The experimental and simulated investigations towards the development of modified monopole antenna which have radiation characteristics highly suitable for mobile handset are presented in this chapter. The omni directional radiation characteristic of the monopole antenna is modified with single null along one direction and considerable radiation along all other directions. Investigations on the radiation characteristic of the monopole antenna with resonating structures like split ring resonator, single metal strip and vertical stripes are conducted and discussed in this chapter.
Chapter 3

3.1 Introduction

In the last two decades, the use of the cellular phones has become the most popular mode of communication across the globe and it is the most common media used for making connections with different people. Moreover, these devices are highly portable and low cost. At the same time, the concerns about the cellular phone radiation effects have increased in the general public. A major controversy exists about the possible adverse, chronic health effects due to human exposure to Electro Magnetic Radiation (EMR). Some researchers hold that exposure to even the low EMR fields for relatively short period of time will positively result in significant increases in cancers, genetic defects and abnormal behavioral patterns [1]. Other experts hold that these findings are failure, so more objective research is required before an accurate risk assessment can be made.

But a working group of 31 scientists from 14 countries after a meeting at the WHO's International Agency for Research on Cancer (IARC), after reviewing all the available scientific evidence suggested that cell phone use should be classified as "possibly carcinogenic". And they admit that mobile phones may increase the risk for brain tumors. In all these aspects, it is necessary to decrease the interaction of electromagnetic energy towards human head when mobile handset is in operation.

3.2 Requirements for Antennas used in mobile handsets

The antenna is the gateway of wireless communication systems. And it interfaces the free-space medium and the RF transceiver systems. In the modern mobile communication systems, due to the technology development, multidisciplinary functional mobile phone antennas are required. Even though a variety of antenna structures have been used in cellular handsets, they are expected to have certain characteristics:
a) Occupy minimum volume
b) Light weight
c) Multi-band operation for different communication standards
d) Adequate bandwidth
e) Omnidirectional radiation characteristics
f) Negligible impact on the biological tissue of the user, to avoid health risks
g) Low fabrication cost
h) Conformability with mounting hosts etc..

It is clear that some of the requirements are mutually exclusive so a compromise has to be worked out in the designing process. The amount of electromagnetic radiation in the environment has increased day by day and at the same time the people are more concerned about the possible health risks of these wireless devices. However, to minimize the amount of energy absorbed by the user is a challenging task from the technical point of view.

To have negligible impact on the biological tissue of the user, two methods can be adopted

a) Reduce the radiated power towards the user.
b) Limiting the time of exposure.

The time factor mainly relates to the time duration and the frequency of mobile phone usage. So the only possibility is to find different methods to reduce the radiation towards user. The reduction of power absorbed by the user can tremendously avoid any possible health hazards. The energy absorbed by the
human tissue should fulfill the radiation limitations. Various techniques are adopted by researchers for reducing the antenna radiation effect towards human head.

Adding an external shield to mobile phones is the most common method adopted for reducing the unnecessary radiations [2]. Here, shielding structure has to be integrated with the antenna to provide better shielding effectiveness. The material selection and position of the external shield is also very important. A ferrite sheet attached to the front side, close to head can also reduce radiation [3]. However, the parameters such as attaching location, size and material properties of ferrite sheet played an important role in the reduction effectiveness. Highly directive antennas [4,5] can also reduce radiation towards human head significantly. But the adoption of highly directive antennas certainly causes degradation in signal reception from other directions. Researchers have explored PIFA (Planar Inverted F Antenna) with EBG (Electromagnetic Band Gap) surface [6] on the ground plane to reduce radiation towards human head. All these techniques adopt separate external shielding elements for reducing the radiation. But this deteriorates the structure simplicity and compactness.

In this chapter, the main concern is to develop a mobile antenna which gives reduced RF interference to the user. The investigations are to develop an antenna with an aim to improve the radiation characteristics of monopole antenna with good radiation characteristics in all directions except in one direction. The modification of the radiation pattern of a monopole antenna is implemented by using different resonating structures. It also provides a detailed discussion about the development of different antennas having this radiation characteristic. The simulation results are experimentally verified and an exhaustive parametric analysis is performed to study the effect of various antenna parameters.
The first section briefly describes planar printed CPW (CoPlanar Waveguide) fed monopole antenna, which is used as the basic antenna for developing proposed mobile antennas with less RF interaction towards the user.

### 3.3 Coplanar Wave Guide feeds: an over view

The coplanar waveguide (CPW) transmission line concept was proposed by Cheng P Wen in 1969. A conventional CPW fed transmission line on a dielectric substrate consists of a centre metallic strip conductor with semi-infinite ground planes parallel and adjacent to the conducting strip on the same side as shown in figure. 3.1.

![Fig. 3.1. CPW fed transmission line](image)

This structure supports a quasi-TEM mode of propagation. The CPW offers several advantages like, low cost, light weight, ease of fabrication, facilitates easy shunt as well as series surface mounting of active and passive devices, eliminates the need for wraparound and via holes, reduces radiation
loss. In addition a ground plane exists between any two adjacent lines, hence cross talk effects between adjacent lines are very week. As a result, CPW circuits are ideally suited for MIC as well as MMIC applications.

### 3.3.1 Field distribution in CPW

Usually the CPW system is excited by connecting center conductor of a coaxial connector to the signal strip and outer ground conductor to the two outer strips. The electric and magnetic field distribution of CPW transmission line is depicted in figure 3.2. In this case the electric field distributions in the slots are out of phase, and it cancels at the far field with the encircled magnetic field on each strips. This forcefully excites the odd mode like field distribution in CPW. This field distribution is maintained in this structure due to the feed symmetry.

Fig. 3.2. E field and H field distribution in a CPW fed transmission line

### 3.3.2 Transmission and reflection characteristics of the conventional CPW transmission line

A 50Ω CPW fed transmission line is designed [7] on a substrate of relative permittivity $\varepsilon_r (4.4)$ and thickness h (1.6mm). For this transmission line the width is found to be 3mm. The magnitude of transmission and reflection characteristics of a 50Ω matched CPW transmission line is shown in figure 3.3(a). It is found from the figure that the system is acting as a perfect transmission line. The line is perfectly
matched and the return loss is better than -18dB in the band of interest. The insertion loss of the system is also very low. This confirms it is acting as a transmission line. The radiation pattern of the line is shown in figure 3.3(b).

![Graph showing transmission and reflection characteristics](image-a)

![Diagram showing radiation characteristic of a CPW transmission line](image-b)

**Fig.3.3.** (a) Transmission and reflection characteristics (b) Radiation characteristic of a CPW transmission line (width=3mm, $\varepsilon_r=4.4$, $h=1.6$mm)
The maximum power radiated along the bore sight direction is -55 dB. This shows the radiation from the system is very feeble. From the above figures it is observed that, this device behaves as a pure transmission line with negligible radiation.

3.4 CPW fed printed monopole antenna

An open ended CPW transmission line can be converted into an efficient radiator by creating discontinuity on the structure. A basic coplanar wave guide (CPW) fed printed monopole antenna is developed by extending the signal strip length of a normal open ended CPW planar transmission line.

The geometry of a CPW fed monopole antenna printed on a substrate of relative permittivity $\varepsilon_r$ and thickness $h$ (top and side view) is shown in figure 3.4.

![Geometry of the Coplanar Waveguide Fed Monopole Antenna](image)

Fig. 3.4. Geometry of the Coplanar Waveguide Fed Monopole Antenna. (a) top view (b) side view ($L_1 = 25\text{mm}$, $W_1 = 3\text{mm}$, $g = 0.35\text{mm}$, $L_2 = 17\text{mm}$, $W_2 = 14\text{mm}$, $h=1.6\text{mm}$ and $\varepsilon_r=4.4$).
The signal strip width $W_1$ and signal to ground gap ($g$) is selected for $50\Omega$ impedance using standard design equations. The main radiating element is a vertical strip of length $L_1 = 25\text{mm}$ and width $W_1 = 3\text{ mm}$. This is acting as a $\lambda g/4$ monopole, where $\lambda g$ is the wavelength in the substrate. The ground plane dimension are $L_2 = 17\text{mm}$ and $W_2 = 14\text{ mm}$. The antenna is excited with a SMA (Sub Miniature Amphenol) connector. The antenna is fabricated using photolithographic technique and the simulation results are experimentally verified using HP8510C Vector Network Analyzer.

3.4.1 Reflection Characteristics

The measured reflection characteristic of the strip monopole antenna with design parameters $L_1 = 0.25\lambda g$, $W_1 = 0.03\lambda g$, $L_2 = 0.17\lambda g$, $W_2 = 0.14\lambda g$, $h = 1.6\text{mm}$ and $\varepsilon_r = 4.4$ is shown in figure. 3.5(a). From the graph it is clear that the strip monopole provides a resonance at $2.3\text{ GHz}$ from $1.98\text{ GHz}$ to $2.58\text{ GHz}$ with a bandwidth of $0.6\text{ GHz}$, $26\%$. The simulated return loss characteristic of the strip monopole antenna is also shown in the same graph for comparison. It is observed that the results are in good agreement.

Figure 3.5(b) shows the input impedance characteristics of the antenna and can be inferred that the input impedance is purely resistive at resonance and both the sides of the resonant frequency the impedance becomes either inductive or capacitive. For the monopole the resonance occurs around $2.3\text{GHz}$ where the input impedance is nearly $50\Omega$. 
Fig. 3.5. (a) Reflection characteristics (b) input impedance characteristics of the CPW fed monopole antenna at 2.3 GHz
($L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}$,
$h=1.6\text{mm}$ and $\varepsilon_r=4.4$).
3.4.2 Resonance phenomenon

The resonance phenomenon of the coplanar wave guide (CPW) fed monopole antenna is similar to a quarter wavelength conventional wire monopole antenna. The resonance of the CPW fed monopole antenna can be explained on the basis of sinusoidal current variation along the strip monopole above finite ground plane.

The simulated surface current distribution of a typical monopole antenna above a finite ground plane is shown in figure 3.6. The length of the strip monopole is $\lambda_g / 4$ (where $\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}}$ and $\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2}$) and width $W_1$ is 3mm. From the figure it is very clear that there is quarter wavelength variation of field along the strip. From the surface current distribution it can be inferred that the surface current at the tip of the monopole is minimum. Maximum surface current is observed near the ground. The simulated current distributions confirm that antenna is resonant with quarter wavelength current variation along the strip.

Fig.3.6. Computed surface current density ($L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}, h=1.6\text{mm}$ and $\varepsilon_r=4.4$).
As predicted from the current density plot it is clear that the radiated electromagnetic signal is linearly polarized along X direction.

3.4.3 Parametric analysis

The parametric analysis of the proposed CPW fed monopole antenna is conducted and effects of various antenna parameters on the antenna characteristics are studied. The results and discussion on various parametric studies are provided in this session. The parametric analysis is carried out using Ansoft HFSS.

3.4.3.1 Effect of signal strip length \((L_1)\) on reflection coefficient

The influence of the length \((L_1)\) of the signal strip on the resonant frequency of the antenna is shown in figure 3.7. The resonant frequency of the antenna highly depends on the length of the strip. The resonant frequency decrease with increase in length as expected. The length of the monopole \(L_1\) is taken to be equal to a quarter of the dielectric wavelength corresponding to operating frequency in the substrate.

![Fig 3.7. Effect of signal strip length \(L_1\) on the input reflection of the monopole antenna](image)

\((W_1 = 3\,\text{mm}, \, g = 0.35\,\text{mm}, \, L_2 = 17\,\text{mm}, \, W_2 = 14\,\text{mm}, h=1.6\,\text{mm} \text{ and } \varepsilon_r=4.4).\)
3.4.3.2 Effect of ground plane width (W₂) on the reflection coefficient

The ground plane dimension is an important factor for the design of compact antenna. The variation of return loss with the ground plane width is shown in figure 3.8. It can be noted that the ground plane width (W₂) significantly affects the band width and matching conditions of the antenna. From the variation studies it is found that better matching is achieved when the ground plane width is 0.14λₔ.

![Figure 3.8](image)

**Fig 3.8.** Effect of ground plane width (W₂) of the monopole antenna on the reflection coefficient
(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, h=1.6mm and εᵣ=4.4).

3.4.3.3 Effect of ground plane length (L₂) on reflection coefficient

The length of the ground plane L₂ is varied by keeping the length of the strip above the ground plane equal to quarter of the dielectric wavelength corresponding to the resonant frequency 2.3GHz. It is not affecting the resonant frequency of the antenna. But it can be noted from figure 3.9 that the ground plane length significantly affects the matching conditions of the antenna. In this case, the ground plane length (L₂) of 0.17λₔ is taken as optimum as far as the
matching is concerned. It is also noted that the resonance frequency is virtually independent of \( L_2 \).

Fig 3.9. Variation of reflection coefficient of the antenna with Ground plane length of the monopole antenna (\( L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, W_2 = 14\text{mm}, h=1.6\text{mm} \) and \( \varepsilon_r=4.4 \)).

3.4.4 Gain

The measured gain of the antenna along the bore sight direction is depicted in figure 3.10.

Fig 3.10. Measured gain of the Coplanar Waveguide Fed printed Monopole Antenna (\( L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}, h=1.6\text{mm} \) and \( \varepsilon_r=4.4 \)).
The antenna provides a moderate gain greater than 1dBi throughout the operating band. The maximum gain in the band is 1.7dBi at 2.43GHz with an average gain of 1.4 dBi.

### 3.4.5 Radiation characteristics

The radiation characteristics of the CPW fed printed monopole antenna is presented in this section. The three dimensional pattern is shown in figure 3.11. It is clear from the simulated 3D radiation pattern that the pattern is omnidirectional in nature with two deep nulls along positive and negative X direction. The nulls are along the axis of the dipole and cannot be conveniently used for reducing radiation towards the user due to mounting problem in the mobile handset. So for better coverage a pattern with single null is desirable.

![Simulated 3D radiation pattern](image)

Fig.3.11. Simulated 3D radiation pattern
(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, W₂ = 14mm, h=1.6mm and εᵣ=4.4).

The 2 D Co-polar and Cross polar radiation patterns of the antenna along E plane and H plane are depicted in figure 3.12(a) and (b) respectively. From the figure it can be seen that the CPW fed monopole antenna exhibits a figure of eight pattern in the E plane and a non-directional pattern in the H plane.
Moreover, the antenna exhibits more than 30dB cross polarization isolation on both E and H plane along the boresight direction.

![Fig 3.12. 2D radiation pattern of the antenna(a) E plane (b) H plane](image)

\(L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}, h=1.6\text{mm and } \varepsilon_r=4.4\).

### 3.4.6 Inferences

Table 3.1 summarizes the characteristics of the CPW fed monopole antenna which is considered as basic antenna for the further studies in the next section of this chapter.

**Table 3.1. Characteristics of the CPW fed monopole antenna**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CPW fed monopole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency and Return loss</td>
<td>2.3 GHz, 23dB</td>
</tr>
<tr>
<td>Band width</td>
<td>±300 MHz</td>
</tr>
<tr>
<td>Radiation pattern</td>
<td>E plane-Figure of Eight</td>
</tr>
<tr>
<td></td>
<td>H plane-Non directional (circular)</td>
</tr>
<tr>
<td>Area</td>
<td>42mm X31.7mm</td>
</tr>
<tr>
<td></td>
<td>(\varepsilon_r= 4.4, h=1.6\text{mm})</td>
</tr>
<tr>
<td>Ground dimension</td>
<td>14mmX17mm</td>
</tr>
<tr>
<td>Gain</td>
<td>1.4dBi</td>
</tr>
</tbody>
</table>
The omnidirectional radiation pattern of the above antenna has to be modified to reduce the RF exposure to human head.

### 3.5 Modified CPW fed antenna with radiation characteristic suitable for mobile handset

The finite ground coplanar waveguide fed monopole antenna is an efficient radiator and can be utilized for modern wireless communication gadgets. The major disadvantage of the printed monopole antenna when it is used in mobile handset is that, the RF interaction with the user is extremely high due to its radiation characteristics.

The electromagnetic interaction between the antenna and the human head can be reduced by modifying the radiation pattern of the monopole antenna. This can be achieved by using different resonating elements like

1) **Split Ring Resonators (SRR)**
2) **Single metallic strip**
3) **Parallel vertical strips**

These elements are printed at the back side of a normal CPW fed monopole antenna.

### 3.5.1 Development of Mobile antenna with Split Ring Resonator (SRR)

The split ring resonators (SRRs) have been used in planar circuit technology for the design of novel compact printed microwave components. SRRs are planar structures with two concentric conducting rings with slits etched on opposite sides.

The schematic diagram of the SRR unit cell is shown in the figure 3.13. It consists of two concentric rings with width ‘w’ and split gap ‘t’. These rings with inner radii of r1 and r2 are separated by a distance ‘d’.

Design and Development of Compact Coplanar Waveguide Fed Antennas for Wireless Applications
SRR can be considered as a parallel LC circuit with a resonant frequency, which can be tuned by varying the dimensions. SRRs would be excited by a time varying magnetic field with significant component parallel to the ring axis. A time varying magnetic field applied parallel to the axis of SRR induces rotating currents in the rings, which produces its own magnetic flux to enhance or oppose the incident field. Due to splits in the rings, the SRR unit can be made to resonate at wavelengths much larger than the diameter of the rings [8]. The second split ring inside and the slit opposite to the first will generate large capacitance in the small gap region between the rings, which enables current flow by means of new displacement current. The dimension of the structure is smaller than the free space wavelength resulting in low radiative losses and so very high quality factor.

The resonance frequency of SRR unit cell is calculated by placing the cell on a microstrip transmission line. SRR is coupled to the conventional microstrip line as shown in figure 3.14(a) [9]. To penetrate the maximum H-field lines through the axis of the resonator, the SRR unit cell is shifted laterally with
respect to the transmission line centre along the x-axis [10]. The S$_{21}$ plot for SRR cell placed above the microstrip line is shown in figure 3.14(b). The SRR unit cell is found to resonate at 2.1 GHz.

![Fig 3.14. (a) SRR unit cell above the microstrip line (b) S$_{21}$ plot of SRR superstrate](image)

In this section the radiation characteristics of a CPW fed monopole antenna loaded with single SRR unit cell is investigated [11]. The presence of SRR at the back of the monopole antenna leads to modify the non-directional radiation pattern in the azimuth plane, along with a small shift in the resonant frequency towards the lower side. The impedance matching and radiation pattern at the resonance frequency depends on the height of the superstrate as well as its relative position with respect to the planar monopole antenna.
3.5.1.1 Antenna geometry

The geometry of the SRR based monopole antenna is shown in figure 3.15.

Fig 3.15. Geometry of the CPW fed monopole antenna with SRR as substrate
(a) Top view (b) side view (L_1 = 25mm, W_1 = 3mm, g = 0.35mm, L_2 = 17mm, W_2 = 14mm, h=1.6mm and ε_r=4.4, r_1 =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm).

The geometry consists of a strip monopole of length, L_1 with lateral ground plane of dimension L_2 x W_2 on dielectric Layer 1. The strip monopole is loaded with a SRR patch on dielectric Layer 2 with outer ring radius of r_1= 6.3mm, ring width w = 0.9mm, separation between the two rings d=0.6mm and split gap t=0.5mm. Both the strip monopole and the SRR unit cell were fabricated on a substrate of relative permittivity, ε_r =4.4 and thickness, h=1.6mm. The SRR is placed at the optimum position and electromagnetically excited with the monopole. The center of SRR unit cell is placed with an offset of 1.7mm ‘a’ from the right edge of the feed and 1.3mm ‘b’ from the top edge of the right ground (figure 3.15(a)).
### 3.5.1.2 Reflection and Impedance Characteristics

The reflection characteristics of the SRR loaded monopole antenna along with the real part of impedance are shown in figure 3.16(a) and (b) respectively.

By loading the SRR unit cell at the optimum position, it is observed that a new resonance appears at the lower frequency centered at 1.74 GHz. But the antenna is found to be poorly matched at this resonant frequency. This is due to the inefficient coupling between the monopole and SRR. The real part of impedance at this frequency is found to be $18.68\,\Omega$ only.

![Reflection characteristics and Impedance plot](image)

**Fig 3.16(a) Reflection characteristics (b) Impedance plot of CPW fed monopole antenna loaded with SRR ($L_1 = 25\,\text{mm}, W_1 = 3\,\text{mm}, g = 0.35\,\text{mm}, L_2 = 17\,\text{mm}, W_2 = 14\,\text{mm}, h=1.6\,\text{mm} \text{ and } \varepsilon_r=4.4, r_1 =6.3\,\text{mm}, W = 0.9\,\text{mm}, d = 0.6\,\text{mm}, t = 0.5\,\text{mm}$).**

### 3.5.1.3 Simulated 3D radiation characteristics

The simulated 3D radiation pattern of the antenna at the first resonant frequency (1.74GHz) is shown in figure 3.17. It is observed that this antenna provides less radiation towards positive Y direction. Without SRR loading the pattern was omni-directional (figure 3.11). With SRR loading a null is observed along positive Y direction. The creation of null in the radiation pattern with
SRR loading is utilized for reducing the radiation towards the user. The antenna radiation in XZ plane is almost unidirectional.

3.5.1.4 Modified monopole with SRR printed on the same substrate.

From the previous studies, it is clear that the SRR structure can provide a resonance at lower side with radiation characteristics suitable for a mobile handset. Even though the antenna is offering a resonance at lower frequency the impedance matching is poor. Moreover, the structure is bulky and mechanically not robust due to the multilayered structure. In this section, the development of an antenna with improved impedance matching on a single layer substrate is discussed. The antenna radiation characteristics and parametric analysis are also discussed.
The geometry of the proposed SRR printed monopole antenna is shown in figure.3.18. The SRR unit cell structure is directly printed at the back side of the conventional monopole to modify the radiation pattern.

![Geometry of the CPW fed monopole antenna with printed SRR](image)

**Fig 3.18. Geometry of the CPW fed monopole antenna with printed SRR**

$L_1 = 25\text{mm}$, $W_1 = 3\text{mm}$, $g = 0.35\text{mm}$, $L_2 = 17\text{mm}$, $W_2 = 14\text{mm}$, $h=1.6\text{mm}$ and $\varepsilon_r=4.4$, $r_1 =6.3\text{mm}$, $W = 0.9\text{mm}$, $d = 0.6\text{mm}$, $t = 0.5\text{mm}$, $a=1.7\text{mm}$ and $b=1.3\text{mm}$.

The monopole is excited with a $50\Omega$ CPW feed line. The antenna is etched on a substrate of thickness $1.6\text{mm}$ and relative permittivity ($\varepsilon_r$) 4.4. The parameters of the monopole antenna and SRR are same as the previous design ($L_1=25\text{mm}$, $W_1 = 3\text{mm}$, $L_2=17\text{mm}$ and $W_2 = 14\text{mm}$, $g=0.35\text{mm}$, $r_1=6.3\text{mm}$, $d=0.6\text{mm}$, $v=0.9\text{mm}$, $t=0.5\text{mm}$, $a=1.7\text{mm}$ and $b=1.3\text{mm}$) but are printed on either side of a single layer substrate.
3.5.1.5 Reflection characteristics

The experimental and simulated reflection coefficients of the SRR loaded monopole antenna are shown in figure 3.19. The simulation result is in good agreement with the measured values. It is seen from the reflection characteristics that the antenna operates from 1.75GHz to 1.91GHz with a fractional bandwidth of 8.7% centered at 1.8GHz. Thus by loading the SRR structure at the optimum position, it is observed that the monopole resonance shifts to a lower resonance of 1.8GHz. The single layer structure of this prototype provides better coupling between the SRR and monopole, resulting in improved impedance matching. Due to the high quality factor of SRR structures the bandwidth of the antenna is only 160MHz.

![Reflection coefficient of the CPW fed monopole antenna with printed SRR](image)

**Fig 3.19.** Reflection coefficient of the CPW fed monopole antenna with printed SRR

(*L1 = 25mm, W1 = 3mm, g = 0.35mm, L2 = 17mm, W2 = 14mm, h=1.6mm and \( \varepsilon_r = 4.4 \), \( r1 = 6.3mm \), \( W = 0.9mm \), \( d = 0.6mm \), \( t = 0.5mm \))

3.5.1.6 Radiation pattern

The simulated 2D radiation patterns along the principle planes at resonance are shown in figure 3.20. It is observed that the antenna provides
nearly constant radiation patterns along XZ plane. The antenna radiation in YZ plane is almost non-directional with single null along the positive Y-direction. This pattern is suitable for mobile handset devices. Compared to the radiated power along the boresight direction it is seen that the radiated power is reduced by nearly 18 dB along the null direction. The antenna is providing very good coverage in the three quadrants with less coverage in one quadrant. This less coverage area can be directed towards the user to reduce the strong illumination. This is an ideal pattern required for a mobile phone with reduced illumination towards the user.

**Fig 3.20 Simulated 2D radiation pattern in XZ and YZ plane of the monopole antenna with printed SRR**

(L1 = 25mm, W1 = 3mm, g = 0.35mm, L2 = 17mm, W2 = 14mm, h=1.6mm and \( \varepsilon_r=4.4 \), r1 =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm)

The measured 2D radiation patterns of the antenna in XY and YZ planes are shown in figure 3.21 (a) and (b) respectively. From the patterns it is clear that there is a reduction in radiated power along the positive y direction \( (\varphi = 90^0) \) degree). It is very interesting to note that the radiated power along the Y direction is reduced considerably and better than -20 dB.
Fig 3.21 Measured 2D radiation pattern of the monopole antenna with printed SRR (a) XY plane (b) YZ plane
(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, W₂ = 14mm, h=1.6mm and εᵣ=4.4, r₁ =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm)

3.5.1.7. 3D radiation pattern

The simulated 3D far field radiation pattern at 1800MHz of the proposed antenna is shown in figure 3.22.

Fig 3.22. Simulated 3D radiation pattern of the monopole antenna with printed SRR
(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, W₂ = 14mm, h=1.6mm and εᵣ=4.4, r₁ =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm)
The directional pattern of the monopole antenna in the elevation plane is modified to a pattern suitable for mobile handset. The figure shows that the proposed antenna is radiating in the negative Y direction and offers a null along the positive Y direction. Moreover, there is only one null appeared in the pattern. The reduction in the field intensity is nearly -18dB.

3.5.1.8 Effect of SRR parameters on antenna performance

The parametric analysis of the proposed antenna is conducted and effects of SRR parameters over the antenna characteristics are studied. The results and discussion on various parametric studies are provided in this section.

3.5.1.8.1. SRR location

The effect of ‘a’ (the position from the right edge of the monopole strip to the center of SRR) on the reflection characteristics of the antenna is shown in figure.3.23. It is found that this affect the impedance match of the antenna.

**Fig 3.23.** The variation of reflection characteristic with the effect of position ‘a’ of the printed SRR
(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, W₂ = 14mm, h=1.6mm and εᵣ=4.4, r₁ =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm, b=1.3mm)
The effect of ‘b’ over the reflection characteristics is depicted in figure 3.24. It is found from the plot that as the position of the SRR varies vertically from 0.5mm to 2.1mm the impedance matching varies drastically. The optimum position is found to be $a = 1.7\text{mm}$ and $b = 1.3\text{mm}$ for maximum impedance matching.

![Figure 3.24. The variation of reflection characteristic with the effect of position ‘b’ of the printed SRR](image)

(L1 = 25mm, W1 = 3mm, g = 0.35mm, L2 = 17mm, W2 = 14mm, h = 1.6mm and $\varepsilon_r = 4.4$, r1 = 6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm, a = 1.7mm)

The SRR is placed at an offset position determined by the parameters ‘a’ (the position from the right edge of the monopole strip to the center of SRR along Y direction) and ‘b’ (distance from the right top edge to SRR center position along negative X direction). Figure 3.25 shows 3D radiation pattern of the antenna at two different positions of SRR ([a = 8mm, b = 1.3mm] and [a = 10mm, b = 1.3mm]), printed above the ground of monopole antenna. In both cases SRR unit cell is positioned without overlapping with the ground plane. This resonating structure like SRR is not showing a radiation pattern suitable for mobile handset when it is
placed with an offset from the ground plane. Thus a ground coupling is essential for the structure to modify the pattern suitable for handheld mobile devices. The patterns shown in figure 3.25 (a) and (b) have two nulls along X axis. As far as the coverage is concerned this is not desirable one.

![Simulated 3D radiation pattern at different position of SRR](image)

**Fig. 3.25. Simulated 3D radiation pattern at different position of SRR**

(a) \(a=8\text{mm}, b=1.3\text{mm}\) (b) \(a=10\text{mm}, b=1.3\text{mm}\) \(L_1 = 25\text{mm}, W_1 = 3\text{mm}, g = 0.35\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}, h=1.6\text{mm}\) and \(\varepsilon_r=4.4, r_1 =6.3\text{mm}, W = 0.9\text{mm}, d = 0.6\text{mm}, t = 0.5\text{mm}\)

It is found that the location of the SRR and its dimension plays an important role in the antenna characteristics. The impedance of the antenna at the lower resonance is highly depending on the offset location of the SRR structure. The SRR structure should have a direct coupling below the ground plane of monopole antenna to modify the radiation pattern. Impedance matching at the resonance changes with the position of SRR.

### 3.5.1.9 Inferences

The radiation characteristics of CPW fed monopole antenna loaded with SRR unit cell as superstrate and printed SRR on the ground plane are presented. The proposed antenna operates at GSM 1800 MHz operating band. Modification of the radiation characteristics of monopole antenna depends on
relative position of SRR with respect to the ground plane. Investigation shows that SRR structure at the back side of a CPW fed monopole antenna can modify the radiation characteristics with less RF exposure.

3.5.2 Development of Mobile antenna with single metal strip

The CPW fed printed monopole antenna with metamaterial structure (SRR) gives a distinct resonance as discussed in the previous section. But the main drawback for that design is the lower bandwidth (8.7%) due to the high quality factor of SRR. In this section the design, development and analysis of a single metal strip printed antenna suitable for mobile handset is presented and discussed.

3.5.2.1 Antenna Geometry

The geometry of the proposed antenna with front, back and side view is shown in figure 3.26. The main radiating element is a vertical strip of length $L_1=25\text{mm}$ and width $W_1=3\text{mm}$ which is acting as a $\lambda_g/4$ monopole. The ground plane dimension are $L_2=17\text{mm}$ and $W_2=14\text{mm}$. The gap between monopole strip and ground plane ($g=0.35\text{mm}$) is designed for $50\Omega$ impedance matching. A single metal strip with length $L_3=26\text{mm}$, width $W_3=9.9\text{mm}$ is printed on the back side of same substrate with a separation ($S$) of $2\text{mm}$ with an offset ($P$) of $4.5\text{mm}$ from the top of the monopole. By properly optimising the metal strip position, the radiation pattern can be modified. The prototype of the antenna is fabricated on a substrate of dielectric constant ($\varepsilon_r$) 4.4 and $h=1.6\text{mm}$ with an overall dimension of $42\times 28\text{mm}^2$. 
3.5.2.2 Reflection characteristics

The simulated and experimental reflection characteristic of the single strip loaded monopole antenna is shown in figure 3.27(a). The antenna is found to resonate at 1.81GHz with a 2:1 VSWR bandwidth of 230MHz (1.76 GHz to 1.99 GHz), which is wide enough to cover the 1.8GHz application band.

The reflection coefficient with and without the metallic strip for this prototype is shown in figure 3.27(b). It is seen from the plot that by introducing the metallic strip the resonant frequency shift to a lower frequency region. Thus the metallic strip can improve the compactness of the antenna at a particular frequency of operation when compared to a normal CPW fed monopole antenna.
Fig. 3.27. The reflection characteristic of the antenna (a) Experiment and simulation (b) with and without metal strip
\((L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, P=4.5\text{mm and } S=2\text{mm})\).

3.5.2.3 Radiation pattern

The simulated 3D far field radiation pattern of the proposed antenna at 1810MHz is shown in figure 3.28. It is interesting to note that the antenna provides a considerable reduction in total radiated power along the positive Y direction. There is only one null in the pattern and the antenna is radiating on all the other three quadrants with almost equal power which is highly suitable for a mobile handset.

Fig 3.28. Simulated 3D pattern of the monopole antenna with printed single strip
\((L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, P=4.5\text{mm and } S=2\text{mm})\)
Thus by placing a metallic strip at the optimum position, the harmful effect of electromagnetic radiation can be avoided. This reduction is approximately 20dB as seen from the figure.

Measured 2D radiation patterns of the antenna in YZ and XY plane at the resonance frequency are shown in figure 3.29(a) and (b) respectively. The measured pattern is very suitable for mobile handset with good radiation in three space quadrants with reduced radiation in one quadrant. This property can be conveniently employed to reduce the EM interaction towards the head of a mobile phone user.

![Fig. 3.29. Measured radiation pattern (a) YZ plane (b) XY plane](image)

$L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \epsilon_r=4.4, P = 4.5\text{mm and } S=2\text{mm}$

The antenna patterns in YZ plane with and without metal strip at the backside are shown in figure 3.30. From the figure it is observed that the figure of eight pattern of the monopole antenna gets modified with a pattern having a single null along positive Y direction. Thus omnidirectional characteristic of the monopole antenna is modified to that suitable for specific mobile applications.
The radiated power is reduced to more than 25dB along the positive Y-direction. Moreover the power remains same in the negative Y-direction. Thus the radiated power was rearranged to that suitable for mobile gadgets.

![Radiation pattern of the antenna with and without printed strip](image)

**Fig. 3.30. Radiation pattern of the antenna with and without printed strip**

\[
L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, P =4.5\text{mm and S}=2\text{mm}
\]

3.5.2.4 Parametric Analysis

In this section the parametric analysis of metal strip on the antenna characteristics, are narrated.

3.5.2.4.1 Effect of strip width (W3) on reflection characteristics of the antenna

The strip width, W3 is varied from 9.5 to 10.3mm and its influence on the reflection characteristics are shown in figure.3.31. From the figure it is seen that the first resonance frequency is virtually independent of strip width. But the strip width has considerable effect on the second frequency. The strip width of 9.9mm is taken as optimum width, which gives the maximum impedance matching.
3.5.2.4.2 Effect of strip length (L3) on reflection characteristics:

The variation of reflection coefficient with L3 is shown in figure 3.32. Strip length L3 is varied from 24mm to 28mm and hence the resonance frequency shifts by 0.055GHz. By increasing L3 the resonant length increases which lowers the resonant frequency. Length of the strip is taken as 26mm by considering the application band.
3.5.2.5 Gain

The gain of the CPW fed monopole antenna with metal strip is depicted in figure. 3.33. The proposed antenna shows an average gain of 1.12dBi. It is also worth to note that, the addition of metallic strip is not adversely affecting the gain of the antenna.

![Gain Graph](image)

Fig 3.33. Measured gain of the antenna with printed strip
(L₁=25mm, W₁=3mm, L₂=17mm, W₂=14mm, g=0.35mm, L₃=26mm, W₃=9.9mm, h=1.6mm, εᵣ=4.4, P=4.5mm and S=2mm)

3.5.2.6 Resonance phenomenon

A better understanding about the resonance and radiation behavior of the proposed antenna can be obtained by analyzing the computed current density plots at three different frequencies. The 3D radiation characteristics at the resonant frequency, at frequencies below and above the resonant frequency are studied.

Radiation characteristics studies revealed that the metal plate affects the nulls of the E plane pattern of a monopole. Without printed metal strip at the back side, antenna is a monopole. The monopole will resonate at a particular
frequency corresponding to $\lambda g/4$ length. When a metal strip of length 26mm is introduced, the system is resonating at 1.81GHz.

The radiation patterns along with the current plots are shown at three different frequencies in figure 3.34 (a), (b) and (c).

(a) 1.62GHz

(b) 1.81GHz

(c) 2.34GHz

Fig. 3.34. 3D radiation characteristic and current density plots at (a) 1.62GHz (b) 1.82GHz (c) 2.34GHz

$L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, P = 4.5\text{mm and } S = 2\text{mm}$
From patterns it is observed that at resonance (1.82 GHz) the pattern is highly suitable for mobile gadgets with single null along positive y direction. But the patterns outside the band are similar to that of monopole. From the studies it is found that a single null pattern is obtained for a band 1.76 GHz to 1.99GHz.

It is found that the pattern is tilted and irregular outside the resonating band from the conventional monopole pattern due to the corresponding coupling with metal plate.

From the above exhaustive parametric studies design parameters for various antenna dimensions are given in the following equations, (3.1)-(3.7)

\[
\begin{align*}
L_1 &= 0.247 \lambda_g \tag{3.1} \\
L_2 &= 0.168 \lambda_g \tag{3.2} \\
W_2 &= 0.139 \lambda_g \tag{3.3} \\
L_3 &= 0.26 \lambda_g \tag{3.4} \\
W_3 &= 0.098 \lambda_g \tag{3.5} \\
S &= 0.019 \lambda_g \tag{3.6} \\
P &= 0.045 \lambda_g \tag{3.7}
\end{align*}
\]

3.5.2.7 Validation at different substrates

The parameters of the antenna resonating at 1.8GHz were calculated from the design equation for different dielectric substrates. The results are summarized in Table 3.2. Reflection characteristics of the antenna with different dielectric substrates are shown in figure 3.35.
Table 3.2. Parameters of the antenna for different dielectric substrates at 1.8GHz

<table>
<thead>
<tr>
<th>Dielectric Material</th>
<th>Relative dielectric constant (εr)</th>
<th>L1 mm</th>
<th>W1 mm</th>
<th>g mm</th>
<th>h mm</th>
<th>L2 mm</th>
<th>W2 mm</th>
<th>L3 mm</th>
<th>W3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT Duroid 5880</td>
<td>2.2</td>
<td>31</td>
<td>5</td>
<td>0.2</td>
<td>1.575</td>
<td>21.08</td>
<td>17.36</td>
<td>32.2</td>
<td>12.276</td>
</tr>
<tr>
<td>Rogers RO 4003</td>
<td>3.38</td>
<td>26.25</td>
<td>3</td>
<td>0.24</td>
<td>1.524</td>
<td>17.85</td>
<td>14.7</td>
<td>27.3</td>
<td>10.395</td>
</tr>
<tr>
<td>FR4 epoxy</td>
<td>4.4</td>
<td>25</td>
<td>3</td>
<td>0.35</td>
<td>1.6</td>
<td>17</td>
<td>14</td>
<td>30</td>
<td>9.9</td>
</tr>
<tr>
<td>Rogers RO 3006</td>
<td>6.15</td>
<td>22.5</td>
<td>3</td>
<td>0.5</td>
<td>1.28</td>
<td>15.3</td>
<td>12.6</td>
<td>23.4</td>
<td>8.91</td>
</tr>
</tbody>
</table>

All the antennas are resonating at 1.8GHz with good impedance matching. This validates the design criteria.

Fig 3.35. Reflection characteristics of the antenna with different substrate materials

(L1=25mm, W1=3mm, L2=17mm, W2=14mm, g=0.35mm, L3=26mm, W3=9.9mm, h=1.6mm, εr=4.4, P=4.5mm and S=2mm)

These developed design equations are validated for different application frequencies on an FR4 substrate and the antenna parameters are shown on Table 3.3.
Table 3.3. Parameters of the antenna for different frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L1 (mm)</th>
<th>L2 (mm)</th>
<th>W2 (mm)</th>
<th>L3 (mm)</th>
<th>W3 (mm)</th>
<th>S (mm)</th>
<th>P (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 MHz</td>
<td>50.2</td>
<td>34.15</td>
<td>28.15</td>
<td>52.85</td>
<td>19.9</td>
<td>4.03</td>
<td>9.04</td>
</tr>
<tr>
<td>1.8GHz</td>
<td>25</td>
<td>17</td>
<td>14</td>
<td>26</td>
<td>9.9</td>
<td>2</td>
<td>4.5</td>
</tr>
<tr>
<td>2.4GHz</td>
<td>18.82</td>
<td>12.8</td>
<td>10.55</td>
<td>19.81</td>
<td>7.47</td>
<td>1.51</td>
<td>3.39</td>
</tr>
</tbody>
</table>

The simulated reflection characteristics of the antenna developed for these different frequencies are shown in figure 3.36. The antennas are showing good impedance characteristics in their corresponding application bands. The simulated 3-Dimensional radiation patterns at the above frequencies are shown in figure 3.37. The pattern shows the antenna is highly suitable for mobile handset with reduced radiation along one direction and wide coverage on all other directions.

Fig. 3.36. Reflection characteristics of the monopole antenna with strip at different frequencies

\( L_1 = 0.247 \lambda_{g}, L_2 = 0.168 \lambda_{g}, W_2 = 0.139 \lambda_{g}, L_3 = 0.26 \lambda_{g}, W_3 = 0.098 \lambda_{g}, h = 1.6 \text{ mm}, \epsilon_r = 4.4, S = 0.019 \lambda_{g}, P = 0.045 \lambda_{g} \)
3.5.2.8 Inferences

Antenna with reduced radiation hazard and operating at GSM 1810 band is developed from the finite ground coplanar waveguide fed strip monopole by integrating a single metal strip at the backside. The antenna offers a bandwidth of 230MHz which is wide enough to cover the band. This antenna structure is very simple with an average gain of 1.12dBi in the application band. Antenna offers 20 dB reduction of radiated power in one quadrant with an enhancement in radiation at other quadrants.

3.5.3 Development of Mobile antenna with vertical metal stripes

Printed vertical metal stripes at the back side of the monopole are used to modify the far field radiation pattern in this study[12]. Experimental and simulation studies of the antenna radiation characteristics are presented and discussed. The power towards the users head can be reduced by 23dB (3dB more than the single strip structure) by using printed vertical metal stripes.

3.5.3.1 Antenna Geometry

The monopole antenna with printed vertical stripes is shown in figure 3.38. Thirteen metal stripes with length(L₃)=30mm and width(W₃)=0.3mm and
a separation of (d) 0.5mm is printed on the back side of CPW fed monopole antenna. These stripes are placed by an offset of (P) 4.5mm from the top of the monopole and ground overlapping distance (Q) of 8.5mm. By properly placing the metal stripes position the radiation pattern can be modified. The prototype was fabricated on a substrate of dielectric constant ($\varepsilon_r$) 4.4 and thickness (h) 1.6mm with an overall dimension of 42X31.7mm$^2$.

Fig. 3.38. Geometry of the antenna (a) 3D schematic diagram (b) bottom view (c) side view

($L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=30\text{mm}, W_3=0.3\text{mm}, d=0.5\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4.$)

3.5.3.2 Reflection characteristics

Measured and simulated reflection characteristics of the antenna with and without vertical stripes are shown in Fig.3.39. It is seen from the plot that the antenna loaded with stripes exhibits 2:1 VSWR bandwidth of 200MHz (1.76GHz - 1.96GHz) centered at 1.8GHz. By placing the metal stripes the
antenna resonance is shifted from 2.3GHz to 1.8GHz. The measurement result reveals that metallic stripes loading can reduce the overall size of the antenna.

Fig. 3.39. Reflection characteristics of the monopole antenna with vertical stripes 

\( \begin{align*}
L_1 &= 25\text{mm}, W_1 = 3\text{mm}, L_2 = 17\text{mm}, W_2 = 14\text{mm}, g = 0.35\text{mm}, \\
L_3 &= 30\text{mm}, W_3 = 0.3\text{mm}, d = 0.5\text{mm}, h = 1.6\text{mm}, \varepsilon_r = 4.4. 
\end{align*} \)

3.5.3.3 Input impedance characteristics

The real and imaginary parts of the impedance of the antenna with varying the number of metal stripes (n) are shown in figures. 3.40 (a) and (b) respectively. The smith chart showing the impedance characteristics is also shown in figure.3.40(c). Addition of parasitic stripes increases the inductive reactance which shifts resonant frequency to lower side. It also increases the coupling between the stripes and ground plane to achieve good impedance match. An optimized strip number of \( n = 13 \) is chosen by considering the application band and impedance matching.
3.5.3.4 Far field radiation characteristics

Measured 2D radiation patterns of the antenna in YZ and XY plane at the resonance frequency are shown in figure 3.41 (a) and (b) respectively. It is observed that the radiation pattern of the conventional monopole gets modified by the addition of the metallic stripes. The printed vertical stripes affect the fringing field between the monopole and any of the lateral ground plane. As a
result the electric field gets redistributed giving a null along positive Y direction and filling the original two nulls of the conventional monopole.

Fig. 3.41. Measured radiation pattern of the proposed antenna in (a) YZ (b) XY plane. 
(L₁=25mm,W₁=3mm,L₂=17mm,W₂=14mm,g=0.35mm,L₃=30mm, W₃=0.3mm, d=0.5mm,h=1.6mm, εᵣ= 4.4.)

The measured 2D radiation patterns in YZ plane with and without vertical stripes are also shown in figure 3.42. From the observed results it is clear that the figure of eight pattern in YZ plane is modified to a pattern with single null along positive Y-axis. A measured 27dB reduction in radiated power is observed along the positive Y-direction, with appreciable power in all other directions.
Fig. 3.42. The 2D radiation patterns of the antenna with and without stripes in YZ plane
\[
(L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=30\text{mm}, W_3=0.3\text{mm}, d=0.5\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4.)
\]

Fig. 3.43. 3D radiation pattern
\[
(L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=30\text{mm}, W_3=0.3\text{mm}, d=0.5\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4.)
\]
The simulated 3D radiation pattern of the antenna is shown in figure 3.43. The antenna radiates in all directions with single null along positive Y direction, which again confirms the suitability of the antenna for mobile handset application.

3.5.3.5 Parametric Analysis

A parametric analysis is performed in order to investigate the effect of various antenna parameters over the antenna characteristics.

3.5.3.5.1 The effect of printed metal stripes parameters (W₃ & d) on reflection characteristics

The reflection characteristics of the antenna for different printed metal stripes parameters are shown in figures 3.44(a) and 3.44(b). It is seen from the Fig 3.44(a) that there is no shifts in the resonant frequency with W₃ by keeping the total length W₃+d as a constant (0.8mm). This in turn reveals that a small change in the parameter W₃ does not affect the resonance frequency.

![Fig. 3.44. Effect of W₃ (a) & d (b) of metal stripes on reflection characteristics of monopole antenna with vertical stripes](image)

*(L₁=25mm,W₁=3mm,L₂=17mm,W₂=14mm,g=0.35mm,L₃=30mm, h=1.6mm, εᵣ= 4.4.)*
The influence of the separation between the stripes \( d \) on the reflection is presented in Figure 3.44(b). From the Figure it can be seen that as \( d \) is increased, the entire band shifts to lower side without changing bandwidth. It is due to increase in the capacitive coupling between stripes and ground plane. Its value is optimized to 0.5mm by considering the resonance in the application band. Therefore it is concluded that by varying \( d \), the resonance frequency can be tuned without much change in the impedance bandwidth.

From the parametric studies, the design parameters of the antenna obtained for the required resonant frequency are given below (equations 3.8-3.14), where \( \lambda_g \) is the dielectric wavelength.

\[
\begin{align*}
L_1 &= 0.25 \lambda_g \quad \text{--- (3.8)} \\
L_2 &= 0.17 \lambda_g \quad \text{--- (3.9)} \\
W_2 &= 0.14 \lambda_g \quad \text{--- (3.10)} \\
L_3 &= 0.31 \lambda_g \quad \text{--- (3.11)} \\
W_3 &= 0.0031 \lambda_g \quad \text{--- (3.12)} \\
P &= 0.044 \lambda_g \quad \text{--- (3.13)} \\
Q &= 0.084 \lambda_g \quad \text{--- (3.14)}
\end{align*}
\]

**3.5.3.5.2 Effects of substrate parameters on reflection characteristics**

The studies are conducted on substrates with different relative dielectric constants. The structural parameters of the antenna operating in the 1.8GHz operating band for different dielectric constants are shown in table 3.4.
Table 3.4. The simulated parameters for different dielectric substrate.

<table>
<thead>
<tr>
<th>Dielectric Material</th>
<th>Relative dielectric constant ($\varepsilon_r$)</th>
<th>$L_1$ mm</th>
<th>$g$ mm</th>
<th>$h$ mm</th>
<th>$L_2$ mm</th>
<th>$W_2$ mm</th>
<th>$L_3$ mm</th>
<th>$W_3$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT Duroid 5880</td>
<td>2.2</td>
<td>31</td>
<td>0.15</td>
<td>1.575</td>
<td>21.08</td>
<td>17.36</td>
<td>37.2</td>
<td>0.37</td>
</tr>
<tr>
<td>Rogers RO 4003</td>
<td>3.38</td>
<td>28.5</td>
<td>0.25</td>
<td>1.524</td>
<td>19.38</td>
<td>15.96</td>
<td>34.2</td>
<td>0.34</td>
</tr>
<tr>
<td>FR4 epoxy</td>
<td>4.4</td>
<td>25</td>
<td>0.35</td>
<td>1.6</td>
<td>17</td>
<td>14</td>
<td>30</td>
<td>0.3</td>
</tr>
<tr>
<td>Rogers RO 3006</td>
<td>6.15</td>
<td>22.5</td>
<td>0.15</td>
<td>1.28</td>
<td>16.15</td>
<td>12.5</td>
<td>27</td>
<td>0.27</td>
</tr>
<tr>
<td>RT Duroid 6010 LM</td>
<td>10.2</td>
<td>19.25</td>
<td>0.13</td>
<td>1.27</td>
<td>13.49</td>
<td>12.29</td>
<td>23.05</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The relative permittivity ($\varepsilon_r$) of the substrate material is varied from 2.2 to 10.2. It is found from the plot (Fig 3.45) that the band width of the antenna decreases rapidly as $\varepsilon_r$ increases.

Fig. 3.45. Variation of Reflection characteristics with different substrate materials ($\varepsilon_r$)  
($L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=30\text{mm}, W_3=0.3\text{mm}, d=0.5\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4$.)

The developed design equations are validated on FR4 substrate for three different application frequencies. The antenna parameters used are shown on table 3.5.
Table 3.5. Parameters of the antenna with vertical stripes for different frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>L₁ (mm)</th>
<th>L₂ (mm)</th>
<th>W₂ (mm)</th>
<th>L₃ (mm)</th>
<th>W₃ (mm)</th>
<th>P (mm)</th>
<th>Q (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 MHz</td>
<td>50.2</td>
<td>34.15</td>
<td>28.15</td>
<td>63</td>
<td>0.63</td>
<td>8.94</td>
<td>17.07</td>
</tr>
<tr>
<td>1.8GHz</td>
<td>25</td>
<td>17</td>
<td>14</td>
<td>31.32</td>
<td>0.313</td>
<td>4.45</td>
<td>8.49</td>
</tr>
<tr>
<td>2.4GHz</td>
<td>18.82</td>
<td>12.8</td>
<td>10.55</td>
<td>23.62</td>
<td>0.24</td>
<td>3.35</td>
<td>6.40</td>
</tr>
</tbody>
</table>

The simulated reflection characteristics of the antenna developed for these different application frequencies are shown in Figure 3.46. The antennas are showing good impedance characteristics in their corresponding application bands. The simulated 3-Dimensional radiation patterns at the above frequencies are shown in figure 3.47. The antenna pattern shows, it is highly suitable for mobile handset with reduced radiation on one direction and wide coverage on all other directions.

Fig 3.46 Reflection characteristics of the antenna at different frequencies
(L₁=0.25λg, L₂=0.17λg, W₂=0.14λg, L₃=0.31λg, W₃=0.0031λg, P=0.044λg, Q=0.084λg)
3.5.3.5.3 Effect on radiation pattern with number of stripes (n)

Simulated 2D radiation patterns in YZ plane with different number of stripes (n) at the corresponding resonant frequency are shown in Figure 3.48.
It is observed that for different number of stripes, the patterns are almost ideal for our specific application. Moreover, the pattern is not varying much with small changes in number of stripes. The strip number is chosen as 13 for using the antenna at GSM 1.8GHz application band.

3.5.3.6 Gain

The measured gain of the antenna by gain comparison method is shown in Fig 3.49. The antenna offers peak gain of 1.9dBi at 1.81GHz with an average gain of 1.14dBi in the frequency band.

Fig. 3.49. Measured gain of the monopole antenna with vertical stripes antenna. 
($L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm},$ 
$L_3=30\text{mm}, W_3=0.3\text{mm}, d=0.5\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4$.)

3.5.4 Inferences

A CPW fed monopole antenna with printed vertical stripes at the back side, produces radiation characteristics suitable for a wireless handset. The proposed antenna operates at GSM 1800 band. A good agreement between measurement and simulation is obtained. The antenna offers a bandwidth of 200MHz when printed on a substrate of dielectric constant ($\varepsilon_r$) 4.4 and
thickness 1.6mm with an overall dimension of 42X31.7mm$^2$. It offers an average gain of 1.14dBi. A 27dB reduction in radiated power is observed at the beam minima, which is more than the previously mentioned structures.

3.5.5 Surface Impedance Plot for Proposed Antennas

From the above studies the radiation pattern is modified to use it for mobile handset with reduced radiation along one direction at resonance frequency. The total radiated power is not found to vary, but redistributed as evident from the radiation patterns. The change in radiation pattern is analysed from the surface impedance plot.

The simulated surface impedance of the proposed antenna, at resonance as well as lower and upper frequencies is shown in figure.3.50, figure.3.51 and figure.3.52. It is clearly evident from the figure that the surface impedance at the resonant frequency is higher than at other frequencies outside the band. This high impedance restricts the propagation of electromagnetic waves towards that direction.

![Surface Impedance Plot](image)

Fig. 3.50. Simulated surface impedance at different frequencies of monopole antenna with printed SRR (a)1.6GHz (b)1.81GHz (c)2.2GHz

(L₁ = 25mm, W₁ = 3mm, g = 0.35mm, L₂ = 17mm, W₂ = 14mm,
h=1.6mm and εᵣ=4.4, r₁ =6.3mm, W = 0.9mm, d = 0.6mm, t = 0.5mm)
Fig. 3.51. Simulated surface impedance at different frequencies of the monopole antenna with single (a) 1.6GHz (b) 1.81GHz (c) 2.2GHz strip 
\(L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, \epsilon_r=4.5\text{mm} \) and \(S=2\text{mm}\)

Fig. 3.52. Simulated surface impedance at different frequencies of the monopole antenna with vertical stripes (a) 1.6GHz (b) 1.81GHz (c) 2.2GHz 
\(L_1=25\text{mm}, W_1=3\text{mm}, L_2=17\text{mm}, W_2=14\text{mm}, g=0.35\text{mm}, L_3=26\text{mm}, W_3=9.9\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, \epsilon_r=4.5\text{mm} \) and \(S=2\text{mm}\)

3.6 Chapter conclusion

The following conclusions can be made from the analysis of different structures from this chapter,

- A mobile antenna operating at GSM 1800 band is developed from the finite ground coplanar waveguide fed strip monopole antenna by integrating a parasitic element at the backside with reduced radiation hazards
The measurement results reveal that, the integration of the addon element has an influence over the resonance and radiation behavior of the antenna.

The parasitic element can modify antenna characteristics which is suitable for a mobile handset.

It is found from the measured antenna characteristics that the antenna modifies the omni-directional radiation pattern to radiation pattern with single null.

This antenna structure is very simple.

Reduction of radiated power in one quadrant of the radiation pattern offers, a reduction of radiation towards the users head.

Table 3.6 show the results of the antennas discussed in this chapter.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Resonant Frequency</th>
<th>Frequency band (GHz)</th>
<th>Average gain</th>
<th>Reduced power in null direction (simulation)</th>
</tr>
</thead>
</table>
| Printed monopole              | 2.3                | 1.98-2.58 600 26%    | 1.4dBi       | -----
| Printed monopole with SRR      | 1.82               | 1.75-1.91 160 8.7%   | 1.2dBi       | 18dB            |
| Printed monopole with single strip | 1.81               | 1.76-1.99 230 12.26% | 1.12 dBi     | 20dB            |
| Printed monopole with vertical stripes | 1.8                | 1.76-1.96 200 10.75% | 1.14 dBi     | 23dB            |
The non directional radiation characteristic in the azimuth plane of the planar CPW fed monopole antenna is modified with different structures printed at the backside. These microwave frequency selective devices, designed as parasitic resonators offer high surface impedance. Radiation pattern of the monopole antenna is modified with these different parasitic resonators. Out of this SRR added structure has the lowest operating band and all other antennas have almost same bandwidth. Antenna with vertical stripes provides maximum power reduction along the user. These antennas can be used for mobile applications with less RF interference towards the user.
References

[1] James c Lin “Advances in Electromagnetic field in living systems” volume 5


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