 mm. This antenna sizes are given in table 3.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangle Width</td>
<td>38</td>
</tr>
<tr>
<td>Rectangle Length</td>
<td>29</td>
</tr>
<tr>
<td>Inset Width</td>
<td>11.48</td>
</tr>
<tr>
<td>Inset Depth</td>
<td>2.921</td>
</tr>
<tr>
<td>Inset Thickness</td>
<td>1.524</td>
</tr>
<tr>
<td>Inset Feed length</td>
<td>19</td>
</tr>
<tr>
<td>Slot thickness</td>
<td>1</td>
</tr>
<tr>
<td>Patch thickness</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The VSWR value is less than 2 for the resonant frequencies. Maximum antenna gain by simulation is close to 0 dB and it is shown in the table 3.3. VSWR vs frequency curve is shown in figure 3.9.
This patch2 antenna's meshing frequency is 3 GHz. Various antenna properties are measured. The simulation and measurement of reflection coefficient vs frequency as return loss is displayed in figure 3.10. It is better than -10 dB. This plot shows two resonant frequencies of 1.2 GHz at -20 dB, 2.21 GHz at -10 dB as resonant bandwidths.

In figure 3.10, For 10dB return loss, dual band bandwidth \((1.2-1.1)/1.15=8.69\%\) and \((2.3-2.2)/2.25=of \ 4\ \%\) is obtained. The simulated
patch antenna efficiency is shown in table 3.3. It shows the dual resonant frequencies efficiency more than 25%. This antenna directivity is about 6.25 dB. Impedance parameter display is taken for antenna1 and antenna2. Impedance is attained around 50 ohms for resonant frequencies. These antennas show good impedance variation. It is as shown in Smith chart results of figures 3.7 and 3.11.

![Smith chart of inset fed patch2](image)

**Figure 3.11: Smith chart of inset fed patch2**

The comparisons are made between these two antennas by their feeding methods. Two resonant modes got from inset feed method as their electrical length varies.

**Table 3.3 Comparison of patch1 and 2 performances**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>C-shaped slot probe fed patch1</th>
<th>C-shaped slot inset fed patch2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency (GHz)</td>
<td>2.1</td>
<td>1.18, 2.21</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.8</td>
<td>1.18, 1.67</td>
</tr>
<tr>
<td>Gain(dB)</td>
<td>1.575</td>
<td>1.68, 1.45</td>
</tr>
<tr>
<td>Directivity(dBi)</td>
<td>6.3</td>
<td>6.25, 5.4</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>25</td>
<td>27,27</td>
</tr>
</tbody>
</table>
Gain of two patches are compared and shown in figure 3.12. Antenna design is proposed with C slot on the patch centre. Both the coaxial and inset feed is used. It is simulated and results exhibit the resonant band of frequencies.

It is concluded that with microstrip line fed slot antenna shows normal radiation characteristics. This antenna design is helpful for wireless communication applications.

3.3 RECTANGULAR PATCH WITH SLITS AND SLOTS

Rectangular patch with slits was introduced by Kin Lu Wong [5]. Unequal slits on the rectangular patch resulted in multi band operation and was reported by L.Sarkar et al [86]. Based on that research, iterations are carried out. First iteration is done on that patch such as patch antenna with two different types of slits combined with tiny slots for wireless network application.

3.3.1 Rectangular patch at 2 GHz

For a 2 GHz resonance frequency, rectangular patch is designed for a 1.6 mm height on a FR4 substrate of dielectric constant $\varepsilon_r$, 4.4. The antenna’s dimensions were patch width 45.64 mm and length 34.84 mm. The patch is fed with a coaxial probe at the center of the patch. By introducing slits and slots multi frequency bandwidth is obtained. The slits size is 17.55 mm,
9 mm length and width 2 mm. It is cut horizontally around the side of the patch. Two tiny slots are provided with the radius 0.5 mm.

The proposed patch antenna offers good antenna and radiation performance. It is shown in figure 3.13 having slits and slots on the patch.

![Rectangular patch geometry with slits and slots](image)

Figure 3.13: Rectangular patch geometry with slits and slots

The feed point is located in the center. The ground size is taken as 55 mm X 45 mm.

Table 3.4 Rectangular patch with slits and slots details

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch width</td>
<td>45.64</td>
</tr>
<tr>
<td>Patch Length</td>
<td>34.84</td>
</tr>
<tr>
<td>Slit Length -1</td>
<td>17.55</td>
</tr>
<tr>
<td>Slit length -2</td>
<td>9</td>
</tr>
<tr>
<td>Slit width</td>
<td>2</td>
</tr>
<tr>
<td>Tiny slots radius</td>
<td>0.5</td>
</tr>
<tr>
<td>Thickness</td>
<td>1.6</td>
</tr>
</tbody>
</table>
The distribution of current in the rectangular patch with slits, slots is displayed in figure 3.14. Around the feed point, the distribution of the current is -24 dB and -45 dB in the vertical edges.

![Figure 3.14: Distribution of current in patch structure](image)

The antenna radiation patterns are presented in the plot for a 360° angular pattern in elevation or azimuthal planes on dB scale. The patch antenna's radiation pattern is displayed in figure 3.15 with three dimensional (3D) pattern. The $E_{\text{total}}$ polarization of 3D pattern display is given for ($\theta, \phi$).

![Figure 3.15: Radiation Pattern of the patch](image)

The microstrip rectangular patch antenna specifications with dielectric constant of 4.4 are shown in table 3.4. The proposed first iterated antenna is meshed with meshing frequency 5 GHz. The simulation and measurement VSWR result is presented in graphs 3.16. Scattering matrix parameter in figure 3.18 gives the return loss better than -10 dB. This graph shows multi frequencies in resonance from 3.40 GHz to 4.80 GHz.
The VSWR shows the mismatch among the antenna and the line. VSWR is close to one is shown in figure 3.16 for the multi resonant frequencies. The antenna maximum gain by simulation is close to 3.5 dB and it is shown in figure 3.17 as total field gain versus frequency curve.

The proposed patch efficiency by simulation is got around 50%. The gain versus frequency curve is given here. For the resonant frequencies corresponding efficiency in percentage is noted. The simulation and measurement of reflection coefficient vs frequency as S–parameter is shown in figure 3.18.
In this figure, 10 dB return loss of bandwidth 3.4 GHz to 4.8 GHz is obtained. The simulated patch antenna directivity is around 7 dB to 8.5 dB for the resonant frequencies.

From Smith chart, good impedance variation for the antenna is shown in figure 3.19. From the Z-parameter graph, impedance is plotted around 50 ohms, for the resonant frequencies.

![Simulation vs Measurement](image)

**Figure 3.18:** S-Parameter of patch geometry with slits and slots.

Microstrip antenna design is analyzed and presented with slot on the side of the patch with tiny slots. The basic patch and first iteration were simulated and the results exhibit the multi band of 3.40 GHz to 4.80 GHz frequencies.

The radiation properties show good performance for the antenna. This design is useful for wireless communication networks applications like WiMax, WLAN, and 802.16a. Systems require wider bandwidth and smaller dimensions antennas than conventional antenna. Thus fractal shaped antenna research initiated in various directions.
Smith chart is a pictorial plot of constant resistance and reactance's. This graph shows antenna impedance variation and radiation parameters in figure 3.19. The impedance is represented in a circular form.

### 3.3.2 Rectangular patch at 2.45 GHz

A. Kaya proposed rectangular patch antennas with slots [46]. However the analysis of the rectangular patch antenna for the 2.45 GHz frequency is presented here.

Its substrate is 1.6 mm thickness, and constant of 4.4. The patch antenna dimensions are synthesized to get width 37.26 mm and length 28.8 mm with edge input impedance of 243 ohms. It is optimized for the value 58 mm X 41.36 mm.

This design is simulated for different thickness, dielectric constant, feed and a slit etched on it. The results of all the proposed patches by simulation show the $S_{11}$ value less than -10 dB and VSWR less than 2. Bandwidth is tabulated with the return loss.
The slit on patch gives multi band characteristics. This study exhibits an idea of microstrip patch antenna and its characteristics. This antenna finds application in wireless communication such as Bluetooth and WLAN.

In general, rectangular microstrip antennas with a narrow dielectric substrate are structures of half to quarter wavelength. They are function at the basic resonant modes $\text{TM}_{01}$ or $\text{TM}_{10}$ given by Cengizhan M. Dikmen [11]. The microstrip patch antenna configuration is illustrated in figures 3.20 and 3.21 as model, equivalent circuit of microstrip patch respectively. Patch variables are length $L$, width $W$, the dielectric constant $\varepsilon_r$, the length due to the fringing field, $\Delta L$. The fringing fields all along the width can be modeled as radiating slots. The patch dimensions are given empirically [1] as:

Now, the patch effective dielectric constant, $\varepsilon_{\text{reff}}$ and length is calculated as from equations 1.7 and 3.3.

The patch length [1] is calculated as

$$L = L_{\text{eff}} - 2\Delta L \quad (3.3)$$

The effective length $L_{\text{eff}}$ at a selected resonant frequency $f_o$, of the patch is calculated as from equation 1.8:

The change in length due to fringing field is given as from equation 1.6:

The approximate ground plane length and width [1] is calculated as:

$$L_g = 6x + L; W_g = 6x + W \quad (3.4)$$

For a rectangular shaped microstrip patch, the $\text{TM}_{mn}$ mode resonance frequency is given as [2]
The parallel Conductances $G_1, G_2$ and Susceptances $B_1, B_2$ are displayed in the transmission model of rectangular patch [8] as equivalent circuit in Figure 3.21;

The input impedance, $Z_{in}$ [4] is given as

$$Z_{in} = \frac{1}{Y_{in}} = R_{in} = \frac{1}{2G1} \quad (3.5)$$

The percentage bandwidth is calculated from the equation 1.12. The cut off frequency $f_c$, is calculated from equation 1.13 whereas $f_{high}$ and $f_{low}$ are the high and low frequencies [3]. The bandwidth would be enhanced using additional techniques such as shorting pin [11-13], slot, wide slits etc [14].

In this section, antenna performance of conventional patch(A1), patch using thick substrate(A2), patch using reduced dielectric constant(A3), patch
using microstrip line feed (A4), patch with shorting pin (A5), patch with slot (A6), and patch with wide slit (A7) are discussed.

The patch antenna design at the frequency 2.45 GHz, dimensions are 49.41 mm × 41.36 mm. The patch length is optimized to 58 mm × 41.36 mm. It is simulated for different properties and a slit etched on patch. First, conventional microstrip patch with rectangular size is designed with the \( W = 58 \text{ mm} \) and \( L = 41.36 \text{ mm} \) using a dielectric material FR4 having dielectric constant, \( \varepsilon_r \) of 4.4, and 1.6 mm thickness of dielectric material. The patch is fed by coaxial probe. At the center of the patch is the feed location. This design A1 is displayed in figure 3.22.

![Figure 3.22: Rectangular patch coaxial feed for f=2.45GHz,A1](image)

Microstrip patch with rectangular size is designed with the \( W = 58 \text{ mm} \) \( L = 41.36 \text{ mm} \) having constant of 4.4 material, and increased thickness ‘h’ of dielectric material 3.2 mm. This patch is energized with coaxial feed technique. The feed location is at the middle of the patch. The design is denoted as A2 shown in table 3.5.

![Figure 3.23: Rectangular patch with microstrip line feed, A4](image)
Again the rectangular microstrip patch with same size is designed with the \( W = 58 \) mm; \( L = 41.36 \) mm, thickness of dielectric 3.2 mm but reduced dielectric constant of 4.2 and designated as A3. This patch is fed by coaxial probe feed. The location of feed is at the center of the patch. Another microstrip patch with rectangular size is designed with the \( W = 58 \) mm \( L = 41.36 \) mm, dielectric constant of 4.4 and 1.6 mm thickness of dielectric with the different feeding technique i.e., microstrip line feed. The location of feed is at the patch right edge side. It is displayed in figure 3.23 as A4.

Conventional patch antenna with shorting pin at a point \( x=12, y=-6.375 \), is designed with probe feed, simulated and named as A5. For the patch with same specifications, 0.5 mm x 5 mm slot is made in the center. This patch is designed and simulated. It is shown in figure 3.24 as A6.

![vertical slot on the patch](image)

Figure 3.24: Rectangular patch with 0.5 mm X 5 mm slot, A6

For the slit patch, the slit is embedded to the rectangular patch. A wide slit is introduced in the microstrip patch with rectangular size. It is designed with the dimension \( W = 58 \) mm \( L = 41.36 \) mm, \( \varepsilon_r \) constant of 4.4, thickness of dielectric 1.6 mm, the slit cut width 20.68 mm, and cut depth 29 mm. The patch is fed by coaxial probe. The location of feed is at the lower right corner of the patch. The design is shown in figure 3.25 as A7.

The table 3.5 shows the antenna specifications of all proposed patches. The antennas even can be considered to have an infinite ground plane for unspecified, but here it is taken finite ground as 68 mm X 52 mm.
The simulations are carried out for the study of characteristics. It contains return loss value from S-parameter display and VSWR ratio from graph display [6].

Figure 3.25: Rectangular patch with large slit, A7

It contains return loss value from S-parameter display and VSWR ratio from graph display [6].

Table 3.5 Antennas A1-A7 design parameters

<table>
<thead>
<tr>
<th>Antenna patch</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>A5</th>
<th>A6</th>
<th>A7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (mm)</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>41.36</td>
<td>41.36</td>
<td>41.36</td>
<td>41.36</td>
<td>41.36</td>
<td>41.36</td>
<td>41.36</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>4.4</td>
<td>4.4</td>
<td>4.2</td>
<td>4.4</td>
<td>4.4</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Substrate thickness (mm)</td>
<td>1.6</td>
<td>3.2</td>
<td>3.2</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Feed Used</td>
<td>coaxial</td>
<td>co</td>
<td>co</td>
<td>micro strip</td>
<td>co</td>
<td>co</td>
<td>co</td>
</tr>
<tr>
<td>Features</td>
<td>Conventional Rectangular shaped</td>
<td>Increased Thickness</td>
<td>Low Dielectric constant</td>
<td>Feed microstrip line</td>
<td>Used shorting pin</td>
<td>Slot on patch</td>
<td>large slit</td>
</tr>
</tbody>
</table>
The VSWR indicates that how far an antenna’s impedance matched to the transmission line characteristic impedance. Large ratio denotes the large mismatch [12]. VSWR value should be closer to unity. Figure 3.26 shows the S-parameter display of reflection coefficient vs frequency in patch A1 resonant frequencies of 2.42–2.46 GHz.

Figure 3.26: S-Parameter display of patch A1 at f=2.45GHz

The patch A2 gives simulation results with the resonant frequency of 2.39–2.44 GHz as given in Table 3.5. The patch antenna A3 simulation results show the resonant frequency of 2.44–2.50 GHz as shown in Table 3.5. The simulated results of patch A4 show 2.45 and 2.46 GHz as the resonant frequencies. It is displayed in figure 3.27

Figure 3.27: S-Parameter display of A4
Patch A5 with shorting pin gives the resonant frequencies of 2.43–2.47 GHz as shown in the table 3.6. Slot patch antenna A6 gives the dual band performance at resonant frequencies 2.42–2.46 GHz, 3.32–3.36 GHz with return loss less than -10 dB. It is shown in figure 3.28.

![Figure 3.28: S-Parameter display of A6](image)

The simulation results of patch A7 gives the multiple resonant frequencies 2.46–2.48 GHz, 3.30–3.34 GHz, 3.66–3.72 GHz and 3.92–3.94 GHz against the return loss < -10 dB due to the wide slit cut horizontally in the right hand radiating side on the rectangular patch. It is shown in Figure 3.29.

![Figure 3.29: S-Parameter display of patch with large slit, A7](image)
In figure 3.29, 10 dB return loss, 1.30 GHz bandwidth, multi band of 2.64 GHz to 3.94 GHz is obtained. The VSWR value for the slit patch A7 lies close to 1 for the resonant frequencies 2.48–3.94 GHz. This shows the good RF performance in multi bands.

Table 3.6 shows the simulated S-Parameter display resonant frequencies, VSWR, and return loss results of patch antennas A1, A2, A3, A4, A5, A6 and A7.

Table 3.6 Simulated results of patch antennas A1-A7

<table>
<thead>
<tr>
<th>Patch Antenna</th>
<th>Resonant Frequencies (GHz)</th>
<th>VSWR</th>
<th>Return loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>2.42-2.46</td>
<td>1.31-1.82</td>
<td>-17.25 to -10.97</td>
</tr>
<tr>
<td>A2</td>
<td>2.39-2.44</td>
<td>1.38-1.78</td>
<td>-15.91 to -10.99</td>
</tr>
<tr>
<td>A3</td>
<td>2.44-2.50</td>
<td>1.31-1.80</td>
<td>-17.36 to -10.85</td>
</tr>
<tr>
<td>A4</td>
<td>2.45-2.46</td>
<td>1.72-1.49</td>
<td>-11.49 to -13.98</td>
</tr>
<tr>
<td>A5</td>
<td>2.43-2.47</td>
<td>1.25-1.74</td>
<td>-18.85 to -11.13</td>
</tr>
<tr>
<td>A6</td>
<td>2.42-3.36</td>
<td>1.28-1.84</td>
<td>-18.11 to -10.54</td>
</tr>
<tr>
<td>A7</td>
<td>2.46-3.94</td>
<td>1.29-1.91</td>
<td>-20.40 to -10.05</td>
</tr>
</tbody>
</table>

The radiation pattern gain display figure 3.30 depict the principal plane cut in $\phi = 0$, $\phi = 90$ at $f = 2.46$ GHz for slit patch A7. These performance studies of rectangular microstrip patch antenna make a bulky substrate with a little permittivity increases the bandwidth, shorting pin reduce the size of the antenna, slot and slit introduce the dual and multi band characteristics.

The radiation pattern at $f=2.46$ GHz, $\phi=0$, $\phi=90$ for antenna A7 is shown.
Rectangular microstrip patch antenna characteristic study is proposed. From the study, by employing proposed patch with various thickness and dielectric constant using coaxial probe feeding technique, microstrip line feeding technique, shorting pin, slot and slit patch shaped design, single resonant bandwidth and multi resonant bandwidth are achieved to the centre frequency 2.45 GHz. Also, antenna return loss and radiation bandwidth characteristics are obtained. The proposed patch has a simple structure with
the dimension of 58 mm X 41.36 mm. The design is appropriate for wireless applications in frequencies of 2.40–2.50 GHz.

### 3.4 CIRCULAR PATCH WITH SLITS AND SLOTS

Nasimuddin, et al had proposed slits on the circular patches [27]. Based on that in this research an attempt has been made to design antenna with slits on the patches.

![Figure 3.31: Electric and Magnetic Field Patterns of Circular microstrip antenna at Resonance](image)

The TM$_{11}$ bipolar mode is used in circular shape microstrip antenna radiation modes. It is analogous to the rectangular patch antenna’s lowest order mode. This is seen in figure 3.31 for the n = 1 mode. This mode is essentially similar in design utility to a rectangular patch antenna driven inTM$_{10}$ mode. The impedance bandwidth is slightly smaller for a circular patch than its rectangular counterpart. The center of a circular patch driven in the TM$_{11}$ mode may be shorted if a direct current (DC) short is required. Circular patch antenna is characterized by the radius (a), substrate thickness (h) and relative permittivity ($\varepsilon_r$). Table 3.7 shows the calculated values of
circular microstrip patch antenna radius for various frequencies from 0.7 GHz to 2.6 GHz for constant 4.4 and thickness 3.2 mm.

\[ a = \frac{8.791}{f_r} - h \]  \hspace{1cm} (3.6)

The expressions to find out the dielectric, conductor, and radiation losses in a microstrip antenna are given in equation (3.7-3.9) as follows:

\[ P_r = \frac{1}{2\eta_0} \int_0^{2\pi} \int_0^{\pi} \left( |E_0|^2 + |E_\phi|^2 \right) r^2 \sin \theta d\theta df \]  \hspace{1cm} (3.7)

\[ P_c = Rs \int_0^{2\pi} \int_0^{\pi} \left( |H_s|^2 \right) dS = \frac{\omega W_T}{h \sqrt{\eta \mu_0 \sigma}} \]  \hspace{1cm} (3.8)

\[ P_d = \frac{\omega \varepsilon_0 \varepsilon_r \tan \delta}{2} \int_0^{2\pi} \int_0^{\pi} |E_z|^2 dV = \omega \tan \delta W_T \]  \hspace{1cm} (3.9)

In the above expression, \( P_r \) is radiation loss, \( P_d \) is dielectric loss, \( P_c \) is conductor loss, \( \tan \delta \) is loss tangent, \( W_T \) is the total power absorbed, and \( \omega \) is the angular frequency [3-4].

Table 3.7 Parameters for frequencies 0.7 GHz To 2.6 GHz

<table>
<thead>
<tr>
<th>Resonant frequencies, ( f_r ) (GHz)</th>
<th>Radius, ( a ) (mm)</th>
<th>Dielectric constant ( (\varepsilon_r) )</th>
<th>Thickness, ( h ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>59.84</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>0.8</td>
<td>52.36</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>0.9</td>
<td>47.64</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>1.0</td>
<td>41.88</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>1.1</td>
<td>38.07</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>2.6</td>
<td>20.00</td>
<td>4.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

In figure 3.32, a circular shaped microstrip patch antenna’s geometry is displayed. The metallic patch of radius ‘a’ and a driving point impedance is placed at ‘r’ at an angle ‘\( \varphi \)’ measured from the x-axis. For rectangular microstrip, the patch is kept at a substrate thickness ‘h’ above ground plane.
An analysis of the circular microstrip antenna is given by Derneryd and referred here [2]. The circular microstrip antenna's electric field is given by the equation 3.10:

$$E_z = E_0 J_n(kr)\cos(n\phi)$$  \hspace{1cm} (3.10)

The magnetic field components $H_r$ and $H_\phi$ are described in equation 3.11 and 3.12,

$$H_r = -\frac{j\omega \varepsilon_n}{k^2 r} E_0 J_n(kr)\sin(n\phi)$$  \hspace{1cm} (3.11)

$$H_\phi = -\frac{j\omega \varepsilon_n}{k} E_0 J_n(kr)\cos(n\phi)$$  \hspace{1cm} (3.12)

Here the propagation constant is denoted by ‘k’. The first kind of order Bessel function is $J_n$. The Bessel function derivative is $J_n'$ with respect to its argument, $\omega$ is the angular frequency ($=2\pi f$). The next highest frequency of operation is in $TM_{21}$ mode next to $TM_{11}$. This mode is helpful in monopole pattern. It produces circular polarization, proposed by Huang [3]. $TM_{21}$ mode is able to excite a patch with a single feed [10].

![Circular microstrip antenna geometry](image)

**Figure 3.32: Circular microstrip antenna geometry**

From figure 3.3, for a single circular patch, the (magnetic field) current is maximum at the centre and minimum near the left and right edges. The (electrical field) voltage is zero at the centre and maximum near the left and minimum near the right edges.

Figure 3.33: Distribution of Current, Voltage, Impedance in CPA

From the current and voltage magnitude, it is concluded as impedance is least at the centre of the patch and highest of 200 Ω, at the edges. Therefore, the impedance of 50Ω point is located and used for feed position. I and Z equations are given in 3.13, 3.14 respectively.

\[ I = \int J \cdot dS \]  
(3.13)

Where ‘J’ represent the current density. Mathematically, if the current distribution is found the impedance is calculated by [15].

\[ Z = \frac{1}{2} \frac{P_{\text{tot}}}{I^2} \]  
(3.14)

Where  
Z is impedance  
P_{\text{tot}} is total power received  
I is current.

### 3.4.1 Working principle of circular patch

When patch is fed by coaxial probe, the ratio of E to H field is proportional to the impedance of the feed location. Since Fringing E-fields between the circumference of the circular patch and the ground plane, add up in phase due to voltage distribution and produce the radiation.
3.4.2 Circular patch with single slit and slot

To design the proposed microstrip circular patch antenna for GSM applications, of the resonance frequency $f_r$ of 0.9 GHz, FR4 glass epoxy (quartz) material having $\varepsilon_r$ constant of 4.4 are selected with the substrate of height, $(h)$ of 3.2 mm.

Outer radius of the patch is selected as 47.6 mm in C1. The dimension of the ground plate is 105 mm squared. The parameters calculated for C2 is slit. The slit length 78.75 mm and width 5 mm is considered for C2. The slot length 40 mm and slot width 0.5 mm along with the slit is taken for C3. The circular patch antenna radius, ‘a’ is determined by the design equation given below in 3.6. Where ‘a’ and ‘h’ are in cm, $\varepsilon_o<\varepsilon_r$.

Circular patch antenna with single slit probe fed, $a=47.6$ mm, $h=3.2$ mm, $\varepsilon_r=4.4$, $L_s=78.75$ mm, and $W_s=5$ mm is designed and shown in figure 3.34. The S-Parameter in terms of return loss results are given in figures 3.35-3.37. The return loss values are less than -10 dB for the resonance frequencies. Slit geometry gives dual band of operation which is figured in figure 3.35.

Radius, simulated frequencies, return loss, bandwidth, radiation efficiency, antenna efficiency, gain and directivity of the designed circular patch antennas (CPA) are tabulated in table 3.8. It is clear that antennas with slit become dual band antenna in 0.5-2 GHz span [15]. The introduction of slit
geometry in microstrip antenna produces dual band operation and slot produces one more band along with the basic bands.

A simple circular microstrip antenna with slot and slit geometry is considered extensively. The proposed antennas show the antenna characteristics suitable for the frequencies range between 0.5 GHz and 2 GHz.

Table 3.8 Comparison of antennas with slot and slits

<table>
<thead>
<tr>
<th>Parameters</th>
<th>antenna C1</th>
<th>antenna C2</th>
<th>antenna C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension Radius (mm)</td>
<td>47.6</td>
<td>47.6</td>
<td>47.6</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>0.894</td>
<td>0.894</td>
<td>0.894</td>
</tr>
<tr>
<td></td>
<td>1.842</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Return Loss (dB)</td>
<td>-14</td>
<td>-17</td>
<td>-16</td>
</tr>
<tr>
<td></td>
<td>-16</td>
<td>-7</td>
<td>-5</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>14</td>
<td>60</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Efficiency (%)</td>
<td>42.8</td>
<td>59.85</td>
<td>65.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>64.12</td>
<td></td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>2.70</td>
<td>4.4</td>
<td>4.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.59</td>
<td></td>
</tr>
<tr>
<td>Directivity (dB)</td>
<td>6.31</td>
<td>7.35</td>
<td>6.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.60</td>
<td></td>
</tr>
</tbody>
</table>
In figure 3.35, C2 patch gives VSWR values of less than 2 for the frequencies 0.894 and 1.842 GHz. In figure 3.36, 10 dB return loss bandwidth of C1, C2, and C3 is compared. C2 geometry is taken for S-parameter, gain calculations.

The simulation results are given below. S11 value is -17 dB at fr1 = 0.894 GHz and -16 dB at fr2 = 1.842 GHz; VSWR value is less than 2 for both frequencies; Maximum gain Gmax of C1, C2 and C3 is obtained as 4.4 dB and shown in figure 3.38; Radiation efficiency is 59.85%
Figure 3.37: Simulation and Measurement S-Parameter results of C2, $f_1=0.894$ and $f_2=1.84$ GHz.

The patch C2 is compared by measuring with simulation of reflection coefficient vs frequency results and shown in figure 3.37. From the simulation results, -10 dB return loss and VSWR value less than 2 is achieved at resonant frequencies $f_{r1}=0.894$ GHz and $f_{r2}=2$ GHz.

Figure 3.38: Gain parameter results of C1, C2, C3

Elevation Radiation pattern gain display diagrams for the antennas 1 and 2 is presented with the $\phi=0$, $\phi=90$ in figure 3.39-3.42. Since C3 is showing the single band result as C1, radiation pattern is not shown here.
Figure 3.39: Radiation Pattern (RP) of C1 at 0.894 GHz
(a) phi=0 (b) theta=0 and 90
Figure 3.40: RP of C2 at 0.894 GHz and 1.842 GHz
(a) φ = 0  (b) θ = 90°
3.4.3 Circular patch with multi slit as meander patch

The design of circular patch with multi slit as meander antenna (A12) is discussed. Circular patch with multi slit as meander (figure 3.4) is designed using FR4 dielectric material with radius, \( a=47.6 \) mm, \( \varepsilon_r =4.4 \), \( h=3.2 \) mm. The ground size is taken as 105 mm X 105 mm.

![Circular patch with multi slit as meander patch](image)

Figure 3.41: Circular patch with multi slit as meander
(a) Geometry (b) Dimensions in mm.

Five slits were introduced to produce multi bands of 1.8, 2.4, 4.8, 5.2, and 5.8 GHz. The slit dimensions are shown in figure 3.41(b). Slit introduces
capacitance effect and induces resonance next to main resonance of the patch. Various slits and their reflection coefficient vs frequency were given in figure 3.42.

![Figure 3.42: S11 Comparison of circular patch multi slit as meander with various slits](image)

Without slit, antenna gives single resonant frequency, 1slit produces two frequencies, 2 slit gives three frequencies, 3 slits gives four frequencies, 4 slits give five frequencies and 5 slits give six frequencies as multi frequencies as displayed in figure 3.44.

Table 3.9 Comparison in meander antenna with various slits

<table>
<thead>
<tr>
<th>Frequencies (GHz)</th>
<th>Return Loss(dB)</th>
<th>Without slit</th>
<th>1 slit</th>
<th>2slits</th>
<th>3slits</th>
<th>4slits</th>
<th>5slits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.885</td>
<td></td>
<td>-10.00</td>
<td>-11.00</td>
<td>-10.15</td>
<td>-10.14</td>
<td>-10.30</td>
<td>-10.14</td>
</tr>
<tr>
<td>1.82</td>
<td></td>
<td>-00.11</td>
<td>-10.00</td>
<td>-11.14</td>
<td>-10.39</td>
<td>-11.68</td>
<td>-12.35</td>
</tr>
<tr>
<td>2.425</td>
<td></td>
<td>-00.23</td>
<td>-01.00</td>
<td>-16.54</td>
<td>-11.21</td>
<td>-10.75</td>
<td>-10.74</td>
</tr>
<tr>
<td>4.79</td>
<td></td>
<td>-00.15</td>
<td>-01.00</td>
<td>-06.10</td>
<td>-10.21</td>
<td>-09.45</td>
<td>-13.32</td>
</tr>
<tr>
<td>5.23</td>
<td></td>
<td>-00.11</td>
<td>-01.00</td>
<td>-05.95</td>
<td>-04.59</td>
<td>-10.69</td>
<td>-11.77</td>
</tr>
<tr>
<td>5.835</td>
<td></td>
<td>-00.09</td>
<td>-01.00</td>
<td>-09.47</td>
<td>-8.68</td>
<td>-07.30</td>
<td>-10.00</td>
</tr>
</tbody>
</table>

Circular patch with five slits as meander patch (A12) is discussed in chapter 3. The Circular patch with multi slit as meander having FR4 dielectric
material $\varepsilon_r$ is 4.4 with radius, $a=47.6$ mm, $h=3.2$ mm, is giving the results of -10.14 dB at 0.885 GHz, -12.35 dB at 1.82 GHz, -10.74 dB at 2.42 GHz, -13.32 dB at 4.79 GHz, -11.77 dB at 5.23 GHz, -10 dB at 5.83 GHz. To get required multi band, it is taken for stacking.

![Figure 3.43: Gain of circular patch with multi slit as meander](image1)

![Figure 3.44: Prototype of circular patch with multi slit as meander](image2)

![Figure 3.45: VSWR results of multi slit meander patch](image3)
Figure 3.43 depicts maximum 6.4 dB in the gain vs frequency curve of the meander patch. Figure 3.44 displays the fabrication of the meander patch. The simulation results match with measured results. The results (figure 3.45) show VSWR, and performance reflection coefficient versus frequency. Reflection coefficient vs frequency as S-parameter is shown in figure 3.46. In this figure, 10 dB return loss 5.5 GHz bandwidth, and multi band of 0.5 GHz to 6 GHz, are obtained. Figure 3.47 depicts the Radar plot results of multi slit meander patch showing radiation pattern.
3.5 SUMMARY

C-shaped slot on rectangular patch antenna is presented with probe fed and Microstrip line fed. Rectangular patch with slits on edges in probe fed for 2.45 GHz are designed. Circular patch with single slit and slot, and multi slits with probe fed for 0.9 GHz are designed. Due to the introduction of C-shaped slot, the simulation frequency 2.1 GHz is achieved in probe fed and the simulation frequencies 2.21 GHz, and 1.18 GHz are from microstrip line fed.

Rectangular patch with slits on edges gives us multiband resonant operation from 2.42 to 3.94 GHz. Circular patch with single slit provides dual band operation 0.894 GHz, and 1.842 GHz. Circular patch with multi slits give multi band operation from 0.5 GHz to 6 GHz. The simulation and measurement results were matching closely.

Four different antenna configurations of microstrip rectangular and circular shaped patches using slots and slits are discussed in the frequency range from 0.5 GHz to 6 GHz for wireless communication application in this chapter. By the introduction of slots and slits, multi band characteristics are preserved along with the radiation characteristics.

It is concluded that low profile antenna can be utilized for multi band applications with the introduction of slots, slits, low power and small size. The next chapter proposes the analysis of circular shaped microstrip antenna by using various feeds and fractal geometry.