This chapter highlights the control of operating frequency and polarization of a rectangular microstrip antenna using reactive loading. The method consists of placing chip capacitor/varactor diodes at appropriate locations provide narrow instantaneous bandwidths that are dynamically selectable at higher efficiency than in conventional antennas. The chapter begins with the mechanical tuning of the operating frequencies and polarizations by inserting different capacitor values at the center of the slot. The chapter concludes with the electronic control of frequency and polarization using varactors.
Chapter 4

4.1 Introduction

Microstrip antennas have the attractive features of low profile, small size and conformability to mounting hosts. However, the size of conventional microstrip antenna is still large at the lower microwave regime, especially those used for mobile applications. Therefore compact broadband techniques have recently attracted much attention among researchers. The size of conventional microstrip antenna can be reduced in different ways such as: the use of high dielectric substrate, the use of reactive loading, the shaping of conventional patch structures by cutting slots or slits in the radiating patch or any combination of these techniques. Generally, small size antennas suffer from bandwidth limitations. Bandwidth can be increased by adding lossy elements but, they significantly affect the efficiency of the antenna. One method to solve the low bandwidth is to use the tunable antenna concept. Tunable antenna concept is based on tuning the antenna to the desired band. Therefore such an antenna would not cover all the bands simultaneously, but provides narrow instantaneous bandwidths that are dynamically selectable at higher efficiency than in conventional antennas.

Microstrip antenna is a resonant element and its resonance frequency can be determined by its lumped element equivalent. Therefore any reactive loading of the patch leads to a change in its resonance frequency. Such loading can be performed either mechanically or electronically. Pins, posts, stubs, adjusting the thickness of dielectric layer and use of chip capacitor enable mechanical tuning, whereas varactor and switching diodes embedded in the patch and optical control of PIN diode impedance can be used for electronic tuning of the patch antenna. This chapter begins with an investigation on cross patch antenna with X-slot to study the impact of antenna geometry on its frequency and polarization tuning characteristics using chip capacitor loading. Further, we modify the antenna configuration to attain an electronic control of the operating frequency and polarization with embedded varactor diodes.
4.2 Frequency reconfigurable microstrip antenna for tunable frequency ratio using capacitive loading

Frequency agile systems must be able to receive signals over a large frequency range and therefore, require either wide-band or tunable antennas. However, the instantaneous bandwidth of microstrip antennas is limited as they become small with respect to the wavelength. Hence, tunable narrow-band antennas can be advantageous if small efficient antennas are required to cover a large frequency range. In addition, tunable narrow-band antennas provide frequency selectivity which relaxes the requirement of the receiver filters. Frequency and polarization reconfigurable antennas extend the flexibility of a system even further. A single feed reconfigurable dual-frequency dual-polarized operation of an X-slot loaded microstrip antenna by embedding a chip capacitor is discussed in this section.

4.2.1 Antenna Geometry

As shown in figure 4.1, the proposed antenna is fabricated on a substrate of thickness $h$ (1.6 mm) and relative permittivity $\varepsilon_r$ (4.4). The antenna structure is obtained by removing the four square regions of side dimension $L_S$ mm from the corners of a rectangular patch of size $L \times W$ mm$^2$. An X-slot of arm length $L_X$ mm and width $W_X$ mm is then carved at the centre of the cross patch and the antenna is electromagnetically coupled using a $50\Omega$ microstrip line fabricated using the same substrate. A chip capacitor $C$ inserted at the center of the slot is oriented parallel to the feed line.
Figure 4.1 Geometry of the frequency reconfigurable cross patch antenna (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm, L_g=W_g=75mm and W_x=2.3mm.)

4.2.2 Simulated and measured results

The cross patch with an X-slot constitutes the fundamental structure for dual frequency dual polarized operation. The X shape is chosen to induce symmetric current distributions for TM_{10} and TM_{01} modes and can be easily modified to obtain a tunable antenna with greater area reduction. The proper selection of the X-slot size modifies the horizontal and vertical electrical lengths of the patch equally so that the two resonant frequencies are lowered to 1.12 GHz and 1.44 GHz from 1.74GHz and 2.3GHz respectively. By
embedding a chip capacitor at the center of the X-slot, the antenna can operate at a particular dual-frequency combination without changing the geometrical parameters of the antenna. The location of the capacitor is chosen parallel to the feed line which minimizes the variations of TM$_{10}$ mode. While the TM$_{01}$ mode of the patch is determined by the selected value of the chip capacitor.

The performance of the antenna against various capacitance values are listed in Table 4.1. It can be seen that the TM$_{10}$ mode remains unaffected against the changes in capacitance values. The TM$_{01}$ mode is lowered to 1.1GHz from 1.44GHz when a 1pF chip capacitor is soldered at the center of the X-slot. The effective resistance of this mode decreases drastically and is suppressed due to very low impedance ($3.2$-$j39.7\Omega$) by increasing the capacitor value to 4.7pF. At the same time, loading a chip capacitor generates an additional TM$_{01}$ mode at higher frequency due to shortest electrical path through the capacitor along Y-direction. This additional resonant frequency is not matched for low C values due to high capacitive reactance and achieves impedance matching by increasing the value of C from 2.2pF onwards. In addition, increase in C offers tuning of 190MHz downwards to 1.95GHz from 2.14GHz and all the frequencies are well matched, except for C=1pF, with a linearly polarized radiation along Y-direction. The TM$_{10}$ mode is well matched for all values of capacitance, which gives a linearly polarized radiation along X-direction. Hence, it is found that the capacitor inserted parallel to the feed line at the center of the X-slot modifies the TM$_{01}$ mode and leaves the TM$_{10}$ mode almost unchanged. This property of the antenna offers more flexibility in frequency tuning where the frequency ratio varies in a wider range from 1.84 to 1.68 when the capacitance is varied from 2.2pF to 82pF with linearly polarized radiation along Y-direction.
The reflection characteristics of the antenna measured for different capacitor values are shown in figure 4.2. Only a few variations are shown for brevity. The variation of resonant modes and frequency ratio against various capacitances is plotted in figure 4.3. From the graph it is clear that the proposed configuration can effectively tune the TM$_{01}$ mode without affecting TM$_{10}$ mode against the changes in capacitance values. The simulated surface current distribution and 3D radiation patterns of the antenna without capacitor and with C=10pF are shown in figure 4.4. An additional shortest electrical length through the center of the X-slot is produced by embedding a capacitor vertically at the center of the X-slot as seen in figure 4.4 (d). This length varies against various capacitance values and determines the frequency ratio of the two operating frequencies.

**Table 4.1** Impedance variation of the frequency reconfigurable cross patch antenna against various capacitances

<table>
<thead>
<tr>
<th>Capacitance, pF</th>
<th>TM$_{10}$, GHz</th>
<th>TM$_{01}$, GHz</th>
<th>Input impedance, $\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TM$_{10}$</td>
<td>TM$_{01}$</td>
<td>Real</td>
</tr>
<tr>
<td>0</td>
<td>1.13</td>
<td>1.43</td>
<td>59.6</td>
</tr>
<tr>
<td>1</td>
<td>1.15</td>
<td>1.23</td>
<td>73.7</td>
</tr>
<tr>
<td>2.2</td>
<td>1.16</td>
<td>0.87, 2.14</td>
<td>44.45</td>
</tr>
<tr>
<td>3.3</td>
<td>1.16</td>
<td>0.74, 2.07</td>
<td>44.6</td>
</tr>
<tr>
<td>4.7</td>
<td>1.16</td>
<td>0.63, 2.04</td>
<td>44.7</td>
</tr>
<tr>
<td>6.8</td>
<td>1.16</td>
<td>2.01</td>
<td>44.7</td>
</tr>
<tr>
<td>8.2</td>
<td>1.16</td>
<td>2</td>
<td>44.8</td>
</tr>
<tr>
<td>10</td>
<td>1.16</td>
<td>1.99</td>
<td>44.8</td>
</tr>
<tr>
<td>15</td>
<td>1.16</td>
<td>1.98</td>
<td>44.8</td>
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<tr>
<td>22</td>
<td>1.16</td>
<td>1.97</td>
<td>44.8</td>
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<tr>
<td>47</td>
<td>1.16</td>
<td>1.96</td>
<td>44.8</td>
</tr>
<tr>
<td>82</td>
<td>1.16</td>
<td>1.95</td>
<td>44.8</td>
</tr>
</tbody>
</table>
Figure 4.2 Reflection coefficient of the antenna without and with various capacitances (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm.)

Figure 4.3 Variation of resonant modes and frequency ratio against various capacitances (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm.)
Figure 4.4 (a) Simulated surface current distribution and 3D radiation pattern of the frequency reconfigurable microstrip antenna without capacitor at 1.13GHz

Figure 4.4 (b) Simulated surface current distribution and 3D radiation pattern of the frequency reconfigurable microstrip antenna without capacitor at 1.43GHz

Figure 4.4(c) Simulated surface current distribution and 3D radiation pattern of the frequency reconfigurable microstrip antenna for tunable frequency ratio with C=10pF at 1.16GHz
A single feed design of novel compact frequency reconfigurable microstrip antenna for tunable frequency ratio is proposed in this section. The concept is based on the tuning of embedded slot in the patch antenna using a chip capacitor. This property of the antenna offers more flexibility in frequency tuning where the frequency ratio varies in a wider range from 1.84 to 1.68 when the capacitance is varied from 2.2pF to 82pF with linearly polarized radiation along Y-direction. Furthermore the proposed antenna has an added advantage of size reduction, moderate gain and low levels of cross-polarized radiation keeping the radiation patterns of each frequency unchanged as the capacitor value is changed.

4.3 Frequency and polarization tuning of a microstrip antenna using capacitive loading

In this section, a novel compact microstrip antenna achieving frequency and polarization tunability is presented. A chip capacitor inserted normal to the feed line at the center of the X-slot is used to tune the operating frequency and polarization of the antenna. Polarization of the antenna is switchable between LP and CP by resoldering the right value for the lumped element without changing the geometrical parameters of the antenna. The frequency ratio can assume any value in the range $1.025 \leq f_R \leq 1.21$. The important aspect of this
design is that it provides an area reduction of 79\% for the first frequency and 66\% for the second frequency when compared with a standard rectangular patch operating at the same frequencies. The validity of this concept is demonstrated by simulated and measured results which show low cross polar level for linear polarization and good axial ratio for circular polarization.

4.3.1 Antenna Geometry

The proposed antenna configuration shown in figure 4.5 is same as that discussed in section 4.2.1 except for the orientation of the chip capacitor. Here, the chip capacitor is inserted horizontally to obtain a dual frequency antenna with adequate control over its frequency ratio.

![Figure 4.5](image)

Figure 4.5 Geometry of frequency and polarization reconfigurable cross patch antenna using chip capacitor (L=30.9mm, W=43.5mm, L_c=5.1mm, L_x=18.3mm, L_g=W_g=75mm and W_c=2.3mm)
4.3.2 Simulated and Measured results

A prototype of the antenna is fabricated on a substrate of \( \varepsilon_r = 4.4 \) and \( h = 1.6 \text{mm} \) with the parameters \( L = 30.9 \text{mm} \), \( W = 43.5 \text{mm} \), \( L_s = 5.1 \text{mm} \), \( L_x = 18.3 \text{mm} \) and \( W_x = 2.3 \text{mm} \). The measurements of the antenna are done using HP8510C vector Network Analyzer. The resonant frequencies of the antenna can be reconfigured by loading a chip capacitor at the center of the X-slot. The location of the capacitor is chosen normal to the feed line that minimizes the variations of TM_{01} mode and at the same time TM_{10} mode can be tuned by changing the value of the capacitor to obtain a frequency and polarization tunable antenna with adequate control over its frequency ratio.

The reflection characteristics of the antenna for different capacitor values are shown in figure 4.6. Only a few variations are shown for brevity. The variation of resonant frequency for different values of chip capacitor is given in Table 4.2. It can be seen that the TM_{10} mode is tuned to 672 MHz from 1.118GHz with capacitor value \( C = 3.3 \text{pF} \). The effective resistance of this mode decreases drastically and is suppressed due to very low impedance \((4.7-j2.5 \Omega)\) by increasing the capacitor values from 10pF onwards. Also, loading a chip capacitor generates an additional TM_{10} mode at higher frequency due to shortest electrical path through the capacitor along X-direction. This third resonant frequency is not matched for low \( C \) values due to high inductive reactance \((68+j58 \Omega)\) and achieves impedance matching by increasing the value of \( C \) from 2.2pF to 100pF. In addition, increase in \( C \) offers tuning to 1.594GHz from 1.748GHz and all the frequencies are well matched, except for \( C = 1 \text{pF} \), with a linearly polarized radiation along x-direction.
The TM$_{01}$ mode is well matched for all values of capacitance ranging from 1pF to 100pF, which gives a linearly polarized radiation along Y-direction. A slight variation is observed when the value of C is increased, but this change is negligible compared to that of third resonant frequency. Hence, it is found that the second resonance is determined by the cross patch antenna with X-slot while the first and third resonance is excited with respect to the chip capacitor value. Thus, the antenna offers a frequency ratio of 1.66 and 1.09 for first and second resonances with linearly polarized radiation along x-direction and y-direction respectively. With capacitor value equal to 15pF, the 2:1 VSWR bandwidth is measured to be 90 MHz, which amounts to 6% with respect to the centre frequency of 1.49 GHz. In addition, the second and third modes come close together which results a circularly polarized radiation at 1.465GHz. The measured resonant frequencies $f_1$, $f_2$ and $f_3$ along with frequency ratio $f_R$ ($f_3/f_2$) with various capacitances is shown in figure 4.7. The
simulated surface current distribution and 3D radiation patterns of the antenna without capacitor, with $C=6.8\,\text{pF}$ and $15\,\text{pF}$ are shown in figure 4.8. An additional shortest electrical length through the center of the X-slot is produced by embedding a capacitor horizontally at the center of the X-slot as seen in figure 4.8 (d). This length varies against various capacitance values and determines the frequency ratio of the two operating frequencies.

The measured axial ratio of the antenna when $C=15\,\text{pF}$ is plotted in figure 4.9. The best CP performance in the broadside direction is achieved at 1.465GHz with 3% CP bandwidth. The measured radiation patterns of the antenna for capacitor values 1pF, 6.8pF and 15pF are plotted in figure 4.10. It is observed that the antenna has similar radiation patterns at both the modes and the shape of the patterns remain unchanged as the capacitor value is changed. A broadside radiation characteristic in both XZ- and YZ-planes with more than 100° half power beam width are obtained in all linear polarization states. Furthermore, low cross polar levels are achieved. The cross-polarization levels are, however, larger at 952MHz due to smaller electrical dimensions of the antenna at this frequency.

The gain is also measured using a double ridged horn as a reference. The antenna shows a peak gain of 3.39dBi in the direction of maximum radiation. The lower gain of the antenna is a result of smaller electrical dimensions at lower frequencies that occurs due to capacitive loading.
Table 4.2 Performance of the frequency and polarization reconfigurable cross patch antenna against various capacitances

<table>
<thead>
<tr>
<th>Capacitance (pF)</th>
<th>$f_1$(GHz), $S_{11}$(-dB)</th>
<th>$f_2$(GHz), $S_{11}$(-dB)</th>
<th>$f_3$(GHz), $S_{11}$(-dB)</th>
<th>Input impedance ($\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$f_1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Re.</td>
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<tr>
<td>0</td>
<td>1.118, 23</td>
<td>1.44, 20</td>
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<td>56</td>
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<tr>
<td>1</td>
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<td>1.447, 21</td>
<td>2.07, 6.7</td>
<td>46</td>
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<td>2.2</td>
<td>0.772, 10.65</td>
<td>1.444, 18</td>
<td>1.748, 14</td>
<td>37.6</td>
</tr>
<tr>
<td>3.3</td>
<td>0.672, 9.5</td>
<td>1.463, 18.5</td>
<td>1.859, 23</td>
<td>22.8</td>
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<td>4.7</td>
<td>0.596, 5</td>
<td>1.46, 23</td>
<td>1.617, 20</td>
<td>13</td>
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<td>6.8</td>
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<td>1.559, 29</td>
<td>18.9</td>
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<td>8.2</td>
<td>0.453, 2.5</td>
<td>1.463, 17</td>
<td>1.552, 28.5</td>
<td>9.5</td>
</tr>
<tr>
<td>10</td>
<td>0.419, 1.6</td>
<td>1.443, 17</td>
<td>1.538, 48</td>
<td>4.7</td>
</tr>
<tr>
<td>15</td>
<td>1.445, 1.535</td>
<td>--</td>
<td>--</td>
<td>57.5</td>
</tr>
<tr>
<td>22</td>
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<td>1.442, 38</td>
<td>1.515, 21</td>
<td>--</td>
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<tr>
<td>47</td>
<td>--</td>
<td>1.444, 20</td>
<td>1.598, 26</td>
<td>--</td>
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<tr>
<td>100</td>
<td>--</td>
<td>1.489, 25</td>
<td>1.594, 32</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 4.7 Variation of resonant frequencies and frequency ratio of frequency and polarization reconfigurable cross patch antenna against different capacitance (L=30.9mm, W=43.5mm, Lc=5.1mm, Lx=18.3mm and Wx=2.3mm).
Investigations on Varactor Controlled Frequency and Polarization Reconfigurable Microstrip Antenna

Design and Development of Reconfigurable Compact Cross Patch Antenna for Switchable Polarization

(a) at 1.1GHz without chip capacitor

(b) at 1.4GHz without capacitor

(c) at 1.448GHz with C=6.8pF
Figure 4.8 Simulated surface current distribution and 3D radiation pattern of the frequency and polarization reconfigurable cross patch antenna for different capacitance values (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm).

Figure 4.9 Measured axial ratio of the frequency and polarization reconfigurable cross patch antenna when C=15pF (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm).
Investigations on Varactor Controlled Frequency and Polarization Reconfigurable Microstrip Antenna

Figure 4. at 952MHz when C=1pF

(b) at 1.45GHz when C=1pF

© at 1.45GHz when C=6.8pF
Figure 4.10 Measured radiation pattern of the frequency and polarization reconfigurable cross patch antenna with various capacitances (L=30.9mm, W=43.5mm, Ls=5.1mm, Lx=18.3mm and Wx=2.3mm).
A single feed design of novel compact frequency and polarization tunable microstrip antenna proposed in this section is based on the tuning of embedded slots in the patch antenna using a chip capacitor. A high tuning range of 34.48% and 14.3% is achieved for the first and third resonant frequencies respectively by minimizing the variations of second resonant frequency. Measurement results of the antenna indicate that its frequency ratio can assume any value in the range $1.025 \leq f_R \leq 1.21$ with linear or circularly polarized radiation by changing the capacitor value from 1pF to 100pF. Furthermore the proposed antenna has an added advantage of size reduction, moderate gain, low levels of cross-polarized radiation and the radiation patterns of each frequency remain unchanged as the capacitor value is changed. By replacing the chip capacitor with a varactor diode the proposed design can be extended to frequency agile polarization diversity antenna.

4.4 Varactor controlled frequency reconfigurable microstrip antenna

One of the demands for future wireless communication systems is higher data rates to offer new services by the service providers. To achieve higher data rates the concept of MIMO (Multiple-Input Multiple-Output) systems has emerged. The basic principle behind MIMO is to use multiple antennas in contrast to the currently deployed systems mostly based on single antenna systems. The handheld devices need to be small and at the same time versatile due to the mobility of the user. To improve the overall performance following the MIMO paradigm, several antenna elements may be introduced on each handheld device. Requiring one feed chain per antenna element, this would result in a considerable increase in space, cost, and complexity and makes the implementation of large MIMO systems a difficult task. One way to overcome
the setbacks is the use of reconfigurable antennas. For a fixed number of
antenna elements in an antenna array, the choice of reconfigurable elements
will increase the number of possibilities. The reconfigurability is preferably
achieved by integrating switches or varactors with the antenna to save space. A
single tunable antenna would eliminate the need for multiple antennas operating
in various frequency bands.

All the results and discussions stated in above sections convincingly
proved the novel concept of tuning mechanism which can be used either to tune
the frequency ratio or to reconfigure the frequency and polarization of the
proposed dual frequency dual polarized single feed cross patch antenna. The
important characteristic of frequency reconfigurable antenna is their flexibility
in operation. That is, one can easily control their operating frequency
electronically without changing the capacitors. This is accomplished by
varactors integrated to the extended slot arms of the dual frequency dual
polarized cross patch antenna.

4.4.1 Varactor diode

A varactor diode is a P-N junction diode that changes its capacitance and
the series resistance as the bias applied to the diode is varied. The property of
capacitance change is utilized to achieve a change in the frequency and/or the
phase of an electrical circuit. The key electrical parameters guiding the
selection and usage of a varactor diode are

- Reverse breakdown voltage and reverse leakage current.
- Capacitance value and the capacitance-voltage change behavior.
• Quality factor (also known as figure of merit), Q.

The junction capacitance of a varactor varies against the bias voltage and can be calculated from the applied bias voltage as,

\[ C = \frac{C_0}{1 - \left(\frac{V}{V_{bi}}\right)^\gamma} \]

Where \( C_0 \) is the varactor capacitance at zero bias voltage, \( V \) is the applied bias voltage, \( V_{bi} \) is the built-in-potential and \( \gamma \) is a constant depending upon the doping profile of the p-n junction. From this equation it is clear that the capacitance value decreases with increase in reverse bias voltage of the varactor.

BB 152 diode from the Philips semiconductors are utilized for the frequency reconfigurable antenna discussed in this section and its characteristics are listed in Table 4.3. During simulation, the varactor is modeled as a lumped capacitor by selecting appropriate values for different bias voltages as provided in the data sheet. The incorporation of a varactor diode and its associated biasing circuitry introduces insertion loss. This will reduce the gain and cross-polarization level of linearly polarized radiation.

4.4.2 Antenna Geometry

The configuration of the proposed antenna is shown in figure 4.11. The antenna is fabricated on a substrate of thickness \( h \) (1.6 mm) and relative permittivity \( \varepsilon_r \) (4.4). The initial cross patch is obtained by removing the four square regions of side \( L_s \) mm from the corners of a rectangular patch of size \( L \times W \) mm\(^2\). An X-slot of arm length \( L_x \) mm and width \( W_x \) mm is then carved at the center of the cross patch. The antenna is electromagnetically coupled using a
50Ω microstrip line fabricated using the same substrate material. The dimension of the ground plane is 75 x 75 mm². Varactor diodes D₁, D₂, D₃, and D₄ are positioned at the extreme end of the slot arms in order to get maximum tuning range and better matching. DC bias voltage is supplied from a battery through chip inductors. The details of the varactor are listed in Table 4.3.

**Figure 4.11** Geometry of frequency reconfigurable microstrip antenna using varactor diodes (L=30.9mm, W=43.5mm, L₅=5.1mm, Lₓ=18.3mm, Lₑ=75mm and Wₓ=2.3mm).

**Table 4.3** Varactor details

<table>
<thead>
<tr>
<th>Type number</th>
<th>BB152</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package</td>
<td>SC-76</td>
</tr>
<tr>
<td>Version</td>
<td>SOD 323</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Philips semiconductors</td>
</tr>
<tr>
<td>Reverse voltage</td>
<td>32V</td>
</tr>
<tr>
<td>Diode series resistance</td>
<td>1Ω</td>
</tr>
<tr>
<td>Diode capacitance</td>
<td>2.48pF-62pF</td>
</tr>
</tbody>
</table>
4.4.3 Simulated and Measured results

To implement electronic reconfigurability, varactor diodes are directly integrated across the extended slot arms and DC bias is applied through two chip inductors. The junction capacitance of the varactors varies against the reverse bias voltage applied and these different capacitive loadings correspond to different electrical lengths and thus different resonant frequencies. The positions of the varactors are so selected to achieve maximum frequency tuning while less perturbing the antenna matching. The measured reflection coefficients of the antenna are shown in figure 4.12. When the reverse bias is OFF, the varactor loadings in all the slot arms correspond to high capacitance. Thus the resonant frequencies are lowered to 1.03 GHz and 1.28GHz with a frequency ratio of 1.279. It is observed that the varactors modify the electrical lengths of TM_{01} and TM_{10} modes of the patch which result an orthogonally polarized dual frequency reconfigurable antenna.

The reconfigurable antenna was then electronically tuned with a reverse DC voltage applied across the diodes. When the bias voltage is varied from 0 to 16 V, the tuning range for the first resonant frequency is found to be 26.3% or 279MHz upwards (from 1.02 to 1.299 GHz) and that of second resonant frequency is 15.3% or 197MHz upwards (from 1.305 to 1.502 GHz). At 16V the frequency ratio is found to be 1.156. The variation of first and second resonant frequencies (f_1 and f_2) with the applied varactor reverse bias voltage is measured and plotted in figure 4.13. The simulated surface current distribution and 3D radiation pattern of the antenna at 1.03GHz and 1.28GHz are given in figure 4.14. It is observed that the varactor loaded X-slot modifies the electrical lengths of TM_{01} and TM_{10} modes of the patch which result an orthogonally polarized dual frequency reconfigurable antenna.
Figure 4.12 Measured reflection coefficient of the dual frequency reconfigurable microstrip antenna (L=30.9mm, W=43.5mm, L_e=5.1mm, L_x=18.3mm and W_x=2.3mm).
Figure 4.13 Variation of resonant frequencies against bias voltages (a) first resonant frequency (b) second resonant frequency (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm).

The E and H-plane radiation patterns of the reconfigurable antenna are measured for different bias voltages. All the patterns show similar broadside radiation characteristics with good cross polarization levels even when the operating frequencies are shifted greatly by applying reverse bias. Typical radiation patterns for the resonant frequencies of 1.03GHz and 1.28Hz for 0V and 1.3GHz and 1.48GHz for 16V are given figure 4.15(a), (b), (c) and (d) respectively. Bandwidths up to 2.26% and 2.36% respectively, have been obtained in the two modes. The polarization planes of the two resonant frequencies are mutually orthogonal in the entire tuning range. The gain is also measured using a double ridged horn as a reference. The peak gain of the reconfigurable antenna is found to be nearly 2.1 dB and 1.2 dB less for the first and second resonant frequencies respectively. The low gain values are due to the opposing currents on either side of the slot arm which cause field cancellation along the axis at the far-field.
Figure 4.14 Simulated surface current distribution and 3D radiation pattern of the frequency reconfigurable cross patch antenna at (a) 1.03GHz and (b) 1.28GHz when biasing 0V (L=30.9mm, W=43.5mm, L₁=5.1mm, L₂=18.3mm and W₁=2.3mm).
**Investigations on Varactor Controlled Frequency and Polarization Reconfigurable Microstrip Antenna**

**Figure 4.15** Measured radiation patterns of frequency reconfigurable cross patch antenna (L=30.9mm, W=43.5mm, Lx=5.1mm, Lc=18.3mm and Wc=2.3mm).

(b) at 1.28GHz when biasing 0V

(c) at 1.3GHz when biasing 16V

(d) at 1.48GHz when biasing 16V
A single feed design of compact, electronically reconfigurable dual frequency microstrip antennas is proposed in this section. The concept is based on the electronic tuning of embedded slots in the patch antenna using varactor diodes. A high tuning range of 26.3% (1.02–1.299 GHz) and 15.3% (1.305–1.502 GHz) is achieved for the two operating frequencies respectively, when the bias voltage is varied from 0 to 16V. The salient feature of this design is that it uses no matching networks even though the resonant frequencies are tuned in a wide range with good matching below −10 dB. The antenna has an added advantage of size reduction up to 77% and 64% for the two operating frequencies compared to conventional rectangular patches. Another feature of this antenna is that the radiation characteristic is remaining essentially unaffected by the frequency tuning.

4.5 Frequency and polarization reconfigurable cross patch antenna using varactor

MIMO systems introduce diversity at the mobile station allowing highly reliable communications compared to a corresponding SISO systems. One possibility to obtain diversity is to displace the antenna elements. This would give space diversity, meaning that the difference in paths for the two antennas is used. A different polarization at the antenna elements is another way of obtaining diversity. By having the possibility to change the receiving polarization the risk of losing information is reduced because of the incoming signal having a certain polarization. A third way of achieving diversity is to use antenna elements with different radiation patterns. By combining elements with different patterns, additional directions could be covered and the risk of losing information because of fading is reduced.
The frequency agility and polarization diversity provide added flexibility to the microstrip antenna. Furthermore, these features are obtained without sacrificing the thin conformal structure of the microstrip antenna and without increasing the complexity of the external microwave feed network. In this section, a simple compact frequency agile microstrip antenna achieving polarization diversity is presented. The proposed antenna reconfigures both frequency and polarization electronically without changing the geometrical parameters and devoid of any impedance matching circuitry. The radiation patterns are independent of tuning voltage which is highly desirable for reconfigurable microstrip antennas. In addition, the antenna requires only a single varactor and less area to occupy the patch and dc-bias circuit compared to conventional polarization diversity antennas available in literature.

4.5.1 Antenna Geometry

As shown in figure 4.16, the proposed antenna is fabricated on a substrate of thickness \( h \) (1.6 mm) and relative permittivity \( \varepsilon_r \) (4.4). The antenna consists of a rectangular patch (\( L \times W \) mm\(^2\)) with square slit of side \( L_s \) mm at the four corners. An X-slot of arm length \( L_x \) mm and width \( W_x \) mm is carved at the centre of the cross patch. The antenna is electromagnetically coupled using a microstrip line fabricated on the same substrate. The position of the feed line is optimized using Ansoft HFSS for \( 50\Omega \) impedance matching. The varactor diode inserted at the centre of the slot is oriented normal to the feed line. The detail of the varactor is listed in Table 4.3. The dc bias lines are connected to the top part of the patch containing dc block capacitors, RF choke and input voltage. Two dc block capacitors (\( C_1 \) and \( C_2 \)) are chosen to isolate the RF components from the dc signal and the RF choke inductor isolate the RF signal from the dc signal.
4.5.2 Simulated and Measured results

The fundamental resonant modes (TM\textsubscript{10} and TM\textsubscript{01}) of the unslotted cross shaped patch are at 1.74 GHz and 2.3 GHz with orthogonal polarizations. The proper selection of the slot size modifies the horizontal and vertical electrical lengths of the patch equally so that the two resonant frequencies are lowered to 1.13GHz and 1.44GHz. It is well evident that the insertion of the slot increases the current path thereby lowering the resonant frequency. The X-slot length is optimized using Ansoft HFSS to achieve maximum area reduction of 79% and 66% for the first and second frequency respectively when compared to a standard rectangular patch operating at the same frequencies.
A varactor diode inserted at the center of the X-slot is oriented normal to the feed line to achieve the reconfigurable polarization capability. The orthogonally polarized dual frequency cross patch antenna can be reconfigured for different polarization with respect to the bias voltage applied across the varactor. The bias circuit consists of two dc block capacitors, RF chokes and input voltage. The dc bias lines are connected to the top of the patch through RF chokes. Two dc block capacitors of $C_1=C_2=47\,\text{pF}$ are chosen to isolate the RF components from the dc signal and RF choke isolate the RF signal from flowing into the dc signal. The junction capacitance of the varactor diode varies against the reverse bias applied and these different capacitive loadings correspond to different electrical lengths along the X-direction. This behaviour results a strong effect on the TM$_{01}$ mode but little on the TM$_{10}$ mode of the patch with respect to the bias voltage. Thus, frequency and polarization agility is achieved electronically.

When the varactor inserted at the centre of the slot is oriented parallel to the feed line (vertical) the different capacitive loadings of the varactor correspond to different electrical lengths along the Y-direction with respect to the bias voltage. This behavior reconfigures the TM$_{10}$ mode to higher frequency with the increase in bias voltage while keeping the TM$_{01}$ mode unaffected.

Extensive parametric analysis is conducted to optimize the dimension of corner notches in the rectangular patch. From figure 4.17, it is observed that the impedance matching becomes poor when $L_s$ is lowered. The increase in $L_s$ causes the splitting of the resonance and $L_s=5.1\,\text{mm}$ is a good selection to achieve two near orthogonal resonant modes at 0V bias condition. The simulated surface current distribution of the antenna at 1.43GHz (biasing 0V) is shown in figure 4.18. A half-wave variation of current is observed through the center of the X-slot and another half wave variation around the edges of the X-slot arm. This behaviour results in the splitting of the current into two near orthogonal resonant modes.
**Figure 4.17** Effect of the corner notches in the frequency and polarization reconfigurable cross patch antenna (L = 30.9mm, W = 43.5mm, L_x = 18.3mm and W_y = 2.3mm).

**Figure 4.18** Simulated surface current distribution of the frequency and polarization reconfigurable cross patch antenna at 1.43GHz with 0V DC bias (L = 30.9mm, W = 43.5mm, L_y = 5.1mm, L_x = 18.3mm and W_y = 2.3mm).
The reflection characteristics of the antenna measured for different bias voltages are shown in figure 4.19. When the biasing voltage is held at 0V, the varactor offers very high reactance so that TM$_{01}$ mode excited by the patch comes close together with the TM$_{10}$ mode. Thus, the resonant frequency of one mode is slightly above the other yielding a circularly polarized (CP) radiation at 1.43GHz with 0.7% CP bandwidth. The antenna retains the CP performance up to 5V by reconfiguring its operating frequency. As the voltage applied across the varactor increases from 5 to 10V the junction capacitance decreases so that the coupling between the two adjacent modes decreases, yielding elliptical polarization. Further increase of bias voltage splits the adjacent modes into two orthogonal ones resulting in a dual frequency orthogonal polarized antenna in which the TM$_{01}$ mode of the antenna can be reconfigured with respect to the bias voltage beyond 10V. A tunable frequency ratio of around 1.09 is achieved for TM$_{01}$ mode against reverse bias applied from 10V to 25V. A slight variation is observed for TM$_{10}$ mode but this change is negligible compared to that of TM$_{01}$ mode. Hence, it is found that the first resonance is determined by the cross patch antenna with X-slot while the second resonance is tuned with respect to the bias voltage. The variation of resonant modes against bias voltage change is plotted in figure 4.20.
Figure 4.19 Measured reflection coefficient of the frequency and polarization reconfigurable cross patch antenna for different bias voltages (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm).

Figure 4.20 Variation of resonant modes with respect to the bias voltage variation of frequency and polarization reconfigurable cross patch antenna (L=30.9mm, W=43.5mm, L_s=5.1mm, L_x=18.3mm and W_x=2.3mm).
The important aspect of this design is that it provides an area reduction of 79% for the first frequency and 66% for the second frequency when compared with a standard rectangular patch operating at the same frequencies. Thus, the antenna offers tuning from 1.43GHz to 1.615GHz with circular, elliptical and linear polarized radiation by varying the bias voltage from 0V to 25V.

The normalized co-polarization component measured at 1.43GHz in XZ- and YZ- planes for different bias voltages are plotted in figure 4.21(a) and (b) respectively. It is observed that the shape of the patterns are unaffected by electronic tuning which is highly desirable for reconfigurable microstrip antennas. Typical far-field radiation patterns of the antenna in two orthogonal planes of RHCP and LHCP mode plotted at 1.43GHz (0V) is given in figure 4.22. The best CP performance in the broadside direction is achieved with 10MHz axial ratio bandwidth.

The measured radiation patterns at 1.45GHz (biasing 10V) are plotted in figure 4.23. It is observed that the antenna is elliptically polarized at this frequency. A broadside radiation characteristic in both XZ- and YZ-planes with more than 100º half power beam width is obtained in all polarization states with a sufficient front-to-back ratio. The front-to-back ratio is determined by the ground plane size which is kept greater than that of the radiator since it strongly affects the radiation pattern and resonant frequency. Figure 4.24 shows the normalized patterns at 1.43GHz and 1.527GHz for the biasing of 15V. The antenna is linearly polarized with cross polar isolation of 8.9dB at 1.43GHz and 12dB at 1.527GHz. The current flowing around the edges of one of the slot arm cancels with that of the opposite arm. This degrades the polarization purity of the proposed antenna. Also, the antenna cross-polarization combines with the isolation of the switch/varactor giving place to a degradation of the polarization purity of the combined polarization diversity antenna.
Figure 4.21 Radiation patterns of the frequency and polarization reconfigurable cross patch antenna measured at 1.43GHz for different bias voltages in (a) XZ-plane and (b) YZ-plane (L=30.9mm, W=43.5mm, Ls=5.1mm, Lx=18.3mm and Wx=2.3mm).

Figure 4.22 Measured radiation patterns of frequency and polarization reconfigurable cross patch antenna at 1.43GHz when biasing 0V (a) XZ-Plane (b) YZ-Plane (L=30.9mm, W=43.5mm, Lc=5.1mm, Le=18.3mm and Wx=2.3mm).
The measured axial ratio of the antenna for different bias voltages is plotted in figure 4.25. The best axial ratio is 0.28dB at 1.43GHz. The CP operating frequency band follows the change of the pass band with respect to the bias voltage up to 5V. The antenna shows an axial ratio of 4.64dB at 1.45GHz when the reverse bias is increased to 10V. Further increase of the bias voltage causes a dramatic increase in the axial ratio which shows that the antenna is linearly polarized and the corresponding axial ratio value represents the cross polarization level of the LP antenna above 10V. The antenna shows a peak gain of 3.65dBi at 1.6GHz for LP and 1.65dBi at 1.42GHz for RHCP in the direction of maximum radiation. The low gain values are due to the opposing current on either side of the slot arm which cause field cancellation along the on-axis at the far-field and is comparable with regular and similar antennas reported in literature. A prototype of the fabricated antenna is given in figure 4.26.
Figure 4.24 Radiation patterns of frequency and polarization reconfigurable cross patch antenna measured with biasing 15V at (a) 1.43GHz and (b) 1.527GHz (L=30.9mm, W=43.5mm, Lx=5.1mm, Lx=18.3mm and Wx=2.3mm).

Figure 4.25 Measured axial ratio of the frequency and polarization reconfigurable cross patch antenna for different bias voltages (L=30.9mm, W=43.5mm, Lx=5.1mm, Lx=18.3mm and Wx=2.3mm).
A new design of single feed compact reconfigurable microstrip antenna with polarization diversity using single varactor is proposed. The prototype fabricated on inexpensive FR$_4$ laminate shows stable radiation characteristics and patterns of each frequency remain unchanged with respect to the voltage variation. Furthermore the antenna has an added advantage of reduced size with low levels of cross-polarized radiation in linear polarization state and a 10MHz axial ratio bandwidth in circular polarization state. In addition, the antenna is simple and requires less area to occupy the patch and dc-bias circuit compared to conventional polarization diversity antennas available in literature. The frequency and polarization diversities of this design provide some potential applications for wireless communications.

4.6 Summarized conjecture at a glance

Inferences obtained from the investigation of frequency and polarization reconfigurable cross shaped microstrip antenna using reactive loading is summarized in this section.
A cross patch antenna with an embedded X-slot in the center excites compact orthogonal resonant modes.

Mechanical tuning of the two orthogonal resonant modes can be varied by inserting a chip capacitor at the center of the X-slot.

Frequency reconfigurable microstrip antenna with tunable frequency ratio is obtained when the chip capacitor is oriented parallel to the microstrip feed line.

If the chip capacitor is positioned normal to the microstrip feed then the frequency reconfigurable microstrip antenna is useful for polarization diversity applications.

Electronic control of the operating frequencies and the frequency ratio between two orthogonal resonant modes can be achieved with four varactors along the X-slot arms.

Frequency reconfigurable polarization diversity operation is possible with a single varactor at the center of the X-slot.

An electronically reconfigurable cross patch operates either in linear polarization or in circular polarization state with respect to the bias voltage applied across the varactor diode at the center of the X-slot.