In this chapter, design and analysis of a wideband antenna using the fabricated cylindrical dielectric resonator (DR) are discussed, with the support of simulated and measured results. Starting with the fundamental broadside operation of a cylindrical dielectric resonator antenna (DRA), a step-by-step development of the proposed wideband antenna, using a low radiation Q-factor design is presented. Computer aided high frequency structure simulator, Ansoft HFSS™ [1] is used for modeling and simulating the antenna. Antenna characteristics such as the return loss, impedance, radiation pattern, gain and radiation efficiency are measured with the help of HP 8510C vector network analyser.

### 4.1 BROADSIDE MODE OPERATION OF A CYLINDRICAL DRA

The antenna study is started with the cylindrical DR, DR-1 of dielectric constant, $\varepsilon_{rd} = 20.8$, unloaded quality factor, $Q_u = 6558$ at 3.94 GHz, diameter, $2a = 24$ mm or $0.24 \lambda_0$ and thickness, $d = 7.3$ mm or $0.073 \lambda_0$, $\lambda_0$ being the free space wave length corresponding to the fundamental mode frequency, $f = 3.03$ GHz of the DRA.

The antenna structure used for broadside radiation operation [2, 3] of a cylindrical DR is shown in Figure 1. A 50 $\Omega$ microstrip line, having a width = 3.3 mm and length = 50 mm fabricated on a 1.6 mm thick microwave substrate of dielectric constant $\varepsilon_{rs} = 4$ and size 115 mm x 115 mm, feeds the DRA. This structure will operate on the fundamental broadside mode which is HEM$_{11\alpha}$ (also
known as TM_{110} [4]) for a cylindrical DR. This mode is very attractive in terms of its lowest-Q factor compared to other modes of a cylindrical DR [5]. Impedance matching between the feed and the DR can be easily achieved by adjusting the DR position relative to the microstrip.

![Diagram of Cylindrical DR (std) and Microstripline](image)

**Figure 1**: Broadside radiation operation of the cylindrical DR

### 4.2 RESULTS

Measured and simulated return loss ($|S_{11}|$) of the DRA as a function of frequency is shown in Figure 2, for an offset distance of $l = 6$ mm that corresponds to the maximum impedance matching. The DRA resonates at 3.03 GHz with a $-10$ dB bandwidth ranging from 2.92 to 3.144 GHz or 7.38 %. This high bandwidth is the result of the low radiation Q-factor of the excited mode. The input impedance measured is $49-j 4 \Omega$ at 3.03 GHz. Simulated resonance occurs at 3.09 GHz with a bandwidth of 4.28 %. The mismatch between the measured and simulated results is attributed to the ideal modeling of antenna
elements in HFSS™, where the dielectrics and conductors are assumed to be perfect.

In the literature [6], accurate closed form formulae for the frequencies of the resonant modes of a cylindrical DR are available. For the $\text{HEM}_{115}$ mode, the resonant frequency is given by

$$f_r = \frac{6.324c}{2\pi a\sqrt{\varepsilon_r} + 2} \left[ 0.27 + 0.36 \frac{a}{2d} + 0.02 \left( \frac{a}{2d} \right)^2 \right]$$  \hspace{1cm} (4.1)

where $c$ is the velocity of light in free space. The formula yields a frequency of 3.05 GHz which is in agreement with the measured value.

![Figure 2: Measured return loss of the cylindrical DRA](image-url)
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Measured far-field radiation patterns in the two principal planes, namely XZ and YZ-planes of the antenna, at 3.03 GHz are shown in Figure 3. Patterns are broadside, similar to that of a horizontal magnetic dipole, with boresight cross-polarisation levels of -22.61 dB and -16.34 dB in the XZ and YZ-planes respectively. Also the boresight front-to-back lobe ratios are -21.18 dB and -25 dB in the XZ and YZ-planes respectively and a gain of 5.71 dBi is measured at the resonant frequency of 3.03 GHz.

Figure 3: Measured radiation pattern of the cylindrical DRA

In the following section, the broadside design shown above is transformed into a wideband, conical beam design.
4.3 LOW Qc / WIDE BAND DESIGN: DESIGN 1

The schematic diagram of the cylindrical DRA for achieving a low radiation Q (Qc) is shown in Figure 4. The dimensions are as given in the previous section. The new parameter introduced here is a vertical branch of height $h$ on which the microstrip line is terminated. The DRA is oriented with its axis along the $Y$-direction and a vertical branch, which is cut from a conducting tape, is attached to the DRA surface and is connected electrically to the tip of the feed line as shown in the figure.

By adjusting the parameter $h$, good impedance matching can be obtained in the same way as that for a broadside mode DRA. This particular design will be termed as design 1 in all the following sections.

![Figure 4: Wideband design of the cylindrical DRA](image)

4.4 RESULTS

Figure 5 shows the measured return loss of the DRA design 1, for various values of $h$ from 5 to 13 mm. It is clear that the impedance matching is very...
sensitive to the parameter $h$. For $h = 9$ mm, a maximum impedance bandwidth of 1120 MHz or 35.94 % from 2.556 to 3.676 GHz is observed. Bandwidth in percentage is calculated with respect to the centre frequency of the $-10$ dB band, which is 3.116 GHz. A minimum return loss of $-42$ dB is obtained at 3.2 GHz.

The wideband effect of design 1 is verified by simulation and the results are shown in Figure 6. Simulated resonant frequency is 3.23 GHz and bandwidth is 1150 MHz or 36.45 % (2.58 to 3.73 GHz) which are in good conformity with the measured values.

Figure 5: Measured return loss of the DRA for various strip heights ($h$)
Figure 6: Measured and simulated return loss of DRA, for $h = 9$ mm

Figure 7: Measured and simulated input impedance of DRA, for $h = 9$ mm
Measured and simulated input impedances of the DRA shown in Figure 7, justify good and steady matching over the band. The radiation patterns of the DRA are measured at 3.2 GHz and are shown in Figure 8.

Figure 8: Measured 2-D radiation patterns of the DRA at 3.2 GHz, for $h = 9$ mm
As evident from the patterns, the XZ-plane pattern is symmetric and conical in nature with a null of \(-24.71\) dB occurring at the boresight or zenith \((\theta = 90^\circ)\) and the maximum radiation at \(\theta = 145^\circ\). The cross-polarisation is \(-12.42\) dB in the direction of maximum radiation and \(-4.92\) dB in the boresight. This high cross-polarisation in the boresight is due to the vertical strip, that may radiate as a monopole antenna in the similar way as for a probe coupled DRA. On the other hand, the YZ-plane pattern shows an asymmetry with a boresight null of \(-10.12\) dB and the maximum radiation at \(150^\circ\). The asymmetry is due to the effect of the coaxial cable and the connector, attached to the feed end of the DRA. The cross-polar level is around \(-10\) dB in the boresight as well as in the peak radiation directions.

Stability of the radiation pattern over the impedance band is further studied by comparing the patterns at different frequencies in the band. The copolar patterns for three different frequencies viz. 2.6, 3.2 and 3.6 GHz in the band are shown in Figure 9. Cross-polar patterns are simply excluded for better differentiation of the individual plots. It is clear that the symmetry and conical nature of the XZ-plane patterns are preserved in the matching band, but the pattern distortion in the YZ-plane becomes worse as moved from the lower end to the higher end of the band. This is because, the disturbance caused by the cable and the connector on the radiation increases with the frequency.

Simulated 3-D gain patterns are shown in Figure 10, which clearly show the pattern distortion or squint in the band. Measured gain is 2.98 dBi at the
resonant frequency of 3.2 GHz, while the peak value in the band is 4.34 dBi measured at 3.48 GHz.

Figure 9: Measured 2-D radiation patterns of the DRA at different frequencies in the band, for \( h = 9 \) mm.
As obvious from Figure 5, the wideband performance depends only on the parameter $h$. Also a change in the center frequency of the operating band requires a change in the DR properties. Thus design 1, though simple and easy to implement, lacks in some free and flexible means for tuning the operating band over a considerable range.

Incorporation of metallic sections on the feed as tuning stubs has been shown to be a potential means for tuning the impedance matching [7] of DRAs. In the present context, instead of fabricating additional metallic elements on the feed, a new approach is used to modify the design 1, wherein the vertical feed position is displaced backward from the strip end in order to add a microstrip stub of length $L$ to the design. As will be shown, the combination of the feed height $h$
Experimental Analysis

and stub length \( L \) effectively helps to tune the impedance matching as well as the operating band.

4.5 MODIFIED DESIGN WITH A HORIZONTAL STUB: DESIGN 2

The design shown in Figure 4 is modified by displacing the DRA and the vertical feed on the microstrip, thereby introducing a horizontal stub of length \( L \) in the design as shown in Figure 11.

![Diagram of Modified Wideband DRA Design](image)

Figure 11: Modified wideband DRA design

4.6 RESULTS

Plots of the measured return loss of the DRA for various strip heights \( h \) and stub lengths \( L \) for a width same as that of the microstrip are shown in Figures 12 (a), (c), (e) and (g). As the figures show, for a given \( h \), an optimum value of \( L \) gives the maximum \(-10 \) dB bandwidth. As \( h \) is increased, the band is shifted to a lower frequency range for a given \( L \) value. The bandwidth variations with \( h \) and \( L \) are depicted in Figures 12 (b), (d), (f), and (h). The parameter \( L \) thus
provides an additional freedom for effectively tuning the impedance and reflection characteristics of the DRA.
Figure 12 (a) - (h): Variation in return loss and bandwidth of the DRA with $h$ and $L$. 

$h = 11$ mm

\\begin{align*} 
\text{Return Loss (dB)} \\
\text{Frequency (GHz)} \\
\text{% Bandwidth} \\
\text{Stub length, } L \text{ (mm)} \\
\end{align*}

$\text{L=25 mm}$
$\text{27.5 mm}$
$\text{30 mm}$
$\text{32.5 mm}$
$\text{35 mm}$
Summary of the reflection characteristics of the wideband DRA obtained from Figure 12 is given below.

Table 1: Reflection characteristics of the DRA for optimum \( h \) and \( L \)

<table>
<thead>
<tr>
<th>Strip height ((h, \text{mm}))</th>
<th>Stub length ((L, \text{mm}))</th>
<th>(-10\text{dB Frequency range (GHz)})</th>
<th>Mid-band frequency (GHz)</th>
<th>Bandwidth (MHz)</th>
<th>% Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>17.5</td>
<td>3.15 – 4.03</td>
<td>3.59</td>
<td>880</td>
<td>24.51</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>2.43 – 3.47</td>
<td>2.95</td>
<td>1040</td>
<td>35.25</td>
</tr>
<tr>
<td>9</td>
<td>27.5</td>
<td>2.01 – 2.85</td>
<td>2.43</td>
<td>840</td>
<td>34.57</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>1.89 – 2.43</td>
<td>2.16</td>
<td>540</td>
<td>25</td>
</tr>
</tbody>
</table>

From the measured results of Table 1, optimum values of \( h \) and \( L \) can be expressed empirically as

\[
h = \frac{\lambda_0}{3\sqrt{\varepsilon_{rd}}} \quad \text{and} \quad L = \frac{\lambda_0}{\sqrt{\varepsilon_{rd}}}
\]  

(4.2)

where \( \lambda_0 \) is the free space wavelength at the mid band frequency and \( \varepsilon_{rd} \) the dielectric constant of the DRA. Here, the designs with \( h = 7 \text{ mm}, \; L = 25 \) (design 2a) and \( h = 9 \text{ mm}, \; L = 27.5 \text{ mm} \) (design 2b) are chosen for further analysis since these provide the broadest bandwidths in excess of 30%. The other two designs \((h = 5 \text{ mm}, \; L = 17.5 \text{ and } h = 11 \text{ mm}, \; L = 30)\) will be treated later. Figure 13 compares the measured and simulated return loss and input impedance of the DRA for design 2a.
Figure 13: Measured and simulated (a) return loss (b) input impedance of the DRA, for design 2a ($h = 7$ mm and $L = 25$ mm)
Simulated $-10\text{dB}$ bandwidth is from 2.4 to 3.41 GHz (1010 MHz) or 34.77 \% at the centre frequency of 2.905 GHz, which are in good agreement with the measured results shown in Table 1 that gives a 2.43 to 3.47 GHz or 35.25 \% band.

Figure 14: Measured radiation patterns at 3.01 GHz, for design 2a
Two dimensional radiation patterns measured at 3.01 GHz that corresponds to the minimum measured return loss in Figure 13 (a) are shown in Figure 14.

As observed from the radiation patterns, the conical nature is maintained in both XZ and YZ-planes than that of the design discussed in the previous section (design 1). The boresight nulls are of $-36.67 \text{ dB}$ and $-24.56 \text{ dB}$ in the XZ and YZ-planes respectively. Cross-polar levels are of $-6.31 \text{ dB}$ and $-12.73 \text{ dB}$ at the boresight respectively for the XZ and YZ-plane patterns. Peak radiation occurs at $130^\circ$ and $150^\circ$ respectively in the XZ and YZ-planes, with the corresponding cross-polarisations of $-14.12 \text{ dB}$ and $-11.84 \text{ dB}$. Gain measurements yielded 4.65 dBi at the resonant frequency of 3.01 GHz and the maximum gain in the band is 5.58 dBi at 3.4 GHz.

Figure 15 shows the measured co-polar patterns at the lower, mid and upper ends of the matching band respectively at 2.5, 3.01 and 3.4 GHz. It is clear that the symmetry and conical nature of the XZ-plane pattern is stable in the matching band similar to the previous design. However, the YZ-plane pattern is less distorted with the increase in frequency unlike that in design 1. This is further confirmed by the 3-D radiation patterns of Figure 16.
Figure 15: Measured 2-D radiation patterns of the DRA at different frequencies in the band, for design 2a
For design 2b, the agreement between measured and simulated results is shown in Figure 17. Simulated bandwidth is 817 MHz or 32.42 % from 2.11 to 2.927 GHz at the mid-band frequency of 2.52 GHz, while that measured is 840 MHz or 34.57 % from 2.01 to 2.85 GHz.
Figure 17: Measured and simulated (a) return loss (b) input impedance of the DRA, for design 2b ($h = 9$ mm and $L = 27.5$ mm)
Figure 18: Measured radiation patterns at 2.43 GHz, for design 2b
Radiation patterns measured at 2.43 GHz, the centre frequency of the band are shown in Figure 18. XZ and YZ plane patterns are more symmetrical and conical shaped than those of the previous designs (design 1 and design 2a). The nulls are at $-40$ dB and $-19.56$ dB in the boresight for XZ and YZ-planes respectively. Cross-polar levels are of $-26.5$ dB and $-14.93$ dB respectively at the boresight for XZ and YZ-plane patterns. Peak radiation occurs at $130^\circ$ and $150^\circ$ respectively in the XZ and YZ-planes, with the respective cross-polarisations of $-14.73$ dB and $-21.47$ dB. Measured mid-band gain is 4.39 dBi and the maximum measured value in the band is 5.57 dBi at 2.36 GHz.

From the 2-D patterns measured for different frequencies, at 2.15, 2.43 and 2.8 GHz shown in Figure 19, it is clear that the design 2b produces good conical radiation patterns over the matching band. Simulated 3-D radiation patterns shown in Figure 20 also confirm the pattern stability over the band.

Measured far-field transmission coefficients ($|S_{21}|$) in the direction of maximum radiation of the DRAs so far studied are compared in Figure 21. It is clear that peak $|S_{21}|$ corresponding to design 1 is lower than that of any other designs in their respective bands, hence results in the lowest gain of all. The peak gain of the broadside DRA is comparable to that of design 2. Table 2 compares the various aspects of the wideband designs so far described.

Radiation patterns at other two combinations of $h$ and $L$, i.e. $h = 5$ mm, $L = 17.5$ and $h = 11$ mm, $L = 30$, shown in Table 1, were also measured. The patterns measured at the centre frequencies of the corresponding bands i.e. 3.59
Experimental Analysis

GHz and 2.16 GHz respectively, are shown in Figure 22. As observed, the conical nature of the patterns is much deteriorated at the higher frequency (3.59 GHz). Also these designs provide maximum gains around 4 dBi.

Figure 19: Measured 2-D radiation patterns of the DRA at different frequencies in the band, for design 2b
Figure 20: Simulated 3-D gain patterns of the DRA for design 2b

Figure 21: Comparison of the far-field $|S_{21}|$ of the DRAs
Table 2: Comparison of the results of the wideband designs (dimensions are in ‘mm’)

<table>
<thead>
<tr>
<th>Design parameters ((h, L - \text{mm}))</th>
<th>-10 dB band (GHz, %)</th>
<th>Frequency of interest ( (f_0, \text{GHz}) )</th>
<th>Boresight null level (dB)</th>
<th>Boresight Cross-polar level (dB)</th>
<th>Peak radiation direction ((\theta_p, \text{Deg.}))</th>
<th>Cross-polar level in ( \theta_p ) (dB)</th>
<th>Gain at ( f_0 ) (dBi)</th>
<th>Maximum gain in the band (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design 1 (9,0)</td>
<td>2.556 – 3.676, 35.94</td>
<td>3.2</td>
<td>-24.71</td>
<td>-10.12</td>
<td>-4.92 -10</td>
<td>145 150</td>
<td>-12.42 -11.5</td>
<td>2.98</td>
</tr>
<tr>
<td>Design 2a (7,25)</td>
<td>2.43 – 3.47, 34.25</td>
<td>3.01</td>
<td>-36.67</td>
<td>-24.56</td>
<td>-6.31 -12.73</td>
<td>130 150</td>
<td>-14.12 -11.84</td>
<td>4.65</td>
</tr>
<tr>
<td>Design 2b (9,27.5)</td>
<td>2.01 – 2.85, 34.57</td>
<td>2.43</td>
<td>-40</td>
<td>-19.56</td>
<td>-26.5 -14.93</td>
<td>135 145</td>
<td>-14.73 -21.47</td>
<td>4.39</td>
</tr>
</tbody>
</table>

4.34 (at 3.48 GHz)
5.58 (at 3.4 GHz)
5.57 (at 2.36 GHz)
Figure 22: Measured radiation patterns for (a) $h = 5 \text{ mm}, L = 17.5$ at $3.59 \text{ GHz}$

(b) $h = 11 \text{ mm}, L = 30$ at $2.16 \text{ GHz}$
4.7  RADIATION FROM THE ANTENNA FEED

In this section, radiation properties of the wideband antenna feed are studied. As described earlier, the antenna feed consists of two sections of microstrip transmission lines of length \( h \) and \( L \). The section of length \( L \) lies on the substrate and is a part of the 50 \( \Omega \) feed. However, the section of height \( h \) extends vertically into the air, and hence can act as a vertical monopole radiator under the influence of the large ground plane. Figure 23 shows the simulated resonance curves of the feeds with various dimensions.

![Figure 23: Simulated return loss of the feed](image-url)
As can be observed from the figure, a $-14$ dB deep resonance exists at 7.55 GHz for the feed of design 1 ($h = 9$ mm, $L = 0$ mm). This value is approximately equal to the resonant frequency of a $\lambda/4$ monopole of length $h = 9$ mm. Simulated 3-D radiation pattern at 7.55 GHz is given in Figure 24.

![Simulated radiation pattern of the feed at 7.55 GHz](image)

Figure 24: Simulated radiation pattern of the feed at 7.55 GHz

As observed from the above figure, the radiation pattern is not of a well defined shape, so that it can hardly be used for any application purpose. This monopole radiation can influence the radiation performance of the DRA if the operating band includes the monopole band also, which could happen when using DRs with low value of dielectric constant ($\varepsilon_{rd}$). This is because, firstly, a higher value of $h$ will be needed for better impedance matching of a low $\varepsilon_{rd}$ DR, and hence the monopole resonance will occur at a frequency lower than that in the present case ($h = 9$ mm). Secondly, the DR will operate at a higher frequency because of the low $\varepsilon_{r}$. Consequence is an effective resonating band, merged by the individual bands of the DR and the monopole at the lower and the higher ends.
respectively, with the radiation pattern distorted towards the higher end of the band.

4.8 WIDEBAND DESIGN USING OTHER DRs – RESULTS

Validity of the wideband design (Design 2) is verified using other DRs also having parameters as follows:

(1) **DR-2**: $\varepsilon_{rd} = 20.8$, diameter $2a = 27.3$ mm or $0.24 \lambda_0$ and thickness $d = 8.4$ mm or $0.074 \lambda_0$, $\lambda_0$ being the free space wave length corresponding to the measured broadside mode frequency, $f = 2.65$ GHz of the DRA.

(2) **DR-3**: $\varepsilon_{rd} = 88.68$, diameter $2a = 24$ mm or $0.166 \lambda_0$ and thickness $d = 7.8$ mm or $0.054 \lambda_0$, $\lambda_0$ corresponds to the measured broadside mode frequency, $f = 2.04$ GHz of the DRA.

The antennas using the above DRs (1) and (2) will be referred respectively as DRA-1 and DRA-2 in the following discussion. HFSS™ simulation is used to optimise the design parameters to yield maximum matching bandwidth and the simulated return loss plots are presented in Figures 25 and 26 respectively for DRA-2 and DRA-3. Tuning of the impedance characteristics is appealing from Figures 25(a) and 26(a). For DRA-2, selection of $h = 10$ mm and $L = 31$ mm gives a bandwidth from 1.9 to 2.65 GHz or 33 %. Measured return loss is compared with the simulated one in Figure 25(b). A matching band from 1.849 to 2.549 GHz or 32 % is obtained for the measurement. This band covers some important wireless communication bands like PCS (1.85 to 1.99 GHz), UMTS (1.9
to 2.2 GHz), WiBro (2.3 to 2.39 GHz) and WLAN (ISM: 2.4 to 2.484 GHz) [Table 2, Chapter 1]. The above figure also shows two merged resonances, at 1.9 GHz and 2.41 GHz constituting the matching band.

For DRA-3, a maximum simulated bandwidth of 11.15% is achieved for \( h = 5 \text{ mm} \) and \( L = 30 \text{ mm} \), while the measured band is from 1.835 to 2.125 GHz or 14.65%. This band covers the PCS and some part of the IMTS and UMTS bands. Corresponding plots are shown in Figure 26.

Measured conical radiation patterns for DRA-2 and DRA-3 are shown in Figure 27 and 28 respectively. Note that the radiation patterns at the two resonances, at 1.9 GHz and 2.41 GHz for DRA-2 are shown in Figure 27, revealing that both resonances have the same radiation characteristics. Measured gain is 3.74 dBi at 1.9 GHz and 3.95 dBi at 2.41 GHz. Also the maximum measured gain in the band is 4.71 dBi, at 2.3 GHz. For DRA-3, the radiation patterns at 1.945 GHz, which is the frequency giving minimum reflection and also is the mid-band frequency, are plotted in Figure 28. Gain measurement yielded a maximum gain of 3.88 dBi at 1.945 GHz, for DRA-3.
Figure 25: (a) Simulated return loss of DRA-2 for various \( h \) and \( L \)
(b) Measured and simulated return loss for \( h = 10 \) mm and \( L = 31 \) mm
Figure 26: (a) Simulated return loss of DRA-3 for various $h$ and $L$

(b) Measured and simulated return loss for $h = 5$ mm and $L = 30$ mm
Figure 27: Measured radiation patterns for DRA-2
Figure 28: Measured radiation patterns for DRA-3
Table 3: Summary of the radiation properties of DRA-2 and DRA-3 (dimensions are in ‘mm’)

<table>
<thead>
<tr>
<th>DRA with ((\varepsilon_r, 2a, d, h, L))</th>
<th>-10 dB band (GHz, %)</th>
<th>Freq. of interest (f_0)GHz)</th>
<th>Boresight null level (dB)</th>
<th>Boresight Cross-polar level (dB)</th>
<th>Peak radiation direction (\theta_p) Deg.</th>
<th>Cross-polar level in (\theta_p) (dB)</th>
<th>Gain at (f_0) (dBi)</th>
<th>Maximum gain in the band (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRA-2 ((20.8, 27.3, 8.4, 10, 31))</td>
<td>1.849 – 2.549, 32</td>
<td>1.9</td>
<td>-24.64</td>
<td>-19.12</td>
<td>-14.36</td>
<td>-13.6</td>
<td>140</td>
<td>150</td>
</tr>
</tbody>
</table>
4.9 Radiation Efficiency

Radiation efficiencies of the DRAs are measured using the Wheeler cap method (Section 3.10.4, Chapter 3). A cylindrical metallic cap of diameter = 17 cm and height = 7.5 cm was used as the radiation shield, for the DRA. Measured efficiencies in the respective operating bands are given in Table 4.

Table 4: Measured radiation efficiencies of the DRAs so far studied
(dimensions are in ‘mm’)

<table>
<thead>
<tr>
<th>DRA</th>
<th>Broadside</th>
<th>Design 1</th>
<th>Design 2a</th>
<th>Design 2b</th>
<th>DRA-2</th>
<th>DRA-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ε₀, 2a, d, h, L)</td>
<td>(20.8,24,7.3,9,25)</td>
<td>(20.8,24,7.3,9,25)</td>
<td>(20.8,24,7.3,9,25)</td>
<td>(20.8,27.3,8.4,10,31.25)</td>
<td>(88.6,24,7.8,5,30)</td>
<td></td>
</tr>
<tr>
<td>Radiation Efficiency (%)</td>
<td>85.3</td>
<td>96.24</td>
<td>93.07</td>
<td>92.85</td>
<td>91.65</td>
<td>76.08</td>
</tr>
</tbody>
</table>

From the above table, it can be made out that the wideband design offers higher radiation efficiency than the fundamental design of a cylindrical DR. Also it is deduced that the DR with low εᵣ is a better radiator than that with high εᵣ, since the energy storage is more in the case of the latter. However, promising size reduction can not be achieved with a lower εᵣ DR, unless special design rules are followed. Thus, when the use of a DR as an antenna is concerned, the choice of εᵣ is as per the requirement of the antenna engineer.
4.10 WIDEBAND DESIGN USING A DIFFERENT SUBSTRATE

In order to confirm the suitability of the wideband design (design 2) with different substrate for the feed, the DRA is simulated using a 50 mm x 4.93 mm microstrip line formed on a 1.6 mm thick RT/Duroid substrate of $\varepsilon_r = 2.2$. The feed was designed using Eq. 3.21 and 3.22 in Chapter 3. The DR parameters are, $\varepsilon_r = 20.8$, $2a = 24$ mm and $d = 7.3$ mm, the same as those of DR-1. The $-10$ dB impedance bands, almost the same as those obtained on the $\varepsilon_r = 4$ substrate, are found here also as,

**Band 1:** 2.43 to 3.45 GHz, for $h = 7$ mm, $L = 31.5$ mm

**Band 2:** 2.1 to 2.91 GHz, for $h = 9$ mm, $L = 37$ mm as shown in Figure 29.

![Figure 29: Simulated return loss of the wideband DRA excited by a microstrip feed on an RT/Duroid substrate](image-url)
CONCLUSION

Development of a wideband cylindrical DRA was presented with the help of measurements using HP 8510C vector network analyser and simulations using Ansoft HFSS™. A bandwidth in excess of 30% with stable conical radiation pattern and good gain was obtained for the proper design. High radiation efficiencies in excess of 90% were obtained, due to the inherent low loss of the DR. Effect of various design parameters on the DRA performance was also studied. The mid-band frequency of the operating band can be tuned by changing the topological and/or material properties of the DRA. However, medium permittivity DRs are preferred for the design, since they provide wider bandwidths, better gains and higher radiation efficiencies than high permittivity DRs.
REFERENCES

[1] High Frequency Structure Simulator (HFSS), Ansoft Corporation, Pittsburgh, PA


