CHAPTER 2

DESIGN AND FABRICATION OF PATCH ANTENNAS

2.1 INTRODUCTION

Microstrip antennas became very popular in the 1970s primarily for aerospace applications. Today, they are used for government and commercial applications. These antennas consist of a metallic patch on a grounded dielectric substrate. The metallic patch can take many patterns; those considered in this thesis, are the most popular ones, such as the square, the rectangular and the circular. There are many configurations that can be used to feed microstrip antennas. In this thesis, the microstrip line, coaxial probe and proximity coupling feeds are used. There are many methods of analysis for microstrip antennas. The most popular models, the transmission-line and cavities are used in the present work.

This chapter discusses the five structures that have been successfully fabricated, namely, the single frequency square patch antenna, the dual frequency slotted rectangular patch antenna, the single frequency circular patch antenna, the triple frequency double layer patch antenna and the triple frequency single layer patch antenna. The single radiating patch which is placed on the grounded dielectric substrate, is used in all the structures except the triple frequency double layer and single layer patch antennas (two are used). In all the structures only one dielectric substrate is used, except in the triple frequency double layer patch antenna (three are used), and the triple frequency single layer patch antenna (two are used). Increasing the number of
layers used in the triple frequency patch antennas to achieve the entire structure, will resonate at three different bands. So a parametric study of the patch antenna is necessary and is discussed in this chapter. Apart from the parametric study of the tri-band double layer patch antenna, the equation needed to design the microstrip line and various shapes of the patch antennas, are explained. Finally, all the patch antennas were designed, fabricated and tested to operate at single, dual and triple frequencies for wireless applications. The performances of all the designed patch antennas will be compared in terms of the simulation and measurement.

2.2 DESIGN OF THE MICROSTRIP LINE

The microstrip line is a conductor of width $w$ printed on a thin grounded dielectric substrate of thickness $h$ and relative permittivity $\varepsilon_r$. The geometry of the microstrip line is shown in Figure 2.1 (Pozar 1992).

![Figure 2.1 Geometry of microstrip line](image)
The effective dielectric constant $\varepsilon_{\text{reff}}$ of a microstrip line is given in equation (2.1) (Pozar 1992)

$$\varepsilon_{\text{reff}} = \left( \frac{\varepsilon_r + 1}{2} \right) + \left( \frac{\varepsilon_r - 1}{2} \right) \left( 1 + \frac{12h}{w} \right)^{-1/2} \quad (2.1)$$

The characteristic impedance $Z_0$ can be calculated and as shown in equation (2.2)

$$Z_0 = \begin{cases} \left[ \frac{60}{\sqrt{\varepsilon_{\text{reff}}}} \ln \left( \frac{8h}{w} + \frac{w}{4h} \right) \right] & \text{for } \frac{w}{h} \leq 1 \\ \left[ \frac{120\pi}{\sqrt{\varepsilon_{\text{reff}}}} \left( \frac{w}{h} + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1.444 \right) \right) \right] & \text{for } \frac{w}{h} \geq 1 \end{cases} \quad (2.2)$$

For a given characteristic impedance $Z_0$, line length $\ell$, phase shift $\phi$ and dielectric constant $\varepsilon_r$, the w/h ratio can be as shown in equation (2.3)

$$\frac{w}{h} = \begin{cases} \left[ \frac{8e^A}{e^{2A} - 2} \right] & \text{for } \frac{w}{h} < 2 \\ \frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left\{ \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r} \right\} \right] & \text{for } \frac{w}{h} > 2 \end{cases} \quad (2.3)$$

where,

$$A = \frac{Z_0}{60} \sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \left( 0.23 + \frac{0.11}{\varepsilon_r} \right) \quad (2.4)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \quad (2.5)$$
\[
\ell = \sqrt{\varepsilon_{\text{reff}}} K_0 \left( \frac{\pi}{180^\circ} \right) \\
K_0 = \frac{2\pi f_0}{c}
\]
(2.6)

(2.7)

where \( f_0 \) - operating frequency
\( c \) - velocity of light

The matching impedance \( Z_0 \) can be calculated by using the formula in (2.8) (Pozar 1992)

\[
Z_0 = \sqrt{Z_1 Z_2}
\]
(2.8)

2.3 DESIGN OF THE PATCH ANTENNAS

2.3.1 Rectangular patch antenna

The rectangular shape of the microstrip patch antenna and its equivalent circuit transmission line model is shown in Figure 2.2. The arrows show how the current flows through the patch and the ground plane (James et al 1989).

Figure 2.2 Geometry of rectangular patch and its equivalent circuit

The patch length \( L \) can be written and shown as in equation (2.9) (James et al 1989)
\[ L = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{reff}}}} - 2\Delta L \]  \hspace{1cm} (2.9)

\[ \Delta L = 0.412h \left( \frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258} \right) \left( \frac{w}{h} + 0.264 \right) \] \left( \frac{w}{h} + 0.8 \right) \]  \hspace{1cm} (2.10)

\[ \varepsilon_{\text{reff}} = \left( \frac{\varepsilon_r + 1}{2} \right) + \left[ \left( \frac{\varepsilon_r - 1}{2} \right) \left( 1 + \frac{12h}{w} \right)^{-1/2} \right] \]  \hspace{1cm} (2.11)

where  
- \( f_0 \) - Operating frequency
- \( c \) - Velocity of light
- \( \varepsilon_r \) - Permittivity of the dielectric substrate
- \( \varepsilon_{\text{reff}} \) - Effective permittivity of the dielectric substrate
- \( w \) - Width of the Patch
- \( L \) - Length of the Patch
- \( h \) - Thickness of the dielectric substrate
- \( \Delta L \) - extension of the length

The patch width \( w \) can be selected and as shown in equation (2.12)

\[ w = \frac{c}{2f_0} \left[ \frac{2}{\varepsilon_r + 1} \right]^{1/2} \]  \hspace{1cm} (2.12)

The input admittance at the radiating edge is given and as shown in equation (2.13)

\[ y_{\text{in}} = y_{\text{slot}} + y_0 \frac{y_{\text{slot}} + jy_0 \tan \beta (L + \Delta L)}{y_0 + jy_{\text{slot}} \tan \beta (L + 2\Delta L)} \]  \hspace{1cm} (2.13)

At resonance, \( Y_{\text{in}} = 2G \)

Based on Harrington, the conductance, \( G \) for the parallel radiator is given in equation (2.14)
\[ G = \frac{\pi w}{\eta \lambda_0} \left[ 1 - \frac{(kh)^2}{24} \right] \]  
(2.14)

\[ k = \frac{2\pi f_0}{c} \]  
(2.15)

\[ \eta = 120\pi \]  
(2.16)

where \( \eta \) - intrinsic impedance, \( G \) - conductance, \( \lambda_0 \) - operating wavelength and \( w \) - width of the patch.

### 2.3.2 Circular patch antenna

Other than the rectangular patch, the next most popular configuration is the circular patch or disk, as shown in Figure 2.3. Coaxial probe feed is easy to fabricate and match, and it has low spurious radiation. The location of feed point is determined for the given mode, so that the best impedance match is achieved.

![Geometry of the circular microstrip patch antenna](image)

**Figure 2.3** Geometry of the circular microstrip patch antenna  
(a) Topview (b) Side view
The modes supported by the circular patch antenna can be found by treating the patch, ground plane, and the material between the two as a circular cavity. As with the rectangular patch, the modes that are supported primarily by a circular microstrip antenna, whose substrate height is small $(h \ll \lambda)$ are the $TM_z$ where $z$ is taken perpendicular to the patch. As far as the dimensions of the patch are considered, there are two degrees of freedom to control (length and width) for the rectangular patch antenna. Therefore, the order of the modes can be changed by changing the relative dimensions of the width and length of the patch (width-to-length ratio). However, for the circular patch there is only one degree of freedom to control (radius of the patch).

$$r = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F} \left[ \ln \left( \frac{\pi F}{2h} + 1.7726 \right) \right] \right\}^{1/2}}$$  \hspace{1cm} (2.17)

where, \( r = \) radius of the patch

$$F = \frac{8.791 \times 10^9}{f_0 \sqrt{\varepsilon_r}}$$  \hspace{1cm} (2.18)

‘$h$’ in equation (2.17) must be in cm.

### 2.4 GEOMETRY OF THE PATCH ANTENNAS

The antenna designs are made by calculating the dimensions of the five different patch antennas; the single frequency square patch antenna, operates at frequency (2.4 GHz), the dual frequency slotted rectangular patch antenna operates at frequency (1.54 GHz, 1.83 GHz), the circular patch antenna operate at frequency (2.3 GHz), the triple frequency double layer patch antenna operate at frequency (1.54 GHz, 1.83 GHz, 2.45 GHz) and the triple frequency single layer patch antenna operates at frequency
(1.57 GHz, 1.8 GHz, 2.83 GHz). The simulation has been done by using the CST Microwave studio software. The fabrication process is started after the optimization result from the simulation. The measurement and simulation result have been compared in terms of the return loss ($S_{11}$), directivity, Voltage Standing Wave Ratio (VSWR), bandwidth and gain of the antenna.

### 2.4.1 Single frequency square patch antenna

The square patch antenna is designed to operate at a frequency of 2.4 GHz. The schematic of the square patch antenna for single frequency, on a classical ground plane, is illustrated in Figure 2.4. The ground plane lies at the bottom side of the substrate with a compact size of $45 \text{mm} \times 45 \text{mm}$. The radiating elements of the proposed antenna consist of a square patch with length $L$ and width $w$ of 27.5 mm each, and is printed on the top of an FR4 substrate with the dielectric constant, $\varepsilon_r$ of 4.4 and the substrate thickness, $h$ of 2.4 mm. The coaxial probe type Subminiature Version A (SMA) connector is used as the feed in designing the antenna. The optimized feed location has been obtained at the co-ordinate (0, 5.6). The total thickness of the antenna is only 2.47 mm.

![Single frequency square patch antenna schematic](image)

**Figure 2.4** Schematic of single frequency square patch antenna
2.4.2 Dual frequency slotted rectangular patch antenna

The schematic of the slotted rectangular patch antenna for dual frequency is shown in Figure 2.5. The ground plane lies at the bottom side of the substrate with a compact size of 60mm × 60mm. The radiating elements of the proposed antenna consist of a rectangular patch and it is printed on the top of a FR4 substrate with a relative permittivity $\varepsilon_r$ of 4.4 and a thickness $h$ of 2.4mm. The total thickness of the antenna is only 2.47mm.

The position of the coaxial probe type SMA connector that is used as the feed is very important in designing the antenna. A trial and error method is used to locate the approximate feed point, to optimize the characteristics of the designed antenna.

By using the formula given in section 2.3.1 with the value of the dielectric constant, $\varepsilon_r$ of 4.4, operational frequencies of 1.54 GHz, 1.83 GHz and the substrate thickness, $h$ of 2.4 mm the dimensions of the antenna shown in Figure 2.6 were calculated. The slotted rectangular microstrip patch antenna is of length ($L$) = 36mm, width ($w$) = 37mm and the slot(s) = 3×12.5 sq.mm.

![Figure 2.5 Schematic of slotted rectangular patch antenna for dual frequency](image-url)
2.4.3 Circular patch antenna

The design of the circular patch antenna is shown in Figure 2.7, by using the formula given in section 2.3.2 with the value of the dielectric constant, $\varepsilon_r$ of 4.4, operational frequency of 2.3 GHz and the substrate thickness, $h$ of 2.4 mm, the radius of the patch, $r$ of 20 mm. The ground plane lies at the bottom side of the substrate. The size of the ground plane and the substrate is $180 \text{ mm} \times 180 \text{ mm}$. The probe is connected to a $50\Omega$ feed point to match the patch antenna with a radius of 0.5 mm placed at $s$ of 6 mm from the center of the patch, which is very important in designing the antenna. The trial and error method is used to locate the approximate feed point, to optimize the characteristics of the designed antenna. The total thickness of the antenna is 2.47 mm.
2.4.4 Triple frequency double layer patch antenna

The schematic of the triband double layer patch antenna is shown in Figure 2.8. Two rectangular patches are printed on two stacked substrates. The upper patch resonates at the frequency of 1.54 GHz and the lower rectangular patch resonates at the frequencies of 1.83 GHz and 2.45 GHz. The same substrate for both the layers with a dielectric constant $\varepsilon_r$ of 4.4 and substrate thickness $h$ of 1.6mm has been taken. The dimensions of the upper patch are length ($L'$) of 17mm, width ($w'$) of 52mm and those of the lower patch are length ($L$) of 36mm, width ($w$) of 28mm. The double layer structure uses, in all totally seven layers. The total thickness of the antenna is 4.94mm.
2.4.5 Triple frequency single layer patch antenna

The geometry of the triband single layer patch antenna is shown in Figure 2.9. In the single layer triband microstrip patch antenna, the upper and lower patches are merged together to form an asymmetric cross structure. So it has only five layers. The first three layers from the bottom to the top are for feeding and the next one is the substrate followed by the patch. The total thickness of the patch is only 3.305mm. This whole structure will resonate at three different bands. The desired frequencies are 1.57 GHz, 1.8 GHz and 2.83 GHz. The dimensions of the two patches and the thickness of the substrate are the same as those of triband double layer patch antenna.

![Figure 2.9 Geometry of the triband single layer patch antenna](image)

2.5 RESULTS AND DISCUSSION

2.5.1 Single frequency square patch antenna

A prototype of the square patch antenna was implemented and fabricated on a 2.4mm thick FR4 substrate \((\varepsilon_r = 4.4, \tan \delta = 0.02)\). The patch is placed on the grounded dielectric substrate. The simulated and measured \(S_{11}\) of the square patch antenna is shown in Figure 2.10. It is clearly indicated that both resonate around 2.4 GHz. The simulated result shows that the resonant frequency of the patch is located at approximately 2.41 GHz, with
the $-10$ dB impedance bandwidth from about 2.366 GHz to 2.45 GHz, which represents the fractional bandwidth of 3.49%. The measured result shows that the resonant frequency of the patch is located at approximately 2.39 GHz, with the $-10$ dB impedance bandwidth from about 2.3476 GHz to 2.4365 GHz, which represents the fractional bandwidth of 3.72%. The measured gain of the conventional patch antenna is 2.6 dBi. From the simulated results, it is observed that the peak gain of the patch antenna is about 2.3 dBi. The photograph of the fabricated square patch antenna is shown in Figure 2.11, and Table 2.1 gives the comparison of the simulated and the measured results of the square patch antenna.

![Figure 2.10](image)

**Figure 2.10** $S_{11}$ of a single frequency square patch antenna
Figure 2.11  Photograph of the fabricated single frequency square patch antenna

Table 2.1  Simulated and measured results of the single frequency square patch antenna

<table>
<thead>
<tr>
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<th>Parameters</th>
<th>Single frequency square patch antenna</th>
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<tr>
<td>2</td>
<td>$</td>
<td>S_{11}</td>
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<tr>
<td>3</td>
<td>Fractional band width (%)</td>
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</tr>
<tr>
<td>4</td>
<td>Gain (dBi)</td>
<td>2.3</td>
</tr>
</tbody>
</table>

2.5.2     Dual frequency slotted rectangular patch antenna

The simulated and measured $S_{11}$ of the slotted rectangular patch antenna is shown in Figure 2.12. It is clearly indicated that the antenna has a
dual-band characteristic. The simulated result shows that the low-band resonant frequency is located at about 1.54 GHz, with the $-10 \, \text{dB}$ impedance bandwidth from about 1.47GHz to 1.658 GHz, and the high band resonant frequency is located at about 1.83 GHz, with the $-10 \, \text{dB}$ impedance bandwidth from 1.76 GHz to 1.96GHz, which represents a fractional bandwidth of 12.2% and 10.93% respectively. The measured result shows that the resonant frequency of the patch is located at about 1.54 GHz, 1.82 GHz, with the $-10 \, \text{dB}$ impedance bandwidth from about 1.425GHz to 1.629 GHz and 1.72 GHz to 1.92 GHz, which represents the fractional bandwidth of 13.25% and 10.98% respectively. The simulated and the measured maximum negative return losses at the centre frequencies are 14, 18 and 16, 17 respectively. The simulation results are validated by measurements. The photograph of the fabricated slotted rectangular patch antenna is shown in Figure 2.13, and Table 2.2 gives the comparison of the simulated and the measured results of the slotted rectangular patch antenna.

![Figure 2.12 $S_{11}$ of dual frequency slotted rectangular patch antenna](image)

**Figure 2.12** $S_{11}$ of dual frequency slotted rectangular patch antenna
Figure 2.13 Photograph of the fabricated dual frequency slotted rectangular patch antenna

Table 2.2 Simulated and measured results of the dual frequency slotted rectangular patch antenna

<table>
<thead>
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<th>Parameters</th>
<th>Dual frequency slotted rectangular patch antenna</th>
<th>Simulated</th>
<th>Measured</th>
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<td>1.83</td>
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</tr>
<tr>
<td>2</td>
<td>$</td>
<td>S_{11}</td>
<td>$(dB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-16</td>
<td>-17</td>
</tr>
<tr>
<td>3</td>
<td>Fractional band width (%)</td>
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<td>12.2</td>
<td>10.93</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>13.25</td>
<td>10.98</td>
</tr>
</tbody>
</table>

2.5.3 Single frequency circular patch antenna

The measured and simulated $S_{11}$ of the circular patch antenna is displayed in Figure 2.14. A good agreement is obtained between the
simulated and measured results for the reference antenna. The measured return loss results of the reference antenna is matched ($|S_{11}|<-10\text{dB}$) from 2.232 to 2.360 GHz, which represents a fractional bandwidth of 5.59% at the center frequency of 2.29 GHz, whereas the simulated one has a bandwidth of 5.5% at the center frequency of 2.32 GHz. The simulated and measured directivity of the patch antenna is 5.2 and 5.5 respectively. The maximum gain of the measured patch antenna is around 5.31 dBi. The radiation efficiency is one of the important parameters of the patch antenna. The antennas have radiation efficiency, of around 70%. The simulated and measured VSWR of the patch antenna are 1.12 and 1.2 respectively. The measurement results support the simulations. The photograph of the fabricated circular patch antenna is shown in Figure 2.15 and Table 2.3 gives the comparison of the simulated and the measured results of the circular patch antenna.

![Figure 2.14 S11 of circular patch antenna](image)

**Figure 2.14** $S_{11}$ of circular patch antenna
Table 2.3 Simulated and measured results of the circular patch antenna

<table>
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<th>Parameters</th>
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<td>Directivity (dBi)</td>
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<td>VSWR</td>
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2.5.4 Triple frequency double layer patch antenna

The simulated and measured $S_{11}$ of the tri-band double layer patch antenna is shown in Figure 2.16. It is clearly indicated that the antenna has a tri-band characteristic. The simulated result shows that the resonant frequency of the patch is located at about 1.54 GHz, 1.83GHz and 2.45GHz with the
fractional bandwidth of 2.27%, 2.49%, and 2.02% respectively. The measured result shows that the resonant frequency of the patch is located at about 1.57 GHz, 1.87GHz and 2.52GHz with the fractional bandwidth of 2.61%, 4.16%, and 1.99% respectively. The simulated and the measured maximum negative return losses at the centre frequencies are 14.07, 15.72, 14.56 and 18.3, 10.7, 19.4 respectively. There is a deviation of 4.73%, 4.23% and 5.26% in the center frequencies 1.54 GHz, 1.83 GHz and 2.45 GHz respectively between the measured and simulated results. This could be due to slight variations in the dielectric constant of the material used for the fabrication of the antenna. The simulated VSWR of the three desired frequencies of 1.54 GHz, 1.83GHz and 2.45GHz are 1.4, 1.3 and 1.4 respectively. The simulated radiation efficiency of the three desired frequencies is 62.9%, 54.9% and 24.36% respectively. The photograph of the fabricated triband double layer patch antenna is shown in Figure 2.17, and the simulated and measured centre frequency, bandwidth and S\textsubscript{11} of the triband double layer patch antenna are given in Table 2.4.

![Figure 2.16 S\textsubscript{11} of triband double layer patch antenna](image)
Figure 2.17  Photograph of the fabricated triband double layer patch antenna

Table 2.4   Comparison of the simulated and measured results for a triband double layer patch antenna

<table>
<thead>
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<th>Parameters</th>
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<th>Measured</th>
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<tr>
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<td>1.87</td>
</tr>
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<td>2.45</td>
<td>2.52</td>
</tr>
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<td>-14.56</td>
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<td></td>
<td></td>
<td>2.02</td>
<td>1.99</td>
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2.5.4.1  Parametric study

The schematic of the triband double layer patch antenna is displayed in Figure 2.8. Two rectangular patches are printed on two stacked substrates. The upper patch resonates at the frequency of 1.54 GHz and the lower rectangular patch resonates at the frequencies of 1.83 GHz and 2.45
GHz. To ensure a large ground plane for the upper patch, its dimension has been carefully taken to be much lesser than that of the lower patch. Thus, the lower patch operates in the lower frequency band. The double layer structure uses totally seven layers. The first three layers include the ground, the substrate and the microstrip feed line for electromagnetic coupling. The next two layers consist of the lower patch and substrate, followed by the upper patch and substrate. A parametric study of the triband double layer patch antenna on the main parameters has been done. Simulations are performed using the CST microwave studio (MWS) software based on the three dimensional Finite Integration Time Domain (FITD) method. The three desired frequencies are 1.54GHz (f1), 1.83GHz (f2) and 2.45GHz (f3).

The parameters used for analysis:

i) Dielectric constant of the substrate ($\varepsilon_r$)
ii) Height of the substrate ($h_s$)
iii) Length of the upper patch ($L'$)
iv) Width of the upper patch ($w'$)
v) Length of the lower patch ($L$)
vi) Width of the lower patch ($w$)
vii) Height of the feed ($h_f$)
viii) Offset of the feed ($f_o$)
ix) Offset of the patch ($P_o$).

To optimize the design, a parametric study was performed. To begin with, the effect of the dielectric constant of the substrate ($\varepsilon_r$) was studied. For lower values of the dielectric constant, the center frequency shifts to a lower value with an increase in the dielectric constant. After reaching a particular point, the center frequency remains constant irrespective of the $\varepsilon_r$ value. The effect of the dielectric constant of the substrate versus frequency is shown in Figure 2.18. The lower frequency f1 is almost independent of the substrate height ($h_s$) variations. The relationship of the other two frequencies
f2 and f3 with the substrate height variations is almost the same. The effect of substrate height versus frequency is depicted in Figure 2.19. The lower frequency f1 depends on the upper patch length variations. The other two frequencies are independent of the upper patch length variations. When the upper patch length increases, the center frequency value (f1) decreases. The effect of the upper patch length versus frequency is displayed in Figure 2.20. The relative sizes of the upper and lower patches are selected in such a way, that the three desired frequency bands should be excited simultaneously, so that the upper patch width (w’) has an effect on the other frequencies too. The effect of the upper patch width versus frequency is shown in Figure 2.21. The lower two frequencies f1 and f2 are independent of the lower patch length (L). But the frequency f3 depends on L. The center resonant frequency f3 decreases with an increase in the lower patch length. The effect of the lower patch length versus frequency is shown in Figure 2.22. The frequency f2 depends only on the lower patch width (w) variations. The other two frequencies are independent of the lower patch width variations. When the lower patch width increases, the center frequency value f2 decreases. The effect of the lower patch width versus frequency is shown in Figure 2.23. The effect of the feed is now studied. The feed height has only a minor effect on the frequency shift. The frequency f3 decreases with an increase in the lower values of the feed height h_f, after that, it remains constant. The effect of the feed height versus frequency is shown in Figure 2.24. As the feed position changes, there is not much change in the center frequency, but the return loss value changes up to a particular point. Beyond which triband double layer patch will not work properly. The effect of the feed offset versus frequency is shown in Figure 2.25. The patch offset (P_o) has a great effect on frequency f2. But frequencies f1 and f3 are almost independent of the patch offset. The effect of the patch offset versus frequency is shown in Figure 2.26.
Figure 2.18  Effect of variation of the dielectric constant on frequency

Figure 2.19  Effect of variation of the substrate height on frequency
Figure 2.20 Effect of length variation of the upper patch on frequency

Figure 2.21 Effect of width variation of the upper patch on frequency
Figure 2.22 Effect of length variation of the lower patch on frequency

Figure 2.23 Effect of width variation of the lower patch on frequency
Figure 2.24 Effect of variation of the feed height on frequency

Figure 2.25 Effect of variation of the feed offset on frequency
2.5.5 Triple frequency single layer patch antenna

The simulated and measured $S_{11}$ of the triband single layer patch antenna is shown in Figure 2.27. It is clearly indicated that the antenna has a tri-band characteristic. The simulated result shows that the resonant frequency of the patch is located at about 1.55 GHz, 1.73GHz and 2.82GHz with the fractional bandwidth of 2.37%, 3.4%, and 2.02% respectively. The measured result shows that the resonant frequency of the patch is located at about 1.57GHz, 1.8GHz and 2.83GHz with the fractional bandwidth of 2.43%, 3.39%, and 2.05% respectively. The simulated and the measured maximum negative return losses at the centre frequencies are 13.95, 13.59, 17.84 and 13, 25.8, 9, respectively. The simulated VSWR of the three desired frequencies of 1.55GHz, 1.73GHz and 2.82GHz are 1.50, 1.52, and 1.29 respectively. The radiation efficiency of the three desired frequencies is 55.2 %, 55.7 % and 56.5 % respectively. The photograph of the fabricated triband single layer patch antenna is shown in Figure 2.28. The simulated and measured centre frequency, bandwidth and return loss of the triband single
layer patch antenna are given in Table 2.5. Finally, Table 2.6 gives the measured results of all the patch antennas.

Figure 2.27 $S_{11}$ of triband single layer patch antenna

Figure 2.28 Photograph of the fabricated triband single layer patch antenna
Table 2.5 Comparison of the simulated and measured results for a triband single layer patch antenna

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Parameters</th>
<th>Triband Single layer patch Antenna</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Center frequency (GHz)</td>
<td>1.55, 1.73, 2.82</td>
<td>1.57, 1.8, 2.83</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-13.95, -13.59, -17.84</td>
<td>-13, -25.8, -9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fractional bandwidth (%)</td>
<td>2.37, 3.4, 2.02</td>
<td>2.43, 3.39, 2.05</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.6 Comparison of the measured results of all the five designed patch antennas

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Parameters of Patch Antenna</th>
<th>square</th>
<th>rectangular slotted</th>
<th>circular</th>
<th>triband double layer</th>
<th>triband single layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Center frequency (GHz)</td>
<td>2.39</td>
<td>1.54, 1.82</td>
<td>2.29</td>
<td>1.57, 1.87, 2.52</td>
<td>1.57, 1.8, 2.83</td>
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<tr>
<td>2</td>
<td></td>
<td>-35.7</td>
<td>-16, -17</td>
<td>-15.3</td>
<td>-18.3, -10.7, -19.4</td>
<td>-13, -25.8, -12</td>
</tr>
<tr>
<td>3</td>
<td>Fractional Band width (%)</td>
<td>3.72</td>
<td>13.25, 10.98</td>
<td>5.59</td>
<td>2.61, 4.16, 1.99</td>
<td>2.43, 3.39, 2.05</td>
</tr>
<tr>
<td>4</td>
<td>Gain (dBi)</td>
<td>2.6</td>
<td>3.2, 1.3</td>
<td>5.31</td>
<td>2.8, 2.1, 1.2</td>
<td>2.4, 2.2, 2.5</td>
</tr>
<tr>
<td>5</td>
<td>Efficiency (%)</td>
<td>63.0</td>
<td>69, 58</td>
<td>70.05</td>
<td>62.9, 54.9, 24.36</td>
<td>55.2, 55.7, 56.5</td>
</tr>
</tbody>
</table>

2.6 SUMMARY

The impedance bandwidth is investigated for several different patch antennas with various ground sizes. They are, the single frequency square patch antenna that operates at 2.4 GHz, the dual frequency slotted rectangular patch antenna that operates at 1.54 GHz, 1.83 GHz, the circular patch antenna
at 2.3 GHz, the triple frequency double layer patch antenna and the triple frequency single layer patch antenna. It is important in many applications for the antennas to be compact and small in size, in addition to being low-profile. To improve the performances such as gain, bandwidth, radiation efficiency and directivity of the antenna, Electromagnetic BandGap structures (EBG) are used. Three types of patch antennas (square, slotted rectangular and circular) are chosen, and they are surrounded by three different EBG structures (mushroom-like, Spiral-like and ring-like) with different sizes of the ground plane and operating at single and dual frequencies. Each represents a different shape, and is fine tuned to exhibit its own resonant frequencies, which are placed above the grounded dielectric substrate. To avoid the complexity, the patch antennas with single substrate structures are chosen, and are incorporated with different EBGs. The above chosen antennas are very compact in nature, and their simulated results show good agreement with the measurements. The next chapter describes the concept, principles of operation, geometries, and the design and development of various EBG structures.