In this chapter, the experimental results obtained for various types of printed dipoles are presented. The studies are conducted in the frequency range of 800 - 2000 MHz. The chapter is divided into three sections as follows:

1. Flared printed dipole

2. Triangular end-loaded printed dipole

3. Parallelogram end-loaded printed dipole

Due to non-availability of proper design criteria of printed dipoles in open literature, a rectangular printed dipole is optimised for maximum impedance bandwidth (2:1 VSWR bandwidth) through experimental iterations. Schematic representation of the dipole is given in Fig. 4.1. The dotted line shows the arm etched on the other side of the substrate. The
Fig. 4.1 Schematic representation of rectangular printed dipole
dipole is matched to 50 Ω feed using a stub and an impedance transformer. The line length and impedance of the stub and transformer are 1.60 cm and 33.5 Ω and 5.80 cm and 42 Ω respectively.

The impedance chart along with the VSWR plot of the dipole are shown in Fig. 4.2. The central frequency of the antenna is 1.498 GHz and the 2:1 VSWR bandwidth is 27%. The co and cross-polar patterns of the principal planes at the central and two end frequencies are given in Fig. 4.3. From this figure, it is clear that the E-plane patterns are broad, similar to that of wire dipole antennas. The deviation in the H-plane patterns from the conventional omnidirectional shape may be due to the finite size of the dielectric substrate and the radiation from the feed structure.

As already mentioned, throughout the experimentation on printed dipoles, the parameters of matching transformer, such as its length and line impedance are kept the same as that in the case of optimised rectangular printed dipole. The optimisation of matching of various dipoles are done by adjusting the length, position and line impedance of the stub.

4.1 FLARED PRINTED DIPOLE

The effect of flaring the dipole arms are studied by providing flaring to the arms of the optimised rectangular printed dipole. The sketch of the antenna is given in Fig. 4.4. Here, all the initial design values are same as that of the optimised rectangular printed dipole. An experimental study of the impedance characteristics with the following antenna parameters has been done:
MARKER 2-1
404.719712 MHz

START 0.795000000 GHz
STOP 2.004375000 GHz

Fig. 4.2 Impedance loci and VSWR plot of rectangular printed dipole
Fig. 4.3 Radiation patterns of rectangular printed dipole

- co-polar: ── 1.296 GHz, ─ 1.498 GHz, ─ 1.700 GHz
- cross-polar: ──× 1.296 GHz, × 1.498 GHz, × 1.700 GHz
Fig. 4.4 Schematic representation of flared printed dipole
1. Flaring angle $\theta$

2. Arms overlapping $O_s$

3. Arm width at feed point $w$

4. Main arm to ground arm ratio $R$

### 4.1.1 Flaring angle

The flaring angle $\theta$ is varied from $0^\circ$ to $20^\circ$, keeping the remaining parameters constant.

The VSWR plots of the dipoles of various flaring angles are given in Fig. 4.5. The $\Delta f$ value in the plots shows the 2:1 VSWR bandwidth. The percentage bandwidths and the central frequencies with optimised stub parameters are given in Table 4.1. It is quite evident from the table that there is considerable improvement in impedance bandwidth with flaring. Although the optimum value of $\theta$ is $10^\circ$, there is little change in percentage bandwidth in the range $5^\circ$ to $15^\circ$. Thus, it can be concluded that the value of $\theta$ is not that critical. Also, with increase in the flaring angle there is a decrease in the central frequency.

#### Table 4.1

<table>
<thead>
<tr>
<th>Flaring angle $\theta$</th>
<th>Stub</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>position (cm)</td>
<td>length (cm)</td>
<td>impedance ($\Omega$)</td>
</tr>
<tr>
<td>$0^\circ$</td>
<td>1.90</td>
<td>1.60</td>
<td>33.5</td>
</tr>
<tr>
<td>$5^\circ$</td>
<td>1.95</td>
<td>2.00</td>
<td>33.5</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>2.15</td>
<td>1.90</td>
<td>36.0</td>
</tr>
<tr>
<td>$15^\circ$</td>
<td>2.30</td>
<td>1.60</td>
<td>32.0</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>2.15</td>
<td>1.05</td>
<td>32.0</td>
</tr>
</tbody>
</table>
Fig. 4.5 VSWR plots of flared printed dipoles for different flaring angles
a) $\theta = 0^\circ$  b) $\theta = 5^\circ$  c) $\theta = 10^\circ$  d) $\theta = 15^\circ$  e) $\theta = 20^\circ$
Since the introduction of flaring to the dipole arms brings a structural modification to the dipole design, its effect on the radiation characteristics is observed in the band of interest. The E and H-plane radiation patterns of the dipole with $\theta = 10^\circ$ are plotted in Fig. 4.6. A comparison with the patterns of the dipole with no flaring (Fig. 4.3) reveals that there is no significant change in the co-polar patterns; but the cross-polar level is high for the flared dipole.

### 4.1.2 Arms overlapping

As a next step towards design optimisation, the flaring angle is selected as $\theta = 10^\circ$ and dipoles are fabricated with different overlapping lengths $O_x$. For this, only the position of main arm, with respect to ground arm is varied; so that other parameters can be kept constant. Thus, along with the overlapping length, the feed point also changes for different dipoles. The VSWR plots of various antennas are given in Fig. 4.7. The percentage bandwidths and the central frequencies along with the optimised stub parameters of different antennas are given in Table 4.2. Although the optimum value of $O_x$ is 9 mm, the effect of change in the arms overlapping length $O_x$ on percentage bandwidth is very small. This is due to the fact that variation in $O_x$ brings only a very little change in the input impedance characteristics of the antenna and is easily compensated by proper selection of stub.

### 4.1.3 Arm width at feed point

The next parameter studied is the width of arms at the feed point. Like previous cases, width $w$ is varied around 8 mm (the value of $w$ for the optimised rectangular printed dipole) in steps of 1 mm, while other parameters are kept constant. The different VSWR plots, and
the percentage bandwidths and the central frequencies are given in Fig. 4.8 and Table 4.3 respectively. Except for $w = 10$ mm, effect of $w$ on the percentage bandwidth is very little. Also the central frequency is shifted towards higher value with increase in $w$. The optimum value of arm width at feed point is $w = 9$ mm.

### Table 4.2

Percentage bandwidths and central frequencies of flared printed dipoles of various arms overlapping with optimised stub parameters

<table>
<thead>
<tr>
<th>Arms overlapping $O_x$ (mm)</th>
<th>Stub</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>position (cm)</td>
<td>length (cm)</td>
<td>impedance (Ω)</td>
</tr>
<tr>
<td>6</td>
<td>2.35</td>
<td>1.40</td>
<td>38.5</td>
</tr>
<tr>
<td>7</td>
<td>2.20</td>
<td>1.40</td>
<td>28.5</td>
</tr>
<tr>
<td>8</td>
<td>2.15</td>
<td>1.90</td>
<td>36.0</td>
</tr>
<tr>
<td>9</td>
<td>1.95</td>
<td>2.00</td>
<td>33.5</td>
</tr>
<tr>
<td>10</td>
<td>1.75</td>
<td>2.00</td>
<td>33.5</td>
</tr>
</tbody>
</table>

### Table 4.3

Percentage bandwidths and central frequencies of flared printed dipoles of various arm widths at feed point with optimised stub parameters

<table>
<thead>
<tr>
<th>Arm width at feed point $w$ (mm)</th>
<th>Stub</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>position (cm)</td>
<td>length (cm)</td>
<td>impedance (Ω)</td>
</tr>
<tr>
<td>6</td>
<td>2.25</td>
<td>1.60</td>
<td>32.0</td>
</tr>
<tr>
<td>7</td>
<td>1.80</td>
<td>1.60</td>
<td>33.5</td>
</tr>
<tr>
<td>8</td>
<td>1.95</td>
<td>2.00</td>
<td>33.5</td>
</tr>
<tr>
<td>9</td>
<td>1.55</td>
<td>2.40</td>
<td>32.0</td>
</tr>
<tr>
<td>10</td>
<td>1.40</td>
<td>2.00</td>
<td>33.5</td>
</tr>
</tbody>
</table>
Fig. 4.6  Radiation patterns of flared printed dipole

coopolar: -- --- 1.197 GHz, --------- 1.441 GHz, -- --- 1.686 GHz

cross-polar: --- x --- 1.197 GHz, ----- x ----- 1.441 GHz, --- x --- 1.686 GHz
Fig. 4.7 VSWR plots of flared printed dipoles for different arms overlapping
a) \( O_1 = 6 \) mm  b) \( O_2 = 7 \) mm  c) \( O_3 = 8 \) mm  d) \( O_4 = 9 \) mm  e) \( O_5 = 10 \) mm
Fig. 4.8  VSWR plots of flared printed dipoles for different arm widths at the feed point
a) w = 6 mm  b) w = 7 mm  c) w = 8 mm  d) w = 9 mm  e) w = 10 mm
4.1.4 Main arm to ground arm ratio

To properly match the balanced dipole to unbalanced microstrip feedline, the dimensions of the ground arm are varied while keeping the main arm dimensions constant. Experiments are conducted for different main arm to ground arm ratio like 1:0.90, 1:0.95, 1:1.00, 1:1.05 and 1:1.10. The corresponding VSWR plots, and the percentage bandwidths and the central frequencies are given in Fig. 4.9 and Table 4.4 respectively. From the table, it is clear that the percentage bandwidth is better for ground arm dimensions larger than the main arm dimensions and increases with the increase in arms ratio. The percentage bandwidth is maximum for the arms ratio 1:1.10, but the difference from the value of percentage bandwidth for ratio 1:1.05 is only 0.41%. It is also well-known that any asymmetry in the arms structure creates asymmetry in the radiation pattern. Thus, as a compromise between the two, the ratio 1:1.05 is selected as the final design value.

Table 4.4

Percentage bandwidths and central frequencies of flared printed dipoles of various main arm to ground arm ratio with optimised stub parameters

<table>
<thead>
<tr>
<th>Main arm to ground arm ratio</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R )</td>
<td>position (cm)</td>
<td>length (cm)</td>
</tr>
<tr>
<td>1:0.90</td>
<td>1.75</td>
<td>2.40</td>
</tr>
<tr>
<td>1:0.95</td>
<td>1.60</td>
<td>2.40</td>
</tr>
<tr>
<td>1:1.00</td>
<td>1.55</td>
<td>2.40</td>
</tr>
<tr>
<td>1:1.05</td>
<td>1.30</td>
<td>2.20</td>
</tr>
<tr>
<td>1:1.10</td>
<td>1.50</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Fig. 4.9 VSWR plots of flared printed dipoles for different main arm to ground arm ratio
a) $R = 1:0.90$  b) $R = 1:0.95$  c) $R = 1:1.00$  d) $R = 1:1.05$  e) $R = 1:1.10$

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From the above results, the optimum parameters of Flared Printed Dipole Antenna (FPDA), shown in Fig. 4.10, are as follows:

- Main arm length \( l_m \) = 4.60 cm
- Flaring angle \( \theta \) = 10°
- Arms overlapping \( O_t \) = 0.90 cm
- Arm width at feed point \( w \) = 0.90 cm
- Feed point location \( l_f \) = 0.45 cm
- Stub length \( S_l \) = 2.20 cm
- Stub position \( S_p \) = 1.30 cm
- Stub line impedance = 33.5 Ω

The ground arm dimensions are 1.05 times larger than the corresponding main arm values.

The impedance plot of FPDA is given in Fig. 4.11. The 2:1 VSWR bandwidth of the antenna is 621.79 MHz with central frequency at 1.588 GHz. Thus, the percentage bandwidth of the antenna is 39.04%.

The E and H-plane radiation patterns of FPDA are given in Fig. 4.12. It can be seen that these patterns do not show significant changes from those of rectangular printed dipole. Thus, it can be stated that the bandwidth enhancement is achieved without any degradation in the radiation characteristics of the dipole.

### 4.1.5 Design details

The design criteria for Flared Printed Dipole Antenna in terms of wavelength \( \lambda_0 \), corresponding to the central frequency, has been developed by fabricating a large number of dipoles of various dimensions. The design details of the antenna, shown in Fig. 4.10, are given below:
Fig 4.10 Schematic representation of optimised flared printed dipole
MARKER 2-1
621.793435 MHz

Fig. 4.11 Impedance loci of FPDA
Fig. 4.12 Radiation patterns of FPDA

coopolar : 1.278 GHz, 1.588 GHz, 1.898 GHz

cross-polar : 1.278 GHz, 1.588 GHz, 1.898 GHz
Main arm length $l_m = 0.243 \lambda_0$
Arm width at feed point $w = 0.048 \lambda_0$
Feed point location $l_f = 0.024 \lambda_0$
Arms overlapping $O_s = 0.048 \lambda_0$
Flaring angle $\theta = 10^\circ$
Stub length $S_t = 0.225 \lambda_d$
Stub position $S_p = 0.133 \lambda_d$
Stub line impedance = 33.5 $\Omega$
Transformer length $l_t = 0.57 \lambda_d$
Transformer line impedance = 42 $\Omega$

All the ground arm parameters are 1.05 times larger than the corresponding main arm values. Here, $\lambda_d = \lambda / \sqrt{\varepsilon_{eff}}$ and the effective dielectric constant $\varepsilon_{eff}$ can be calculated using the formula [139] given below:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{\ln \left( \frac{\pi}{2} \right) + \frac{1}{\varepsilon_r} \ln \left( \frac{4}{\pi} \right)}{\ln \left( \frac{8h}{w} \right)}$$

where, $\varepsilon_r$ is the dielectric constant, $h$ is the thickness of the substrate and $w$ is the width corresponding to the line impedance.

### 4.2 TRIANGULAR END-LOADED PRINTED DIPOLE

As mentioned in the earlier chapter, investigations are also carried out on the effect of different shapes of end-loading on the impedance bandwidth of flared printed dipole antenna. For this, the design values of FPDA are used along with various shapes of loads like triangular, circular, parallelogram etc. The VSWR plots of different antennas are given
in Fig. 4.13 and the corresponding percentage bandwidths and the central frequencies are
given in Table 4.5. It can be seen from the table that the central frequency is much higher
for the triangular and parallelogram loads compared to the rest of the shapes. Also,
percentage bandwidth is maximum for the triangular shape.

To observe the effect of triangular shaped loads at the dipole arms' ends, on the
radiation characteristics, radiation patterns of the antenna are measured and plotted in
Fig. 4.14. From the E and H-plane patterns, it is clear that there is no significant change
in the co-polar patterns with respect to optimised rectangular printed dipole antenna
(Fig. 4.3). Only 3-dB beamwidth for the triangular end-loaded printed dipole is slightly
more than that of the rectangular dipole. Also the cross-polar level is slightly higher for the
triangular end-loaded dipole. From the above observations it can be concluded that
end-loading of dipole arms does not adversely effect the radiation properties of the printed
dipoles.

The sketch of triangular end-loaded printed dipole is given separately in Fig. 4.15.
To optimise the impedance bandwidth of triangular end-loaded printed dipole, the design
values of FPDA are used as initial design values and the effect of the following parameters
on the impedance bandwidth of the antenna is studied.

1. Triangle dimensions
2. Arm width at feed point \( w \)
3. Main arm to ground arm ratio \( R \)
4. Flaring angle \( \theta \)
Fig. 4.13 VSWR plots of FPDA with different shapes of end-loads
  a) Triangular  b) Parallelogram  c) Circular  d) Semi-circular

\[ \Delta f = 652.20 \text{ MHz} \]
\[ \Delta f = 582.71 \text{ MHz} \]
\[ \Delta f = 482.03 \text{ MHz} \]
\[ \Delta f = 461.79 \text{ MHz} \]
Fig. 4.13 VSWR plots of FPDA with different shapes of end-loads
(e) Square  f) Rev-triangular  g) Rev-semi-circular
Table 4.5

Percentage bandwidths and central frequencies of FPDA with various load shapes and optimised stub parameters (a = 1.75 cm)

<table>
<thead>
<tr>
<th>Antenna Loading</th>
<th>Antenna structure</th>
<th>Stub position (cm)</th>
<th>Stub length (cm)</th>
<th>Stub impedance (Ω)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (in GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangle</td>
<td><img src="image" alt="Triangle Antenna" /></td>
<td>1.40</td>
<td>2.50</td>
<td>36.0</td>
<td>42.09</td>
<td>1.547</td>
</tr>
<tr>
<td>Parallelogram</td>
<td><img src="image" alt="Parallelogram Antenna" /></td>
<td>1.60</td>
<td>2.50</td>
<td>39.0</td>
<td>36.96</td>
<td>1.577</td>
</tr>
<tr>
<td>Rev-triangle</td>
<td><img src="image" alt="Rev-triangle Antenna" /></td>
<td>2.25</td>
<td>2.70</td>
<td>39.0</td>
<td>35.74</td>
<td>1.276</td>
</tr>
<tr>
<td>Circle</td>
<td><img src="image" alt="Circle Antenna" /></td>
<td>1.70</td>
<td>2.55</td>
<td>33.5</td>
<td>34.48</td>
<td>1.398</td>
</tr>
<tr>
<td>Rev-semi-circle</td>
<td><img src="image" alt="Rev-semi-circle Antenna" /></td>
<td>2.20</td>
<td>2.25</td>
<td>36.0</td>
<td>34.38</td>
<td>1.245</td>
</tr>
<tr>
<td>Semi-circle</td>
<td><img src="image" alt="Semi-circle Antenna" /></td>
<td>2.00</td>
<td>2.25</td>
<td>36.0</td>
<td>34.35</td>
<td>1.345</td>
</tr>
<tr>
<td>Square</td>
<td><img src="image" alt="Square Antenna" /></td>
<td>1.95</td>
<td>2.50</td>
<td>42.0</td>
<td>32.84</td>
<td>1.385</td>
</tr>
</tbody>
</table>
Fig. 4.14  Radiation patterns of triangular end-loaded printed dipole

co-polar : --- 1.221 GHz, --- 1.546 GHz, ---- 1.872 GHz
cross-polar : * 1.221 GHz, * 1.546 GHz, * 1.872 GHz
Fig 4.15 Schematic representation of triangular end-loaded printed dipole
In the optimisation procedure of FPDA, it was observed that the effect of change in arms overlapping $O_x$ on the impedance bandwidth is very small. Therefore this parameter is not considered here for investigation.

4.2.1 Triangle dimensions

To optimise the dimensions of the triangle, the triangle height $h_t$ is varied from 1.50 cm to 2.50 cm in steps of 0.25 cm and the apex angle $\alpha$ is varied from $80^\circ$ to $120^\circ$ in steps of $10^\circ$. The VSWR plot, and percentage bandwidth and the central frequency along with optimised stub parameters of each antenna are given in Fig. 4.16(i) - (v) and Table 4.6 respectively. From the table, it can be seen that except for very large and very small load size, the percentage bandwidth is improved considerably compared to FPDA. For smaller size of the triangle, the effect of loading is less, hence no improvement is observed in the impedance bandwidth. Conversely, for large size of the triangle, the loading effect is very prominent which considerably alters the input impedance of the dipole and results in drastic reduction in the percentage bandwidth of the antenna. Also from the table, percentage bandwidth is maximum for the triangle height $h_t = 2.00$ cm and the apex angle $\alpha = 100^\circ$.

4.2.2 Arm width at feed point

Keeping the apex angle and the triangle height at their optimum values, the main arm width is varied around 9 mm (the design value of FPDA) in steps of 0.5 mm. The VSWR plots of different antennas are given in Fig. 4.17. The percentage bandwidths and central frequencies along with the optimised stub parameters are given in Table 4.7. From the table, it is clear that the main arm width at the feed point as 9 mm is still the best choice.
Fig. 4.16(i) VSWR plots of triangular end-loaded printed dipoles for different apex angles
\( h_i = 1.50 \, \text{cm} \)

a) \( \alpha = 80^\circ \)  b) \( \alpha = 90^\circ \)  c) \( \alpha = 100^\circ \)  d) \( \alpha = 110^\circ \)  e) \( \alpha = 120^\circ \)
Fig. 4.16(ii) VSWR plots of triangular end-loaded printed dipoles for different apex angles (ht = 1.75 cm)

a) $\alpha = 80^\circ$  b) $\alpha = 90^\circ$  c) $\alpha = 100^\circ$  d) $\alpha = 110^\circ$  e) $\alpha = 120^\circ$
Fig. 4.16(iii) VSWR plots of triangular end-loaded printed dipoles for different apex angles

\( h_r = 2.00 \text{ cm} \)

a) \( \alpha = 80^\circ \)  b) \( \alpha = 90^\circ \)  c) \( \alpha = 100^\circ \)  d) \( \alpha = 110^\circ \)  e) \( \alpha = 120^\circ \)
Fig. 4.16(iv) VSWR plots of triangular end-loaded printed dipoles for different apex angles

(h = 2.25 cm)

a) α = 80°  b) α = 90°  c) α = 100°  d) α = 110°  e) α = 120°
Fig. 4.16(v) VSWR plots of triangular end-loaded printed dipoles for different apex angles 
\( h_i = 2.50 \text{ cm} \)

a) \( \alpha = 80^\circ \)  
b) \( \alpha = 90^\circ \)  
c) \( \alpha = 100^\circ \)  
d) \( \alpha = 110^\circ \)  
e) \( \alpha = 120^\circ \)
Table 4.6

Percentage bandwidths and central frequencies of triangular end-loaded printed dipoles of various apex angles and heights of triangle with optimised stub parameters

<table>
<thead>
<tr>
<th>Apex Angle α</th>
<th>Triangle height ( h_t )</th>
<th>1.50 cm</th>
<th>1.75 cm</th>
<th>2.00 cm</th>
<th>2.25 cm</th>
<th>2.50 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 80^\circ )</td>
<td>1.631 GHz 1.35 cm 1.90 cm 36 Ω</td>
<td>34.71% 1.620 GHz 1.90 cm 36 Ω</td>
<td>36.42% 1.616 GHz 1.90 cm 36 Ω</td>
<td>38.37% 1.616 GHz 1.90 cm 36 Ω</td>
<td>40.60% 1.593 GHz 1.90 cm 36 Ω</td>
<td>39.74% 1.552 GHz 1.90 cm 36 Ω</td>
</tr>
<tr>
<td>( 90^\circ )</td>
<td>1.613 GHz 1.35 cm 2.15 cm 42 Ω</td>
<td>39.30% 1.547 GHz 1.40 cm 36 Ω</td>
<td>42.09% 1.553 GHz 2.25 cm 32 Ω</td>
<td>43.66% 1.557 GHz 2.20 cm 32 Ω</td>
<td>46.80% 1.517 GHz 2.20 cm 32 Ω</td>
<td>46.25% 1.505 GHz 2.20 cm 32 Ω</td>
</tr>
<tr>
<td>( 100^\circ )</td>
<td>1.532 GHz 1.35 cm 2.35 cm 32 Ω</td>
<td>41.51% 1.485 GHz 1.40 cm 32 Ω</td>
<td>43.94% 1.488 GHz 2.35 cm 32 Ω</td>
<td>48.55% 1.430 GHz 2.70 cm 32 Ω</td>
<td>45.81% 1.853 GHz 42 Ω 42 Ω</td>
<td>43.12% 1.398 GHz 42 Ω 42 Ω</td>
</tr>
<tr>
<td>( 110^\circ )</td>
<td>1.404 GHz 1.70 cm 2.35 cm 32 Ω</td>
<td>40.18% 1.357 GHz 2.40 cm 42 Ω</td>
<td>41.18% 1.351 GHz 2.40 cm 42 Ω</td>
<td>45.89% 1.305 GHz 2.40 cm 42 Ω</td>
<td>43.89% 2.05 cm 42 Ω</td>
<td>33.53% 1.297 GHz 42 Ω</td>
</tr>
<tr>
<td>( 120^\circ )</td>
<td>1.329 GHz 1.95 cm 2.20 cm 42 Ω</td>
<td>40.18% 1.278 GHz 2.40 cm 42 Ω</td>
<td>43.07% 1.224 GHz 2.40 cm 42 Ω</td>
<td>41.01% 1.224 GHz 2.40 cm 42 Ω</td>
<td>18.23% 0.95 cm 42 Ω</td>
<td>12.92% 0.991 GHz 42 Ω</td>
</tr>
</tbody>
</table>
Fig. 4.17 VSWR plots of triangular end-loaded printed dipoles for different arm widths at the feed point
a) w = 8.0 mm  b) w = 8.5 mm  c) w = 9.0 mm  d) w = 9.5 mm  e) w = 10.0 mm
Table 4.7

Percentage bandwidths and central frequencies of triangular end-loaded printed dipoles of various main arm widths at feed point with optimised stub parameters

<table>
<thead>
<tr>
<th>Main arm width at feed point ( w ) (mm)</th>
<th>Stub position (cm)</th>
<th>Stub length (cm)</th>
<th>Impedance (Ω)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>1.85</td>
<td>2.75</td>
<td>42.0</td>
<td>45.37</td>
<td>1.430</td>
</tr>
<tr>
<td>8.5</td>
<td>1.70</td>
<td>2.40</td>
<td>42.0</td>
<td>46.77</td>
<td>1.457</td>
</tr>
<tr>
<td>9.0</td>
<td>1.55</td>
<td>2.70</td>
<td>42.0</td>
<td>48.55</td>
<td>1.488</td>
</tr>
<tr>
<td>9.5</td>
<td>1.40</td>
<td>2.50</td>
<td>36.0</td>
<td>43.51</td>
<td>1.480</td>
</tr>
<tr>
<td>10.0</td>
<td>1.50</td>
<td>2.50</td>
<td>36.0</td>
<td>43.77</td>
<td>1.485</td>
</tr>
</tbody>
</table>

4.2.3 Main arm to ground arm ratio

The ratio of main arm to ground arm is varied from 1:0.90 to 1:1.10 as in the case of flared printed dipole antenna and the corresponding VSWR plots are given in Fig. 4.18. The percentage bandwidths and the central frequencies of different antennas are given in Table 4.8. Here, the percentage bandwidth is maximum for the ratio 1:1.05; whereas for the flared printed dipole, it is maximum for the ratio 1:1.10.

4.2.4 Flaring angle

As a last step towards the design optimisation, the flaring angle \( \theta \) is varied from 5° to 15° in steps of 2.5°. The VSWR plot of each antenna and the corresponding percentage bandwidth and the central frequency are given in Fig. 4.19 and Table 4.9 respectively. As in the case of flared printed dipole, the effect of change in the flaring angle on the
Fig. 4.18 VSWR plots of triangular end-loaded printed dipoles for different main arm to ground arm ratio
a) $R = 1:0.90$  b) $R = 1:0.95$  c) $R = 1:1.00$  d) $R = 1:1.05$  e) $R = 1:1.10$
Fig. 4.19 VSWR plots of triangular end-loaded printed dipoles for different flaring angles
   a) $\theta = 5.0^\circ$ b) $\theta = 7.5^\circ$ c) $\theta = 10.0^\circ$ d) $\theta = 12.5^\circ$ e) $\theta = 15.0^\circ$
impedance bandwidth is very small. Also from the table, the percentage bandwidth is maximum for $\theta = 10^\circ$.

**Table 4.8**

Percentage bandwidths and central frequencies of triangular end-loaded printed dipoles of various main arm to ground arm ratio with optimised stub parameters

<table>
<thead>
<tr>
<th>Main arm to ground arm ratio $R$</th>
<th>Stub position (cm)</th>
<th>Stub length (cm)</th>
<th>Stub impedance (Ω)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:0.90</td>
<td>1.65</td>
<td>2.40</td>
<td>36.0</td>
<td>43.23</td>
<td>1.513</td>
</tr>
<tr>
<td>1:0.95</td>
<td>1.65</td>
<td>2.50</td>
<td>36.0</td>
<td>45.05</td>
<td>1.458</td>
</tr>
<tr>
<td>1:1.00</td>
<td>1.70</td>
<td>2.40</td>
<td>42.0</td>
<td>47.51</td>
<td>1.458</td>
</tr>
<tr>
<td>1:1.05</td>
<td>1.55</td>
<td>2.70</td>
<td>42.0</td>
<td>48.55</td>
<td>1.488</td>
</tr>
<tr>
<td>1:1.10</td>
<td>1.65</td>
<td>2.70</td>
<td>42.0</td>
<td>47.45</td>
<td>1.443</td>
</tr>
</tbody>
</table>

**Table 4.9**

Percentage bandwidths and central frequencies of triangular end-loaded printed dipoles of various flaring angles with optimised stub parameters

<table>
<thead>
<tr>
<th>Flaring angle $\theta$</th>
<th>Stub position (cm)</th>
<th>Stub length (cm)</th>
<th>Stub impedance (Ω)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0$^\circ$</td>
<td>1.70</td>
<td>2.50</td>
<td>36.0</td>
<td>46.08</td>
<td>1.393</td>
</tr>
<tr>
<td>7.5$^\circ$</td>
<td>1.55</td>
<td>2.50</td>
<td>36.0</td>
<td>47.44</td>
<td>1.446</td>
</tr>
<tr>
<td>10.0$^\circ$</td>
<td>1.55</td>
<td>2.70</td>
<td>42.0</td>
<td>48.55</td>
<td>1.488</td>
</tr>
<tr>
<td>12.5$^\circ$</td>
<td>1.35</td>
<td>2.50</td>
<td>36.0</td>
<td>47.83</td>
<td>1.522</td>
</tr>
<tr>
<td>15.0$^\circ$</td>
<td>1.45</td>
<td>2.50</td>
<td>36.0</td>
<td>45.94</td>
<td>1.515</td>
</tr>
</tbody>
</table>

From the above results, it is clear that all the design values of FPDA are still valid for triangular end-loaded printed dipole antenna. Thus, it can be stated that the optimisation of the dimensions of the triangular load is related to the other design parameters.
The design data for optimized Triangular End-Loaded Printed Dipole Antenna (TELPDA) are as follows:

- Height of the triangle \( h_i \) = 2.00 cm
- Apex angle \( \alpha \) = 100°
- Stub length \( S_t \) = 2.70 cm
- Stub position \( S_p \) = 1.55 cm
- Stub line impedance = 42 \( \Omega \)

The remaining design parameters are having the same values as that of FPDA.

The impedance plot of the antenna is given in Fig. 4.20. The 2:1 VSWR bandwidth is 723.12 MHz and the central frequency is 1.488 GHz. This corresponds to 48.55% impedance bandwidth. It is interesting to note that the central frequency of FPDA is 1.588 GHz. That is, for the same arms length, there is considerable decrease in the central frequency of TELPDA. This can be attributed to the loading effect of the dipole.

The radiation patterns of the antenna at start, end and central frequencies are given in Fig. 4.21. The co-polar patterns are almost identical to that of the previous dipole patterns but the cross-polar level is slightly high and increases with frequency. This may be due to the fact that, at higher frequencies, sides of the triangle become appreciable fraction of wavelength.

As described in Chapter 3, a comparative gain measurement of TELPDA is done with a standard half wave wire dipole antenna, resonating at 1.496 GHz, which is approximately at the center of the frequency band of TELPDA. Fig. 4.22 shows the \(|S_{21}|\) of the antenna with respect to the wire dipole. From the figure, the gain of TELPDA is only 0.55 dB less than the wire dipole at the resonating frequency of the wire dipole (i.e. at 1.496 GHz). This is obvious because of large impedance bandwidth of TELPDA as
MARKER 2-1
723.117237 MHz

Fig. 4.20 Impedance loci of TELPDA

START 0.795000000 GHz
STOP  2.004375000 GHz
Fig. 4.21 Radiation patterns of TELPDA

co-polar : \(--\) 1.127 GHz, \(\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\) 1.488 GHz, \(\_\_\_\_\_\_\_\_\_\_\_\_\) 1.849 GHz

cross-polar : \(--\times\) 1.127 GHz, \(\_\times\) 1.488 GHz, \(\times\_\times\) 1.849 GHz
Fig. 4.22 $|S_{21}|$ of TELPDA with respect to half wave wire dipole resonating at 1.496 GHz
compared to the wire dipole. Thus, it can be stated that the bandwidth enhancement of the triangular end-loaded printed dipole is achieved without much sacrifice of the gain of the antenna.

4.2.5 Cavity backed triangular end-loaded printed dipole

To produce an unidirectional radiation pattern, dipoles are often used with a reflector plate placed at finite distance away from it, thus forming a cavity backed structure. The effect of reflector plate on the impedance bandwidth of TELPDA is studied by varying the separation $h$ between the reflector plate and the dipole. The VSWR plots for different separations are given in Fig. 4.23. From the plots, it can be seen that VSWR of the antenna increases in the middle portion of the frequency band with decrease in separation between the reflector plate and the dipole and it is more than 2 for separation $h = 4.0$ cm. The change in the percentage bandwidth and the central frequency with separation are given in Table 4.10. From the table, it can be seen that the central frequency increases with separation. Also, percentage bandwidth is maximum for $h = 6$ cm and is selected as the design value.

The impedance plot of Cavity Backed Triangular End-Loaded Printed Dipole Antenna (CBTELPDA) with optimum separation ($h = 6$ cm) is plotted in Fig. 4.24. The impedance bandwidth of the antenna is 786.02 MHz and the central frequency is 1.469 GHz. Thus, the central frequency of CBTELPDA is almost equal to the central frequency of TELPDA. The impedance bandwidth of the antenna is 53.51%. This is nearly 5% more than TELPDA.
Fig. 4.23 VSWR plots of cavity backed TELPDA for different separations between the reflector and the dipole

a) $h = 4.0$ cm  
   b) $h = 4.5$ cm  
   c) $h = 5.0$ cm  
   d) $h = 5.5$ cm  
   e) $h = 6.0$ cm  
   f) $h = 6.5$ cm
MARKER 2-1
786.024598 MHz

START 0.800000000 GHz
STOP 2.000000000 GHz

Fig. 4.24 Impedance loci of CBTELPDA
Table 4.10

Percentage bandwidths and central frequencies of cavity backed triangular end-loaded printed dipole for different separations between the dipole and the reflector plate

<table>
<thead>
<tr>
<th>Separation h (cm)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>15.41 / 19.74</td>
<td>1.181 / 1.672</td>
</tr>
<tr>
<td>4.5</td>
<td>52.25</td>
<td>1.452</td>
</tr>
<tr>
<td>5.0</td>
<td>52.40</td>
<td>1.458</td>
</tr>
<tr>
<td>5.5</td>
<td>52.83</td>
<td>1.459</td>
</tr>
<tr>
<td>6.0</td>
<td>53.51</td>
<td>1.469</td>
</tr>
<tr>
<td>6.5</td>
<td>51.26</td>
<td>1.485</td>
</tr>
</tbody>
</table>

The radiation patterns of CBTELPA are given in Fig. 4.25. Like TELPDA, the cross-polar level is higher at the upper frequency side of the band of interest. The co-polar patterns of the antenna are almost similar to that of TELPDA. Only at higher frequency side, E-plane patterns show a dip of around 0.5 dB at the bore-sight direction. This is due to effective increase in the separation between the dipole and the reflector with the increase in frequency.

Like the case of TELPDA, gain of CBTELPA is compared with the same standard wire dipole antenna, resonating at 1.496 GHz. The $|S_{21}|$ of the antenna with respect to the standard wire dipole is given in Fig. 4.26. The gain of CBTELPA is 4.43 dB more than the standard wire dipole at 1.496 GHz. This increase in gain of CBTELPA is due to the presence of reflector, which enhances the gain of the antenna by making the radiation unidirectional from bidirectional and narrowing the beamwidth compared to TELPDA.
Fig. 4.25  Radiation patterns of CBTELPDA

co-polar  :  ---  1.076 GHz,    ---  1.469 GHz,  ---  1.862 GHz

cross-polar :  ---  *  1.076 GHz,  *  1.469 GHz,  *  1.862 GHz
Fig. 4.26 $|s_{21}|$ of CBTELPDA with respect to half wave wire dipole resonating at 1.496 GHz
4.2.6 Design details

The empirical design criteria for Triangular End-Loaded Printed Dipole Antenna has been developed through experimental iterations. The design details of the antenna, shown in Fig. 4.15, are given below in terms of the wavelength ($\lambda_0$) corresponding to the central frequency.

- Main arm length $l_m = 0.228 \lambda_0$
- Height of the triangle $h_t = 0.099 \lambda_0$
- Arm width at feed point $w = 0.045 \lambda_0$
- Feed point location $l_f = 0.022 \lambda_0$
- Flaring angle $\theta = 10^\circ$
- Apex angle $\alpha = 100^\circ$
- Stub length $S_l = 0.25 \lambda_d$
- Stub position $S_p = 0.143 \lambda_d$
- Transformer length $l_t = 0.54 \lambda_d$
- Transformer line impedance = $42 \Omega$

All the dimensions of ground arm are 1.05 times larger than the corresponding main arm values. Here, $\lambda_d = \lambda_0 / \sqrt{\varepsilon_{ef}}$ and the effective dielectric constant $\varepsilon_{ef}$ can be calculated using the formula given in (1).

From the experimental results of TELPDA and CBTELPDA, it can be seen that the difference in the central frequency of the antennas is negligible compared to the bandwidth of the antennas. Thus, all the design criteria of Triangular End-Loaded Printed Dipole Antenna are valid for Cavity Backed Triangular End-Loaded Printed Dipole Antenna with a separation between the dipole and the reflector of $0.3 \lambda_0$. 
4.3 PARALLELOGRAM END-LOADED PRINTED DIPOLE

From Table 4.5, the next choice of the shape of end-load, after triangle, is parallelogram. Attempts made to enhance the impedance bandwidth of flared printed dipole by parallelogram shaped end-loads are described in this section.

Initial attempts for improving the bandwidth just by changing the size of the parallelogram do not yield much improvement in impedance bandwidth from the value given in Table 4.5. Thus, the design parameters of FPDA are thoroughly modified through experimental iterations.

The schematic diagram of parallelogram end-loaded printed dipole is given in Fig. 4.27 and different initial design values are given below:

- Main arm length \( l_m \) = 4.90 cm
- Main arm width at feed point \( w_m \) = 1.00 cm
- Ground arm width at feed point \( w_g \) = 1.10 cm
- Arms overlapping \( O_s \) = 1.25 cm
- Feed point location \( I_f \) = 0.50 cm
- Flaring angle \( \theta \) = 10°

The ground arm length and the load dimensions are 1.05 times larger than the corresponding main arm values.

The parallelogram dimensions are optimised by varying the bisecting length \( l_p \) from 3.00 cm to 3.75 cm and the angle \( \beta \) from 80° to 120°, while keeping the other parameters constant. The VSWR plots of different antennas are given in Fig. 4.28(i) - (iv) and the corresponding percentage bandwidths and the central frequencies with optimised stub parameters are given in Table 4.11. It is clear from the table that the percentage bandwidth increases with the increase in the size of the parallelogram. The bisecting length
Fig. 4.27 Schematic representation of parallelogram end-loaded printed dipole
Fig. 4.28(i) VSWR plots of parallelogram end-loaded printed dipoles for different angles ($l_p = 3.00 \text{ cm}$)

a) $\beta = 80^\circ$  b) $\beta = 90^\circ$  c) $\beta = 100^\circ$  d) $\beta = 110^\circ$  e) $\beta = 120^\circ$
Fig. 4.28(ii) VSWR plots of parallelogram end-loaded printed dipoles for different angles ($l_p = 3.25$ cm)

(a) $\beta = 80^\circ$  b) $\beta = 90^\circ$  c) $\beta = 100^\circ$  d) $\beta = 110^\circ$  e) $\beta = 120^\circ$
Fig. 4.28(iii) VSWR plots of parallelogram end-loaded printed dipoles for different angles ($l_p = 3.50\ cm$)

a) $\beta = 80^\circ$  
b) $\beta = 90^\circ$  
c) $\beta = 100^\circ$  
d) $\beta = 110^\circ$  
e) $\beta = 120^\circ$
Fig. 4.28(iv) VSWR plots of parallelogram end-loaded printed dipoles for different angles ($l_p = 3.75$ cm)

a) $\beta = 80^\circ$  b) $\beta = 90^\circ$  c) $\beta = 100^\circ$  d) $\beta = 110^\circ$  e) $\beta = 120^\circ$
Table 4.11

Percentage bandwidths and central frequencies of parallelogram end-loaded printed dipoles of various angles and bisecting lengths with optimised stub parameters

<table>
<thead>
<tr>
<th>Angle $\beta$</th>
<th>Bisecting length $l_p$</th>
<th>3.00 cm</th>
<th>3.25 cm</th>
<th>3.50 cm</th>
<th>3.75 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°</td>
<td>23.67% 1.594 GHz 1.40 cm 2.50 cm 39 $\Omega$</td>
<td>23.93% 1.627 GHz 1.40 cm 2.30 cm 42 $\Omega$</td>
<td>26.35% 1.573 GHz 1.40 cm 2.50 cm 42 $\Omega$</td>
<td>30.40% 1.559 GHz 1.40 cm 2.50 cm 36 $\Omega$</td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td>25.28% 1.568 GHz 1.40 cm 2.50 cm 39 $\Omega$</td>
<td>28.18% 1.540 GHz 1.40 cm 2.50 cm 39 $\Omega$</td>
<td>30.14% 1.530 GHz 1.45 cm 2.25 cm 36 $\Omega$</td>
<td>31.90% 1.519 GHz 1.45 cm 2.50 cm 42 $\Omega$</td>
<td></td>
</tr>
<tr>
<td>100°</td>
<td>31.23% 1.513 GHz 1.40 cm 2.50 cm 36 $\Omega$</td>
<td>33.73% 1.482 GHz 1.35 cm 2.50 cm 36 $\Omega$</td>
<td>34.14% 1.511 GHz 1.45 cm 2.25 cm 36 $\Omega$</td>
<td>37.44% 1.498 GHz 1.40 cm 2.50 cm 36 $\Omega$</td>
<td></td>
</tr>
<tr>
<td>110°</td>
<td>35.48% 1.434 GHz 1.50 cm 2.70 cm 36 $\Omega$</td>
<td>37.45% 1.449 GHz 1.45 cm 2.50 cm 36 $\Omega$</td>
<td>39.48% 1.469 GHz 1.45 cm 2.25 cm 36 $\Omega$</td>
<td>42.21% 1.525 GHz 1.40 cm 2.30 cm 42 $\Omega$</td>
<td></td>
</tr>
<tr>
<td>120°</td>
<td>40.71% 1.385 GHz 1.50 cm 2.70 cm 36 $\Omega$</td>
<td>42.55% 1.434 GHz 1.45 cm 2.50 cm 42 $\Omega$</td>
<td>46.52% 1.435 GHz 1.40 cm 2.55 cm 36 $\Omega$</td>
<td>48.74% 1.514 GHz 1.25 cm 2.50 cm 42 $\Omega$</td>
<td></td>
</tr>
</tbody>
</table>
$l_p = 3.75$ cm and the angle $\beta = 120^\circ$ are the maximum possible values of the parallelogram. Further increase in the values of these parameters means overlapping of the loading structure with the feed structure, which will completely change the impedance characteristics of the antenna. Thus, $l_p = 3.75$ cm and $\beta = 120^\circ$ are taken as the optimum design parameters.

While optimising the triangular end-loaded printed dipole, it was observed that the optimisation of the dimensions of the end-load is related to other design parameters. Thus, no attempt has been made to reconfirm the optimisation of other parameters.

The final design values of optimised Parallelogram End-Loaded Printed Dipole Antenna (PELPDA) are as follows:

- Bisecting length $l_p = 3.75$ cm
- Angle $\beta = 120^\circ$
- Stub length $S_t = 2.50$ cm
- Stub position $S_p = 1.25$ cm
- Stub line impedance = 42 $\Omega$

The remaining design values are same as that given earlier.

The impedance plot of the antenna is given in Fig. 4.29. The 2:1 VSWR bandwidth is 738.26 MHz and the central frequency is 1.514 GHz. Thus, the percentage bandwidth is 48.74\%, which is almost the same as that of TELPDA.

The radiation patterns of the antenna at start, stop and central frequencies are given in Fig. 4.30. The radiation patterns are almost identical to that of TELPDA. The only difference is that the cross-polar level is higher in this case. This may be due to the large size of the end-loads.
MARKER 2-1
738.26295 MHz

START 0.000000000 GHz
STOP 2.000000000 GHz

Fig. 4.29 Impedance loci of PELPDA
Fig. 4.30 Radiation patterns of PELPDA

- co-polar: 1.145 GHz, 1.514 GHz, 1.883 GHz
- cross-polar: 1.145 GHz, 1.514 GHz, 1.883 GHz
The gain of PELPDA is measured by measuring the $|S_{21}|$ of the antenna with respect to the same standard half-wave dipole used for TELPDA. From the $|S_{21}|$ plot (Fig. 4.31), it can be seen that at 1.496 GHz (resonating frequency of standard dipole), the gain of PELPDA is less than that of wire dipole by 1.64 dB.

4.3.1 Cavity backed parallelogram end-loaded printed dipole

Similar to Cavity Backed Triangular End-Loaded Printed Dipole, the effect of reflector plate on the impedance bandwidth of PELPDA is studied. The separation $h$ between the dipole and the reflector plate is varied from 4.5 cm to 6.5 cm in steps of 0.5 cm and the corresponding VSWR plots are given in Fig. 4.32. The VSWR of the antenna is more than 2 in the central part of the frequency band for the separation $h = 5$ cm and increases with the decrease in the separation. The percentage bandwidths and the central frequencies for different separations are given in Table 4.12. Although VSWR bandwidth is maximum for $h = 5.5$ cm, from the corresponding VSWR plot (Fig. 4.32(c)), it can be seen that at 1.4 GHz VSWR is 1.98. This is too close to VSWR = 2 limit. Thus, $h = 6$ cm is selected as the design value, for which VSWR is sufficiently below VSWR = 2 limit in the middle portion of the band of interest.

The impedance plot of Cavity Backed Parallelogram End-Loaded Printed Dipole Antenna (CBPELPDA) with separation $h = 6$ cm is given in Fig. 4.33. The 2:1 bandwidth is 817.34 MHz and the central frequency is 1.489 GHz. This corresponds to 54.85% impedance bandwidth. This is 6% more than PELPDA and 1% more than CBTELPDA.
Fig. 4.31 $|S_{21}|$ of PELPDA with respect to half wave wire dipole resonating at 1.496 GHz
Fig. 4.32 VSWR plots of cavity backed PELPDA for different separations between the reflector and the dipole
a) h = 4.5 cm  b) h = 5.0 cm  c) h = 5.5 cm  d) h = 6.0 cm  e) h = 6.5 cm
Fig. 4.33 Impedance loci of CBPELPDA
Table 4.12

Percentage bandwidths and central frequencies of cavity backed parallelogram end-loaded printed dipole for different separations between the dipole and the reflector plate

<table>
<thead>
<tr>
<th>Separation $h$ (cm)</th>
<th>Percentage bandwidth</th>
<th>Central frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>22.31 / 26.17</td>
<td>1.205 / 1.677</td>
</tr>
<tr>
<td>5.0</td>
<td>25.92 / 25.36</td>
<td>1.227 / 1.677</td>
</tr>
<tr>
<td>5.5</td>
<td>55.42</td>
<td>1.488</td>
</tr>
<tr>
<td>6.0</td>
<td>54.85</td>
<td>1.489</td>
</tr>
<tr>
<td>6.5</td>
<td>53.04</td>
<td>1.502</td>
</tr>
<tr>
<td>7.0</td>
<td>49.54</td>
<td>1.526</td>
</tr>
</tbody>
</table>

The principal planes radiation patterns at the start, end and central frequencies of the band of interest are given in Fig. 4.34. The radiation patterns are almost identical to that of CBTELPDA. As compared to PELPDA, cross-polar level is higher for this antenna.

Like previous cases, the same standard wire dipole, resonating at 1.496 GHz, is used to measure the gain of CBPELPDA. The $|S_{21}|$ plot of the antenna with respect to standard wire dipole is given in Fig. 4.35. The gain of the antenna is 3.13 dB more than wire dipole at 1.496 GHz. This is almost 5 dB more compared to PELPDA at 1.496 GHz. The increase in gain is due to the presence of the reflector plate and narrowing of the beamwidth.

4.3.2 Design details

The design criteria of Parallelogram End-Loaded Printed Dipole Antenna have been evolved through experimental iterations, as in the case of Triangular End-Loaded Printed Dipole. The design details of the antenna, shown in Fig. 4.27, are given below in terms of the wavelength ($\lambda_0$) corresponding to the central frequency.
Fig. 4.34 Radiation patterns of CPFELPA

- co-polar
- cross-polar

1.081 GHz, 1.490 GHz, 1.899 GHz
Fig. 4.35 $|s_{21}|$ of CBPELPDA with respect to half wave wire dipole resonating at 1.496 GHz
Main arm length $l_m = 0.243 \lambda_0$
Bisecting length $l_p = 0.189 \lambda_0$
Main arm width at feed point $w_m = 0.050 \lambda_0$
Feed point location $l_f = 0.025 \lambda_0$
Arms overlapping $O_k = 0.063 \lambda_0$
Flaring angle $\theta = 10^9$
Angle $\beta = 120^9$
Stub length $S_t = 0.235 \lambda_d$
Stub position $S_p = 0.118 \lambda_d$
Stub line impedance = 42 $\Omega$
Transformer length $l_t = 0.55 \lambda_d$
Transformer line impedance = 42 $\Omega$

Ground arm length and the load dimensions are 1.05 times larger than the corresponding main arm values and the ground arm width at feed point is 1.10 times larger than the corresponding main arm value. Here, $\lambda_d = \lambda_0 / \epsilon_{ef}$ and the effective dielectric constant $\epsilon_{ef}$ can be calculated from (1).

The difference in central frequency of PELPDA and CBPELPDA is negligible as compared to the bandwidth of the antennas for all practical purposes. Thus, all design criteria of Parallelogram End-Loaded Printed Dipole Antenna are valid for Cavity Backed Parallelogram End-Loaded Printed Dipole Antenna with a separation between the dipole and reflector of 0.3 $\lambda_0$. 