The experimental and simulated investigations towards the development of compact gain enhanced microstrip antennas are discussed in this chapter. Principle of stacking is effectively implemented and the position of the upper parasitic patch is offsetted to enhance the gain of single band and broadband square patch antennas, without deteriorating the impedance matching performance of the antenna. Two single band prototypes along with the two slotted broadband designs discussed in the previous chapter are taken here for consideration. Experimental and simulated studies for explaining the gain enhancement mechanism are described in detail in this chapter.
5.1 An overview of gain enhancement techniques for microstrip patch antennas

Researchers all over the world have extensively studied the gain enhancement techniques for microstrip patch antennas. Siew Bee Yeap et al. increased the gain of microstrip antennas [1] by partially removing the substrate over which the patch antenna is fabricated. Partial substrate removal reduces the losses due to surface waves and dielectric substrates. It can enhance the gain up to 2.7 dBi. A very simple technique to enhance the gain of microstrip antennas is to load the antenna with a superstrate. The measured gain will be maximum, when the superstrate thickness is equal to the one quarter of the wavelength of the wave propagating in the superstrate. Chih-Yu Huang et. al. proposed a compact superstrate loaded broadband microstrip patch antenna [2] with enhanced gain performance. Here, the bandwidth enhancement and size reduction is achieved by chip resistor loading. Gain enhancement to compensate the reduction in gain due to reduction in size of the patch and ohmic loss of chip resistor loading is achieved by the loading of a high permittivity superstrate layer.

Multiple resonator model is an effective technique to enhance the gain of microstrip antennas. It can be done by implementing the patch resonators in a plane as an array or can be stacked vertically. The microstrip antenna arrays [3-6] can enhance the gain of the structure by utilizing a larger area. Microstrip yagi antenna is a modification of the microstrip array which can be used for enhancing the gain of the antenna. Gerald DeJean proposed a microstrip Yagi array configuration [7] utilizing seven microstrip elements, one as the driven element, two reflector elements and four director elements. It can enhance the gain up to 15.6 dBi and it exhibits good F/B ratio around 8-10 dB. But the major disadvantage of such designs is that they are very bulk in size and so they cannot be integrated with microwave monolithic integrated circuits.
So stacking is a reasonable choice for enhancing the gain of microstrip antennas. Stacking can be implemented for increasing the bandwidth of the antenna and also for enhancing the gain of the structure. Nishiyama et al. [8] has extensively studied the effect of stacking on microstrip antenna characteristics. They concluded that when the size of the parasitic patch is nearly equal to the fed patch, and the distance between the fed patch and the parasitic patch is approximately 0.1 wavelengths, then the bandwidth is increased. When the distance is approximately half wavelength, then gain enhancement is achieved. They have conducted experimental and simulation studies by varying the spacing between the feed patch and the parasitic patch. It was observed that the space between the feed patch and the parasitic patch acts like a cavity and when the distance between the feed patch and the parasitic patch becomes equal to 0.05λ, the electric field between the patches consists of $E_z$ component mainly and the cavity resonates in the $TM_{10}$ mode. If the distance between the patches is held at 0.25λ, the $E_z$ component is found to be decreasing, while the $E_x$ component increases. When the distance is held at 0.5λ, the electric field between the patches consists of the $E_x$ components and the space between the patches acts like a leaky cavity, which mainly contributes for the radiation. The fringing fields between the patches and the ground become in phase and it enhances the radiation from the antenna, thereby increasing the gain. They have conducted experiments with two parasitic patches; the first parasitic patch for increasing the bandwidth and the other for increasing the gain of the antenna [8]. But the major drawback of stacking is that it occupies a larger volume, since the distance between the patches is of the order of half wavelengths.

The major challenge in the stacked array antenna design is to reduce the volume of the antenna while maintaining good impedance matching and
enhanced gain performance. This chapter describes a simple and effective technique to reduce the volume of the stacked antennas without deteriorating impedance matching performance. Stacking is successfully implemented and the position of the parasitic patch is offsetted to enhance the gain performance of the antenna without increasing the height of the parasitic resonator. Offsetting the position of the upper parasitic patch makes the space between the two patches as a leaky cavity and more fringing fields are observed as compared to the stacked antennas without offset. The fringing fields of the lower and upper patches become in phase and the fields produced by them get added up in the far field giving a high gain at the far field.

A single band square microstrip antenna working around 2.63 GHz and the broadband strip loaded tilted square slotted and polygonal slotted antennas discussed in chapter 4 are taken here for consideration. This technique is comparatively easier to fabricate and is devoid of spacers to support the parasitic patch since the parasitic patch is loaded at a height which is equal to the height of the FR4 substrate. Simulated fringing electric field models are discussed in detail for explaining the gain enhancement mechanism for the antennas. The section starts with an electromagnetically coupled square patch antenna. Then its stacked configurations, with and without offset, along with the comparison study with a two element array configuration, are discussed. Finally, the stacked offset configurations of the tilted square slot loaded and polygonal slot loaded broadband antennas are discussed.

5.2 Electromagnetically coupled square patch antenna

An electromagnetically coupled square patch antenna is discussed in this section. The reflection characteristics of this antenna is taken as the reference, since it acts as the feed patch for the stacked configuration described in the
preceding sections. The square patch antenna having a size of $L_1 \times L_1$ mm$^2$ is fabricated on a substrate of dielectric constant 4.2. The total height of the antenna is found to be 3.2mm including the feed substrate. The patch antenna along with the parameters is depicted in fig. 5.1.

The antenna is excited using a 50$\Omega$ microstrip transmission line with feed offset parameter $L_2$ from the right edge of the patch and its length is denoted by $L_f$. The ground plane dimension is denoted as $L_g \times W_g$.

The reflection characteristics of the antenna are shown in fig. 5.2. The fundamental resonance of the antenna is found to be at 2.63 GHz with 4% bandwidth. The antenna parameters are held at $L_1=27$mm, $L_f=17$mm, $L_2=6.75$mm, $W_f=3$mm, $L_g=80$mm, $W_g=54$mm and h=1.6mm. The reflection
coefficient value at the resonance is found to be -21.6 dB and the -10 dB bandwidth of the antenna is 110 MHz.

The experimental and simulated radiation patterns of the antenna at the resonant frequency are shown in fig.5.3 and fig.5.4 respectively. It can be concluded that the antenna offers broadside radiation coverage and the pattern maximum lies along the on-axis of the antenna. The cross polar isolation is found to be 10 dB for both the XZ and YZ planes. The estimated gain of the antenna is shown in fig.5.5. The antenna shows a maximum gain of 2.34 dBi at the resonant frequency. The efficiency of the antenna is measured and is found to be 64%.
5.3 Electromagnetically coupled stacked square patch antenna without offset

This section deals with the stacked configurations of the electromagnetically coupled square patch antenna discussed in the previous section. The section starts with the stacked configuration without any offset in the position of the upper patch and then proceeds into the offset configurations. The geometry of the stacked antenna with the associated parameters is shown in fig. 5.6. Here the separation between the fed patch and the parasitic patch is held at 1.6mm, which is the dielectric thickness of the FR4 substrate. Initially, the offset parameter is made to be $L_0=0\text{mm}$.

![Fig. 5.6 Geometry of the stacked square patch antenna](image)

The antenna parameters are found to be $L_1=27\text{mm}$, $L_f=17\text{mm}$, $L_2=6.75\text{mm}$, $W_f=3\text{mm}$, $L_g=80\text{mm}$, $W_g=54\text{mm}$ and $h=1.6\text{mm}$. Care should be taken to mount the parasitic patch over the feed patch. A slight shift in the
position of the parasitic patch will result in a change in resonant frequency and hence degradation of impedance matching properties of the antenna.

The reflection characteristics of the antenna are shown in fig. 5.7. The measured and simulated values are in good agreement. The antenna is resonating at 2.48 GHz with the reflection coefficient value of –33 dB and has 5.6% bandwidth (-10 dB bandwidth of 140 MHz) around the resonance. It is observed that the resonant frequency of this stacked configuration is found to be lower than that of the square patch antenna without the parasitic patch as discussed in the previous section. This lower shift is due to the fact that the placement of the upper patch affects the fringing fields of the lower patch, thereby increasing the effective dielectric constant of the lower patch.

The XZ and YZ plane experimental and simulated 3D far field radiation patterns of the proposed antenna are shown in fig. 5.8 and fig. 5.9 respectively. It is observed that the antenna shows broadside radiation characteristics with the pattern maximum directed along the bore sight. The cross polar isolation is found to be 10 dB for both the XZ and YZ planes.

The gain of the stacked antenna is shown in fig. 5.10. The antenna shows a maximum gain of 1.78 dBi at 2.48 GHz. The radiation efficiency of the antenna is found to be 38% at the resonance. The reduction in the gain of the antenna can be well explained using the simulated electric field distributions of the antenna. A comparison study of the fringing electric field distributions of the simple patch antenna, stacked patch antenna with and without offset are described in detail in section 5.4.4.
5.3.1 Effect of parasitic loading height

In this section the effect of parasitic loading height on the resonant and radiation characteristics of the stacked patch antenna are studied. The resonant frequency and the gain are the major parameters under consideration. In order to perform the height variation studies, the stacked patch antenna with the geometrical parameters $L_1=27\text{mm}$, $L_2=6.75\text{mm}$, $L_f=17\text{mm}$, $L_g=80\text{mm}$ and $W_g=54\text{mm}$ printed on the FR4 epoxy substrate is taken into consideration for simulation.
The effect of the stacking height on the reflection characteristics is plotted in fig. 5.11. The height is varied from 0.8mm to 4mm in steps of 0.4mm. It is observed that increase in the stacking height lowers the resonant frequency. Corresponding to the height variation from 0.8mm to 4mm, the resonant frequency shift is from 2.56 GHz to 2.37 GHz. It is observed that corresponding to a stacking height of 0.8mm, the resonant frequency is found to be 2.56 GHz and increase in the stacking height decreases the resonant frequency. Good matching is observed when the stacking height is equal to 1.6mm. Increase in stacking height above 1.6mm deteriorates impedance matching gradually. The cause of the degradation in impedance matching is well explained using the input impedance variation of the antenna. The input impedance variation of the stacked antenna with stacking height is shown in fig. 5.12. It is observed that increasing the height of the parasitic patch will decrease the real part of the input impedance and due to the decrease in the coupling between the patches, the imaginary part of the impedance is shifted towards the inductive side.

![Fig. 5.11 Effect of stacking height on reflection characteristics](image-url)
The variation of the gain of the stacked square patch antenna without offset against the stacking height is studied and is tabulated in table 5.1. For a stacked microstrip patch antenna, increase in the stacking height increases the gain of the antenna. The same observation is valid here also. The gain of the simple square patch antenna without the parasitic patch is also taken at the same feed point as that of the stacked antenna without offset as a reference. The
maximum gain achieved for the stacked configuration is only 2.52 dBi at a stacking height of 2.4mm. Increasing the height above 2.4 mm deteriorates the matching performance of the antenna and hence gain decreases gradually. It is observed that the stacking height above 1.6mm can only give an enhanced gain as compared to the standard square patch antenna.

### Table 5.1 Height Variation Study

<table>
<thead>
<tr>
<th>Height, mm</th>
<th>Resonant frequency, GHz</th>
<th>Gain, dBi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Single patch)</td>
<td>2.63</td>
<td>2.3600</td>
</tr>
<tr>
<td>0.4</td>
<td>2.6</td>
<td>2.1800</td>
</tr>
<tr>
<td>0.8</td>
<td>2.56</td>
<td>2.1700</td>
</tr>
<tr>
<td>1</td>
<td>2.54</td>
<td>2.1600</td>
</tr>
<tr>
<td>1.2</td>
<td>2.52</td>
<td>2.2300</td>
</tr>
<tr>
<td>1.4</td>
<td>2.51</td>
<td>2.2900</td>
</tr>
<tr>
<td>1.6</td>
<td>2.5</td>
<td>2.3200</td>
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<tr>
<td>2</td>
<td>2.47</td>
<td>2.5000</td>
</tr>
<tr>
<td>2.4</td>
<td>2.46</td>
<td>2.5200</td>
</tr>
<tr>
<td>2.8</td>
<td>2.44</td>
<td>2.5100</td>
</tr>
<tr>
<td>3.2</td>
<td>2.43</td>
<td>2.4700</td>
</tr>
<tr>
<td>3.6</td>
<td>2.42</td>
<td>2.3300</td>
</tr>
</tbody>
</table>

### 5.4 Stacked Offset Patch Antenna Configurations

In this section, offsetting technique is successfully implemented on the stacked square patch antenna configuration discussed in the previous section. The upper parasitic patch is offsetted in the +Y direction by a displacement of $L_0$. The geometry of the design is shown in fig. 5.6. Offsetting procedure should
Investigations on stacked offset single band and broadband gain enhanced microstrip antennas

be done with maximum care, because any misalignment of the parasitic patch adversely affects the resonant and radiation behavior of the antenna.

5.4.1 Offset variation studies

The initial aim is to find out the change in the resonant frequency of the structure with offset parameter L₀. A detailed parametric analysis has been carried out to find out the effect of offset parameter on the resonant frequency and is illustrated in fig.5.13. The offset parameter ‘L₀’ is varied up to 7mm in steps of 1mm.

![Fig. 5.13 Effect of offset parameter L₀](image)

The other antenna parameters are kept at L₁=27mm, L₂=6.75mm, Lₚ=17mm, Lₐ=80mm and Wₐ=54mm. It is noted that as L₀ increases, the resonant frequency is found to be decreasing.

5.4.2 Stacked offset antenna with L₀=3mm

The experimental realization of the offset configurations were taken for two configurations, one with offset parameter L₀=3mm and the other with
$L_0=5\text{mm}$. Initially the stacked antenna configuration with offset parameter $L_0=3\text{mm}$ is taken into consideration. The geometric parameters of the antenna are found to be $L_1=27\text{mm}$, $L_2=6.75\text{mm}$, $L_f=17\text{mm}$, $L_0=3\text{mm}$, $L_g=80\text{mm}$ and $W_g=54\text{mm}$. The antenna is printed on the same FR4 substrate and fed via a printed microstrip transmission line fabricated using the same substrate as that of the stacked antenna without offset.

The antenna is found to be resonating at $2.36\text{GHz}$ with a reflection coefficient value of $-21.5\text{dB}$ as depicted in fig. 5.14. The $-10\text{dB}$ bandwidth of the antenna is found to be $110\text{MHz}$ with $4.6\%$ bandwidth around the resonance. As compared to the antenna without offset, the antenna is resonating at a lower resonating frequency with $120\text{MHz}$ frequency difference.

The gain of the antenna is measured and it is illustrated in fig.5.15. It is interesting to note that the antenna has a peak gain of $4.49\text{dBi}$ at the resonating frequency. The experimental and simulated radiation patterns of the antenna at the resonant frequency are shown in fig.5.16 and fig.5.17 respectively. The cross polar isolation is found to be $8.5\text{dB}$ in both the planes. The $3\text{dB}$ beamwidths are found to be $71^\circ$ and $96^\circ$ in the XZ and YZ planes respectively.
5.4.3 Stacked offset antenna with $L_0=5\text{mm}$

Finally, stacked offset patch antenna with offset parameter $L_0=5\text{mm}$ is taken into consideration. The reflection and gain characteristics of the proposed design are shown from fig. 5.18 and fig. 5.19 respectively. The antenna parameter are found to be $L_1=27\text{mm}$, $L_2=6.75\text{mm}$, $L_f=17\text{mm}$, $L_0=5\text{mm}$, $h=1.6\text{mm}$, $L_g=80\text{mm}$ and $W_g=54\text{mm}$.

The antenna is found to be resonating at 2.3 GHz with a -10 dB bandwidth of 100MHz and the reflection coefficient value at the resonance is found to be $-22\text{dB}$. The antenna has a maximum gain of 4.8 dBi at the resonant frequency which is greater than twice as that of the antenna without offset in the position of the upper patch. The experimental and the simulated 3D radiation patterns of the antenna at the resonant frequency are shown in fig. 5.20 and fig. 5.21 respectively. It is observed that the antenna is showing broadside radiation coverage with a cross polar isolation of 7.7 dB and 5.4 dB in the XZ and YZ planes respectively.
The previous sections deal with the stacked configurations of square patch antenna with and without offset. This section gives an elaborate study of the electric field distributions of the antennas. It gives an idea about the radiation characteristics of the antennas and the reason for gain enhancement is clearly explained here. A comparison study on the radiation patterns of the different stacked configurations discussed in the previous sections is also included. The electric field distributions of the simple patch antenna, stacked patch antenna with \( L_0 = 0 \text{mm} \) and \( h = 1.6 \text{mm} \) and stacked patch antenna with \( L_0 = 5 \text{mm} \) and \( h = 1.6 \text{mm} \) are illustrated in fig. 5.22. It is observed that for a simple square patch antenna, the fringing fields along the radiating edges of the patch acts like two slots separated
by half wavelength which aids the radiation mechanism and is shown in fig. 5.22(a). But the placement of the upper parasitic patch affects the fringing fields of the fed patch and if the two patches are very close to each other, the space between the patches acts like strong cavity and a small fringing field is observed along the periphery of the patch. This gives reduced radiation and hence gain of the antenna is reduced. Offsetting the parasitic patch makes the cavity leaky and more fringing fields are observed along the periphery of the patches. Here the \( E_x \) component dominates than that of the \( E_y \) component making polarization along the X-axis and hence it gives an enhanced radiation resulting in a high gain as compared to the simple patch antenna and the stacked antenna without offset. The offset in the position of the upper parasitic patch decreases the cross polar isolation slightly in both the planes. This is because of the enhanced radiation provided by the \( E_y \) component in the fringing field and it can be best understood by looking into the fringing electric field pattern shown in fig.5.22 (c). Also the increase in offset parameter increases the 3 dB beamwidth in the YZ plane gradually.

Fig. 5.22 Fringing Electric field distributions of the antennas a) Single patch antenna, b) Stacked patch antenna with \( L_0=0\)mm and \( h=1.6\)mm and c) Stacked patch antenna with \( L_0=5\)mm and \( h=1.6\)mm
5.5 The two element array: a comparison study

In this section, a comparative study of the radiation performance of the stacked offset square patch antenna with that of a two element array is carried out. The same square patch antenna used for the construction of the stacked offset patch antenna configuration act as the basic element of the array configuration. The two elements are fed centrally through the Wilkinson power divider arrangement fabricated on FR4 substrate of dielectric constant 4.2. The inter element spacing is made to be half wavelength. The geometry of the proposed two element array antenna is shown in fig. 5.23. The geometrical parameters of the antenna are $L_1=27\text{mm}$, $L_f=13\text{mm}$, $L_s=36\text{mm}$, $L_g=85\text{mm}$ and $W_g=80\text{mm}$, $h=1.6\text{mm}$ and $\varepsilon_r=4.2$.

![Diagram of the two element array configuration](image)

Fig. 5.23 Geometry of the two element array configuration
The experimental and simulated reflection characteristics of the proposed array antenna configuration are shown in fig. 5.24. It is observed that the antenna is resonating at 2.5 GHz. The antenna has a reflection coefficient value of -18.7 dB at the resonance and is exhibiting 4.3% bandwidth from 2.45 GHz to 2.56 GHz. The gain of the antenna is computed and it has a maximum gain of 5.3 dBi at the resonance.

The XZ and YZ plane measured radiation patterns of the antenna are shown in fig. 5.25. It is observed that the antenna exhibits a cross polar isolation of 17.5 dB for both the planes and the 3 dB beamwidth is found to be 67° for both the planes.

The experimental gain chart for the fabricated designs is shown in fig. 5.26. It is noted that the stacked antenna without any offset in the position of the upper parasitic patch shows a gain of 1.69 dBi at the resonant frequency. It is noted that offsetting the position of the upper patch lowers the resonant frequency, but it enhances the gain performance of the antenna. The antenna with offset parameter \( L_0 = 3 \text{mm} \) is showing a gain of 4.49 dBi whereas the antenna with \( L_0 = 5 \text{mm} \) is showing a maximum gain of 4.8 dBi. It is found that...
increase in \( L_0 \) increases the gain of the antenna. The two element array on the other hand shows a maximum gain of 5.3 dBi, but it occupies a larger volume. It is worthwhile to note that the stacked antenna with \( L_0=5\text{mm} \) shows a comparable gain performance as compared to the two element array configuration while maintaining satisfactory radiation and matching characteristics with an added advantage of compact mode of operation. It gives a volume reduction of 24.78 % as compared to the two element array configuration.

![Graph showing measured gain of fabricated antennas](image)

**Fig. 5.26 Measured gain of the fabricated antennas**

The experimental radiation patterns of the stacked antenna with \( L_0=0\text{mm} \) and \( h=1.6\text{mm} \), stacked offset antenna with \( L_0=3\text{mm} \) and \( h=1.6\text{mm} \), stacked offset antenna with \( L_0=5\text{mm} \) and \( h=1.6\text{mm} \) and the array antenna configurations at the resonant frequencies are depicted in fig. 5.27. It is observed that for the stacked antenna without any offset in the position of the upper patch, -10 dB cross polar isolation is observed for both the planes. It shows a 3 dB beamwidth of 74° in the XZ plane and 67° in the YZ plane. The offset in the position of the upper parasitic patch decreases the cross polar
isolation slightly in both the planes. This is because of the enhanced radiation provided by the $E_y$ component in the fringing field and it can be best understood by looking into the fringing electric field pattern shown in fig. 5.22(c). Also the increase in offset parameter increases the 3 dB beam width in the YZ plane gradually. When $L_0=3\text{mm}$, the cross polar isolation is found to be 8.5 dBi for both the planes. The 3 dB beamwidths are found to be $71^{\circ}$ and $96^{\circ}$ in the XZ and YZ planes respectively.

For $L_0=5\text{mm}$, the cross polar isolation is of the order of 7 dB and the antenna shows a 3 dB beamwidth of $77^{\circ}$ in the XZ plane and $129.5^{\circ}$ in the YZ plane. For the two element array configuration, a high cross polar isolation is observed and is of the order of 17.5 dB for both the planes. The 3 dB beamwidth is found to be $67^{\circ}$ for both the planes.

![Radiation characteristics of the antennas](image)

Fig. 5.27 Radiation characteristics of the antennas a) stacked patch antenna without offset, b) stacked offset antenna with $L_0=3\text{mm}$, c) Stacked offset patch antenna with $L_0=5\text{mm}$ and d) two element array configuration
The important conclusions arrived from the above studies are summarized below:

- Principle of offsetting can be effectively applied on the stacked single band antenna configuration to achieve high gain performance without deteriorating the impedance matching performance of the antenna.

- In conventional stacked high gain antennas, gain enhancement is achieved by stacking the parasitic patch at a height equal to the half wavelength of the resonating frequency. The offsetting technique greatly reduces the volume of the antenna without deteriorating the impedance matching performance of the antenna.

- The single band design working around 2.3 GHz has a stacking height of the order of $0.025\lambda_g$, where $\lambda$ is the guided wavelength corresponding to the resonant frequency of the antenna and gain of the antenna is found to be 4.8 dBi.

Based on the above important conclusions, the offset stacking technique is applied to the two broadband designs depicted in chapter 4 and their detailed studies are discussed in the following sections.

### 5.6 Stacked offset broadband microstrip patch antennas

In this section, principle of stacking and parasitic patch offsetting is successfully implemented for strip loaded tilted square slot loaded and polygonal slot loaded broadband microstrip antenna designs discussed in chapter 4.

#### 5.6.1 Stacked Tilted Square Slot loaded broadband patch antenna with zero offset

The broadband strip loaded patch antenna discussed in chapter 4 is stacked with the same structure with zero offset in the position of the parasitic
Investigations on stacked offset single band and broadband gain enhanced microstrip antennas

upper patch. The experimental and simulation studies of the structure are discussed in detail in this section.

5.6.1.1 Antenna Geometry

The geometry of the proposed antenna is shown in fig. 5.28. The antenna consists of strip loaded tilted square slotted antenna as the lower patch. The dimensions of this fed patch are found to be $L_1=35\text{mm}$, $L_2=17.5\text{mm}$, $L_3=7.8\text{mm}$, $W=2\text{mm}$ and $L_f=10.5\text{mm}$. The ground plane dimension is selected to be $44\times55\text{mm}^2$. The patch is fabricated on a substrate of dielectric constant 4.2 and thickness 1.6mm. The antenna is electromagnetically coupled using a $50\Omega$ microstrip transmission line. The transmission line is fabricated using the same substrate. The same patch antenna fabricated on the same substrate is stacked over the initial antenna so that the total height of the antenna is found to be 4.8mm, including the transmission line. The offset parameter is made to be $L_0=0\text{mm}$.

Fig. 5.28 Geometry of the antenna
5.6.1.2 Reflection Characteristics

Fig. 5.29 shows the reflection characteristics of the stacked antenna with zero offset in the position of the upper parasitic patch. The antenna has a 2:1 VSWR bandwidth of 32.51% from 4.07 GHz to 5.65 GHz. It is understood that placement of the upper patch shifts all the resonant frequencies to the lower side. This lower shift is due to the increase in the effective dielectric constant of the driven patch because the parasitic patch affects the fringing field of the driven patch.

![Reflection Characteristics](image)

Fig. 5.29 Reflection characteristics of the antenna without offset

It is observed that the minor resonance around 5 GHz for the antenna without the parasitic patch is found to be predominant for the stacked configuration and it is found to be at 4.8 GHz. The other resonances are found to be around 4.3 GHz, 5.1 GHz and at 5.4 GHz.

5.6.1.3 Effect of stacking height

In order to study the effect of the parasitic patch height on antenna reflection characteristics, a thorough parametric analysis has been performed.
Fig. 5.30 shows the effect of stacking height on antenna reflection characteristics. It is found that the parasitic patch height majorly affects the matching for the higher resonant frequencies and the lower resonance is found to be unaffected. When the stacking height exceeds 3.2mm, the lower two resonances will be predominant and the matching for the higher resonance is found to be deteriorating.

5.6.1.4 Radiation patterns and gain of the antenna

The measured radiation patterns of the antenna at the resonant frequencies are shown in the fig. 5.31. It is observed that the XZ plane radiation patterns are almost identical throughout the entire frequency of operation. For all the resonances, the XZ copolar pattern shows lesser power as compared to the corresponding YZ copolar pattern. The simulated 3D radiation patterns of the antenna at the resonant frequencies are shown in fig. 5.32. The cross polar isolation throughout the entire frequency band of operation for both the planes is studied in detail and is shown in table 5.2.
Fig. 5.31 Radiation patterns of the antenna
Fig. 5.32 3D Radiation patterns of the antenna at a) 4.3 GHz, b) 4.8 GHz, c) 5.1 GHz and d) 5.4 GHz

Table 5.2 Cross polarization characteristics of the antenna

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>Cross polarization (dB)</th>
<th>XZ Plane</th>
<th>YZ Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>15</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>20</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>30</td>
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</tr>
<tr>
<td>4.7</td>
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<td>5</td>
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</tr>
<tr>
<td>4.9</td>
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<td>5.5</td>
<td>34.7</td>
<td>34.7</td>
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</tr>
</tbody>
</table>
The gain of the antenna is shown in fig. 5.33. The maximum gain of the antenna is found to be 8.13 dBi at 5.5 GHz. The average gain of the antenna over the band is only 6.56 dBi.

Fig. 5.33 Gain of the antenna

5.7 The stacked offset microstrip antenna

The stacked offset microstrip patch antenna discussed in section 5.7.1 cannot increase the gain considerably, especially for the centre frequencies in the band of operation. This is due to the strong coupling between the feed patch and the parasitic patch. Gain enhancement can be achieved by making the cavity leaky. This is accomplished by offsetting the position of the upper patch along +Y-direction. The experimental and simulation studies guiding into the gain enhancement technique of the antenna are discussed in detail in this section.

5.7.1 Antenna geometry

The geometry of the proposed offset stacked microstrip patch antenna is shown in fig. 5.28. The antenna is obtained by offsetting the position of the
upper patch along +Y direction by a distance $L_0$ as compared to the antenna without offset. The other antenna parameters remain the same as that of the stacked antenna without offset. The antenna parameters at the optimum design are found to be $L_1=35\text{mm}$, $L_2=17.5\text{mm}$, $L_3=7.8\text{mm}$, $W=2\text{mm}$, $L_f=10.5\text{mm}$, $L_0=4\text{mm}$ and $h=1.6\text{mm}$ at the optimum design. The antenna is fabricated on a substrate of dielectric constant 4.2.

**5.7.2 Reflection characteristics**

The reflection characteristics of the stacked offset microstrip patch antenna at the optimum offset distance are shown in fig. 5.34. The antenna has a 2:1 VSWR bandwidth of 34.9 % from 3.73 GHz to 5.73 GHz. The wide bandwidth is obtained by merging five resonances centered around 3.8 GHz, 4.27 GHz, 4.76 GHz, 5.1 GHz and 5.49 GHz. It is an interesting observation that the offset in the position of the upper patch introduces an additional lower new resonance around 3.8 GHz which merges together with the other resonances to enhance the bandwidth of the antenna.

![Reflection Coefficient Curve](image)

**Fig. 5.34 Reflection characteristics of the stacked offset microstrip antenna**
5.7.3 Effect of offset parameter

In order to study the effect of offset parameter $L_0$ on antenna reflection characteristics, a rigorous parametric analysis has been performed. Fig. 5.35 shows the effect of $L_0$ on antenna reflection characteristics.

![Effect of offset parameter $L_0$ on reflection characteristics](image)

It is observed that offsetting the parasitic patch introduces a lower resonance and as $L_0$ increases the newly generated resonance shifts towards the lower side from the 4.3 GHz resonance. No predominant shift in the other resonant frequencies is observed. An optimum offset parameter of $L_0=4\text{mm}$ is selected to attain the maximum bandwidth of the antenna. It is concluded that the offset structure itself acts as the origin of the newly generated resonance as in [9].

5.7.4 Upper substrate height variation

Here, the effect of the upper substrate height on the reflection characteristics of the antenna is studied. It is shown in fig. 5.36. It can be seen that the antenna attains broadband operation when the substrate thickness is
increased above 1mm. Below h=1mm, the resonances are not properly merged. The maximum available bandwidth is obtained when h=1mm. It is also noted that increasing h above 1mm decreases the percentage bandwidth of the antenna. This is because increase in ‘h’ above 1mm deteriorates the impedance matching corresponding to the higher resonant frequency.

Fig. 5.36 Effect of upper substrate height variation

5.7.5 Radiation pattern and gain of the antenna

The experimental and simulated radiation patterns of the antenna at the resonances are shown in fig.5.37 and fig.5.38 respectively. It is observed that for all the resonances, a symmetrical stable XZ copolar pattern is observed for the entire operating band and the YZ copolar patterns show fluctuations. For the first four resonances the YZ plane cross polar power is lower as compared to that of the XZ plane. The maximum cross polar isolation is found to be 33 dB at 5.1 GHz in the XZ plane and 36.7 dB at 5.49 GHz in the YZ plane patterns. The variation of cross polar level and 3 dB beam width over the entire operating band is studied and is shown in Table 5.3.
Fig. 5.37 Measured radiation patterns of the antenna
Fig. 5.38  Simulated radiation patterns of the antenna at a) 3.8 GHz, b) 4.27 GHz, c) 4.76 GHz, d) 5.1 GHz and e) 5.49 GHz
Table 5.3 Measured Cross-Polar Level and 3db Beamwidth

<table>
<thead>
<tr>
<th>Frequency, GHz</th>
<th>Cross polar level along the on axis, dB</th>
<th>3 dB Beam width, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XZ Plane</td>
<td>YZ Plane</td>
</tr>
<tr>
<td>3.75</td>
<td>25.48</td>
<td>18.76</td>
</tr>
<tr>
<td>3.95</td>
<td>22.8</td>
<td>18.8</td>
</tr>
<tr>
<td>4.15</td>
<td>22.5</td>
<td>15.7</td>
</tr>
<tr>
<td>4.35</td>
<td>25.4</td>
<td>15</td>
</tr>
<tr>
<td>4.55</td>
<td>25.8</td>
<td>15.4</td>
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<tr>
<td>4.95</td>
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<td>23.1</td>
<td>29.6</td>
</tr>
<tr>
<td>5.55</td>
<td>17.5</td>
<td>31.33</td>
</tr>
<tr>
<td>5.73</td>
<td>12.5</td>
<td>16.2</td>
</tr>
</tbody>
</table>

The gain of the antenna is shown in fig. 5.39. The antenna shows a maximum gain of 8.07 dBi at 3.9 GHz which is very much higher than that of a conventional patch antenna fabricated on the same substrate and it is also noted that the gain of the centre resonant frequencies are also enhanced as compared to the antenna with zero offset (L₀=0mm) in the position of the upper patch.

![Fig. 5.39 Measured Gain of the antenna](image-url)
5.8 The offset stacked polygonal slot loaded broadband microstrip antenna

In this section, principle of stacking and offsetting is implemented on the polygonal slot loaded broadband microstrip patch antenna discussed in chapter 4. Here, the offset parameter is maintained at $L_0=2\text{mm}$. The geometry of this final design is shown in fig. 5.40. The other geometrical parameters of the antenna are found to be $L_1=35\text{mm}$, $L_2=14.3\text{mm}$, $L_3=5.8\text{mm}$, $W=3\text{mm}$, and $L_f=10.55\text{mm}$. The total thickness of the antenna is found to be $4.8\text{mm}$.

![Fig. 5.40 Electric field distributions of the stacked antenna with zero offset](image)

5.8.1 Reflection and Radiation characteristics

The simulated, experimental and computed reflection characteristics of the proposed offset stacked patch antenna are shown in fig.5.41. It is found that the antenna is covering a wide bandwidth from 4.01 GHz to 5.57 GHz having 32.56% bandwidth. The resonances are found to be at 4.18 GHz, 5GHz and 5.37 GHz.
The gain characteristics of the proposed antenna are shown in fig. 5.42. A comparison study of the gain of the antennas with and without offset is depicted in the same figure. It is observed that the antenna shows better gain characteristics as compared to the antenna without offset throughout the entire frequency of operation. The maximum gain of the antenna is found to be 8.9 dBi at 4.2 GHz.

The experimental radiation patterns of the antenna at the resonant frequencies are shown in fig. 5.43. For all the resonant frequencies, a dip along the on axis of the antenna is noted for the XZ cross polarization patterns. The cross polar isolation is found to be 21 dB, 19 dB and 24 dB for the XZ plane radiation patterns of the antenna at 4.2 GHz, 5 GHz and 5.37 GHz respectively. For the 4.2 GHz resonance, the cross polar power level is 7.2 dB below the co polar power along the on axis in the YZ plane pattern. The resonances centered around 5 GHz and 5.37 GHz shows cross polar isolation of 1.8 dB and 13 dB respectively for the YZ plane pattern.
5.8.2 Fringing Electric field models of the antenna

The fringing electric field models of the antenna are computed using FDTD method. It is concluded from the earlier discussion that, offsetting enhances the fringing electric fields of the patches and it is found that the major contribution is from the $E_y$ component of the electric field. So for this study only the $E_y$ component of the fringing electric field for the top and bottom layer of the patches is taken into consideration here.
The fringing electric fields of the top and bottom patches of the antenna at 4.19 GHz are shown in fig. 5.44 and 5.45 respectively. It is observed that there is a strong contribution from the $E_y$ component on the top and bottom sides of the patches. From the figures, it is observed that the space between the patches acts like a leaky cavity and hence enormous fringing electric fields are noted along the radiating edges of the patches and hence the gain is found to be increased.

Fig. 5.44 Computed $E_y$ component of Electric field on the upper patch at 4.19 GHz

Fig. 5.45 Computed $E_y$ component of Electric field on the lower patch at 4.19 GHz
5.9 Conclusions

The chapter highlighted a novel technique to enhance the gain of single band and broadband microstrip patch antennas. Principle of stacking is successfully implemented and the position of the upper parasitic patch is offsetted to enhance the fringing electric fields of the stacked antenna. The design greatly reduces the separation between the patches without degrading the impedance matching performance of the antenna. The single band design working around 2.3 GHz has a stacking height of the order of $0.025\lambda_g$, where $\lambda$ is the guided wavelength corresponding to the resonant frequency of the antenna and gain of the antenna is found to be 4.8 dBi. The offset stacked tilted square slotted and polygonal slotted broadband designs exhibits a bandwidth of 34.9% and 32.56% respectively and shows a maximum gain of 8.07dBi and 8.9dBi respectively.

5.10 References


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