Chapter 3

Hemispherical and Conical Dielectric Resonator Loaded Hybrid Monopole Antennas
3.1 INTRODUCTION

A hybrid monopole-DRA has been described in Chapter 2 using a new pawn-shaped DRR. This pawn-like shape was realized as a combination of two geometries: a hemispherical DRR (HDRR) placed on top of a conical of DRR (Co-DRR). The aim was to improvise the DRR shape to provide favorable interactions and adjustment of electromagnetic (EM) fields between the DRR and the electric monopole (EMP).

Compared to a cylindrical DRR [1]-[4], a hemisphere by virtue of its shape offers smoother transition of the domain of EM interactions. The geometry of a cone also offers a smooth tapering in the interaction zone.

Instead of using the combination, either a hemispherical or a conical DRR alone is found to be efficient enough to provide similar ultra-wide operating bandwidth. These designs involve relatively simpler shapes which are easier to design and fabricate employing lesser amount of dielectric material, machining, cost and weight. Systematic studies leading to optimized design parameters for both the geometries are presented. Fabrication tolerance has been examined and two sets of prototypes have been physically realized for the measurements.

It is observed that the nature of resonant modes change as soon as HDRR is replaced by CoDRR or vice versa, keeping the monopole and the ground plane unchanged. This has been studied and discussed. An efficient design guideline has been developed for each of the geometries. Reliability of the proposed designs has also been verified for different frequency ranges.

About 120-126% impedance bandwidth with consistent monopole-like radiation over the entire operating band has been experimentally demonstrated. As much as 4 dBi peak gain has also been obtained experimentally. Proposed antenna geometries, their characteristics, designs, fabrication tolerance and experimental studies are presented in the following sections.
3.2 HYBRID MONOPOLE-DRA GEOMETRIES

Proposed hybrid configurations of monopole DRAs are shown in Fig. 3.1. A vertical monopole of length $l$ is fitted with a circular ground plane of diameter $d$. A hemispherical dielectric resonator (relative permittivity $\varepsilon_r$, radius $a$) is drilled through its center to form a cylindrical hole of radius $b$. Thus a hemispherical dielectric ring is formed and this is placed on the ground plane surrounding monopole. The spacing between monopole surface and dielectric body is determined by the parameter $s = b - r$, $r$ being the radius of the monopole. The radius of the base of the cone is $a$ and that of the central cut is $b$. The height of the cone may be calculated as $\frac{a^2}{(a-b)}$, which after drilling the central hole reduces to effective height $h$. The top views of both the geometries are identical. The centrally cutout hole in either dielectric body not only provides a space for accommodating the vertical monopole, but also plays a significant role in coupling the electromagnetic fields between the monopole and dielectric resonant structure.

3.3 HYBRID MONOPOLE USING HEMISPHERICAL DRR (HDRR)

This investigation was started with design parameters as used in [4] and just replacing cylindrical DRR by a hemispherical DRR. Then a thorough parametric study has been performed to achieve optimum operating bandwidth and also to examine the fabrication tolerance of the practical structure. A physical insight into the resonances of the hybrid structure resulting in ultra-wide impedance bandwidth has been developed. Detailed discussions along with a set of representative results are provided below.
Fig. 3.1. (a) Top view of either structure, (b) cross-sectional view for HDRR-loaded monopole, (c) cross-sectional view for CoDRR-loaded monopole.
3.3.1 Parametric Studies and Optimized Design

Figure 3.2 compares two simulated $S_{11}$ versus frequency for an electric monopole ($l = 10$ mm and $r = 0.65$ mm) when it is successively loaded by a cylindrical and a hemispherical DRR, respectively, both being made of identical material ($\varepsilon_r = 10$) and of same radius $a = 4.2$ mm. The monopole using HDRR shows about 12% extra impedance bandwidth indicating a promise for much improved optimized design. This indeed needs optimization of antenna parameters.

Unlike cylindrical DRA, the hemispherical structure needs only one dimensional parameter ‘$a$’ and its effect on the input impedance is examined in Fig. 3.3. For a set of antenna parameters, indicated in Fig. 3.3, the values of $a$ varying between 4.5 - 5.0 mm appear to be the best choice from bandwidth point of view. Fabrication tolerance of about 0.5 mm is evident.
Taking \(a = 5\) mm, the monopole has been optimized in Fig. 3.4. The length of the monopole determines its resonances and details about this will be discussed in section 3.3.3. However for the present configuration, \(l = 10\) to 11 mm appears to be optimum choice. As \(l\) is increased gradually, some additional resonances start appearing on either side of the frequency band, which definitely correlate the resonances due to the monopole. Also using longer monopole, the intermediate \(S_{11}\) improves indicating clear minima.

The coupling between the monopole and the DRR is controlled by the parameter \(s\) or \(b = (r + s)\) related to the cut-out cylinder. Larger values of \(b\) deteriorate the performance. Its optimum choice is found to be in between 1.5 mm and 2 mm for the present case. In Fig. 3.5, we have varied the parameter \(b = (r + s)\) instead of \(s\) since there is hardly any scope of varying \(r\), the probe radius. Any value of \(b\) lying between 1.3 and 2.0 mm works well indicating acceptable tolerance in manufacturing the device.

But from scientific point of view, it is equally important to examine the effect of different \(r\) values as shown in Fig. 3.6. The value of \(r = 0.65\) mm is considered as a...
standard one for a commercial SMA probe commonly used in our laboratory. Increase in $r$ value up to about 50% is quite acceptable.

Fig. 3.4. Simulated $S_{11}$ versus frequency for different probe length $l$, $a = 5$ mm, other parameters as in Fig. 3.2.

Fig. 3.5. Simulated $S_{11}$ versus frequency of DRA loaded monopole for varying $b$ values. Parameters $a = 5$ mm, $l = 11$ mm, $r = 0.65$ mm.
Fig. 3.6. Simulated $S_{11}$ versus frequency of HDRA. Parameters $a = 5$ mm, $l = 11$ mm, $b = 2$ mm.

Fig. 3.7. Simulated radiation characteristic for optimum hybrid-monopole HDRA. $a = 5$ mm, $b = 2$ mm, $l = 11$ mm, $r = 0.65$ mm and $\varepsilon_r = 10$. 
So far, we have discussed about the impedance bandwidth only, which for a set of optimum parameters, is promising for operating frequencies covering 6-22 GHz. The monopole-DRA radiates vertically polarized fields, which is azimuthally symmetric. Fig. 3.7 shows its radiation characteristics at any vertical plane for different frequencies over the entire bandwidth. This ensures consistent monopole-like radiations with about 2-4 dBi peak gain occurring around 30°-70° away from bore sight. The 3 dB beam width varies from 30°-50°. To earn confidence in the simulated data, experimental measurements have been executed and presented below.

### 3.3.2 Experimental Studies and Verification

The hemispherical dielectric resonator has been shaped from Eccostock HiK material with $\varepsilon_r = 10$. A 70 mm diameter brass plate, centrally flitted with a PE 4128 SMA probe, has been used as the monopole structure. The hybrid configuration of the prototype is shown in Fig. 3.8.

![Prototype fabricated from Eccostock HiK material with $\varepsilon_r = 10$, $a = 5.04$, $r = 0.65$, $b = 1.82$, $l = 11$ (all dimensions are in mm).](image)

Fig. 3.8. Prototype fabricated from Eccostock HiK material with $\varepsilon_r = 10$, $a = 5.04$, $r = 0.65$, $b = 1.82$, $l = 11$ (all dimensions are in mm).
The prototype has been measured using Agilent's E8363B network analyzer to study its resonance characteristics. For the radiation measurements, Agilent's E8257D signal generator (250 KHz-40 GHz) has been used as a broadband source connected to the transmitting horns and Agilent's E4418B power meter fitted to the antenna under test for recording the received power. Figure 3.9 shows measured $S_{11}$ trace of the prototype with start and stop frequencies as 5 GHz and 25 GHz, respectively. Considerable impedance matching has been obtained over 5-21 GHz indicating more than 4:1 ratio and about 126.5 % bandwidth ($S_{11}$ ≤ -10 dB). Fig. 3.9 compares this measured result with the simulated data, obtained using [5]. The measurement closely follows the nature of the simulated curve, but shows a relative shift towards the lower side of the spectrum. Small amount of capacitive loading during its measurement is apparent, which causes shift in $S_{11}$ values to the lower frequency. Sometimes it becomes unavoidable due to imperfections in some interconnects between commercial probes, SMA connectors and adapters used.

Fig. 3.9. Measured $S_{11}$ of the prototype of Fig. 3.8 compared with simulated data.
The combined response of the monopole and the DRA and its corresponding impedance locus on a smith chart are shown in Fig. 3.10. Multiple loops within VSWR≈2 circle around the centre indicating multiple resonances in sequence, can be noticed in Fig. 3.10.

Figure 3.11 shows measured radiation patterns of the prototype obtained at two different frequencies in X- and Ku bands, respectively. They closely agree with the
simulated data as incorporated in the figure for comparison. Nearly 4 dBi peak gain is evident at either frequency. In measurements, a large ground plane with $d = 70$ mm has been used, which is about 1.5 times the wavelength corresponding to the first resonance ($\lambda_1$). Smaller and also practical ground plane may be used and value of $d$ as small as $0.6\lambda_1$ is quite acceptable without causing degradation of radiation patterns, peak gain and impedance bandwidth.

![Simulated and Measured Radiation Patterns](image)

**Fig. 3.11** Measured radiation patterns of the prototype of Fig. 3.8 compared with simulated data. (a) 10 GHz, (b) 17 GHz.
3.3.3 Physical Insight into the Ultrawide Bandwidth

Understanding the antenna behaviour, particularly when a DRR simple loading results in a dramatic change in the impedance matching over ultrawide frequency band is very important for various reasons. For the present HDRR loaded hybrid monopole, $S_{11}$ versus frequency plot reveals four distinct minima as shown in Fig. 3.12.

![Simulated return loss characteristics of bare monopole, monopole-fed DRA and isolated DR radius $a = 5.01$ mm.](image)

This indicates four resonances around 6.8, 13, 16 and 20 GHz, respectively. If we look at Fig. 3.2, one additional resonance due to HDRR is apparent. At the first step, let us examine two more individual cases:

(i) a standalone monopole (removing HDRR from Fig. 3.8) and (ii) a centrally fed HDRR (reducing the monopole height to 2.5 mm), respectively. Their individual resonance characteristics are incorporated in Fig. 3.12. The monopole alone shows two resonances near 6.5 and 19.5 GHz, respectively. These are corroborated by the theoretical calculations. The monopole with $l = 11$ mm should theoretically resonate with the fundamental mode ($l = \lambda/4$) near 6.8 GHz and then with the first higher mode ($l = 3\lambda/4$) near 20.45 GHz. They indeed correspond to two extreme resonances due to the hybrid...
structure and one may, therefore, surmise that two extreme resonances in the monopole-DRA are caused by the monopole itself. The centrally fed hemispherical DRR shows a trace of resonance around 17 GHz. This is due to TM_{101} mode in the HDRR and corresponds to the third resonance (near 16 GHz) of the hybrid antenna.
It is confirmed through further investigations and shown in Fig. 3.13. DRRs of different radii have been excited by identical probe of length 2.5 mm. The third $S_{11}$ minima changes with the change in 'a' value.

The third minimum near 15-16 GHz is caused solely by HDRR. A small probe is used to excite the DRR only and the $S_{11}$ value is shown in Fig. 3.14. The $S_{11}$ minimum appears exactly at 15 GHz and thus ensures that the resonance near 15-16 GHz is caused by DRR only.

We are finally left with one unidentified resonance occurring near 13 GHz. This needs the second phase of investigation as shown in Fig. 3.15. This uses simulated electric field and current distributions in the dielectric and metallic resonators, respectively at four distinct frequencies. At 6.8 GHz (Fig. 3.15(a)), the electric fields in HDRR are insignificant, but the surface current on monopole reveals a profile for the fundamental mode. It is important to note that all the simulated fields and currents are captured with identical scale of intensity. Original figures are in color where red indicates the maximum intensity and the minimum is represented by blue. In grey scale, those appear as deep dark and faint grey shades, respectively. For better recognition, the
simulated current intensity on monopole has been translated to current profile and is added against each diagram.

![Graph of S11 versus frequency characteristic of HDRR excited centrally by a small probe of length 1.5 mm and radius 0.3 mm.](image)

Fig. 3.14. $S_{11}$ versus frequency characteristic of HDRR excited centrally by a small probe of length 1.5 mm and radius 0.3 mm.

Now let us look at Fig. 3.15(d), where the current profile confirms the first higher mode in the monopole. In here, the HDRR should be free from any excited field. But DRR's own resonance ($f \approx 16$ GHz) occurs so close to this that considerable amount of electric field is found to share in the DRR body. Figure 3.15(c) shows significant electric fields concentrated in the DRR with TM$_{101}$ mode, but no significant currents on the monopole. This corroborates our conjecture as discussed earlier based on the results of Fig. 3.12. Finally, the resonance at 13 GHz, examined in Fig. 3.15(b), appears to be quite interesting. In here, both the radiating elements bear indicative electric current and field distributions. The current profile looks like a monopole of reduced height and the nature of electric fields in DRR indicates a strong coupling between the monopole and the DRR. The strong coupling restricts the currents in the monopole, particularly towards its upper
part and thus effectively produces a reduced height monopole. Pictorially it is nearly half of its actual height and a rough calculation following $L_{\text{equivalent}} = 0.5l = \lambda/4$ results in 13.6 GHz.

Fig. 3.15. Electric field, surface current and effective surface current profile of HDRA and monopole at different frequencies respectively. (a) 6.8 GHz, (b) 13 GHz, (c) 16 GHz, (d) 20 GHz)
This is very close to the actual value (13 GHz). This second resonance thus appears as the product of marriage between the monopole and the HDRR. From the above investigation, it is important to note that the hemispherical geometry is advantageous over cylindrical ring resonator [4] since it allows the loaded monopole to resonate up to in its first higher mode. This indeed adds an additional resonance over and above [4] and results in about 22-26% additional bandwidth.

3.4 HYBRID MONOPOLE USING CONICAL DRR (CoDRR)

Hybrid monopole-DRA using HDRR is examined above. If the HDRR is replaced by an identical (same radius and material) CoDRR, its impedance bandwidth remain exactly the same.

3.4.1 Optimum Design and Results

A detailed study is presented in this section. The $S_{11}$ of hybrid monopoles using CoDRR is compared with that using HDRR in Fig. 3.16. Only difference lies in their resonances, which are examined in a following section.

![Graph](image)

**Fig. 3.16.** Simulated $S_{11}$ versus frequency for two hybrid monopole-DRA structures. Parameters as in Fig. 3.8, CoDRR $h = 5$ mm.
Fig. 3.17 Simulated $S_{11}$ versus frequency of Co-DRA loaded monopole: (a) change with varying radius $a$, (b) change with varying $b$. $\varepsilon_r = 10$, $h = 5$, $r = 0.65$, $l = 11$ (all dimensions are in mm).
Like HDRR, its fabrication tolerances are shown in Fig. 3.17. Any value of its radius lying in between 5.0 and 5.5 mm offers optimum impedance bandwidth. $S_{11}$ values are equally sensitive to the radius of the central cut-out cylinder. In here also, $b = 1.825$ mm appears as an optimum parameter.

Figure 3.18 shows a prototype, which uses the same monopole as in Fig. 3.8 and a physically realized CoDRR shaped from the same Eccostock HiK material. The measured $S_{11}$ values are shown in Fig. 3.19 along with the simulated data. Close agreement between them is revealed. Measured radiation patterns in X- and Ku-bands are shown Fig. 3.20. It shows almost identical peak gain values with those produced by HDRR (Fig. 3.11).

![Prototype fabricated from Eccostock HiK material with $\varepsilon_r = 10, h = 5.01, a = 5.045, r = 0.65, b = 1.825, l = 11$ (all dimensions are in mm).]
Fig. 3.19. Measured $S_{11}$ of the prototype of Fig. 3.18 compared with simulated data.
Fig. 3.20 Measured radiation patterns of the prototype of Fig. 3.18 compared with simulated data. (a) 10 GHz, (b) 17 GHz.

### 3.4.2 IDENTIFICATION OF RESONANT MODES

A study similar to that in Fig. 3.12 is repeated in Fig. 3.21 for CoDRR loaded monopole. Like Fig. 3.12, the first resonance of the standalone monopole coincides with the first $S_{11}$ minimum due to the hybrid antenna. The second resonance of the standalone monopole almost coincides with that due to CoDRR alone and both of them appear near 22 GHz, which again is very close to the third $S_{11}$ minimum of the hybrid antenna.

Like Fig. 3.15, the modes are pictorially examined in Fig. 3.22. Instead of four, three frequencies corresponding to $S_{11}$ minima (Fig. 3.21) are examined here. Fig. 3.22(a) resembles a quarter wave monopole resonating with its fundamental mode. Fig. 3.22(c) obtained at 22 GHz indicates the first higher resonance due to the monopole. The electric fields in the DRR are not significantly strong. This in other way indicates that CoDRR cannot resonate itself in the hybrid configuration. Fig. 3.22(b) obtained for the second resonance exactly corroborates the same portrays studied in Fig. 3.15(b). It is indeed
produced by a reduced height monopole caused by a strong coupling between the DRR and the monopole. As was already discussed in section 3.3.3, similar approximate relation $l_{\text{equivalent}} = 0.5l = \lambda/4$ results in a resonance near 13.6 GHz. It is therefore relevant to note that, a CoDRR loaded monopole effectively looses one resonance and that may affect the desired wideband matching in particular cases.

Fig. 3.21. Simulated return loss characteristics of bare monopole, monopole-fed DRA and isolated DRA for DR radius $a = 5.0425$ mm.
Fig. 3.22. a, b, c, Electric field in DRR. Surface current and effective surface current profile on monopole at three different resonant frequencies (a) 6.5, (b) 14 GHz and (c) 22 GHz respectively.
3.5 COMMON DESIGN GUIDELINE AND VERIFICATION

Based on the above studies and thorough understanding of the resonant modes, a design guideline is proposed which is valid for either DRR shape.

DESIGN STEPS

(i) Frequency of Operation:
If the operating frequency is specified by its lower and upper values as $f_L$ and $f_H$, respectively, then for the present hybrid monopole DRA, they are related as $f_H \approx 4f_L$.

(ii) Dimension of Monopole: The first $S_{11}$ minimum relates the dominant mode resonance due to the monopole itself and it occurs near $f_1 = 1.25 f_L$. Its corresponding wavelength is $\lambda_1 (= c/f_1$, c being the velocity of light in free space). First higher mode due to monopole resonates at $f_2 = 3f_1$.

Monopole Length ($l$): $l = \lambda_1/4$, (1)
Radius ($r$): $s \geq r \geq s/2$, (2)
with $0.019 \lambda_1 \leq s \leq 0.042\lambda_1$, (3)

where, $s$ is the spacing between monopole and Inner boundary of the DRR (Fig.3.1).

(iii) HDRR and CoDRR Parameters:
Radius $a$ can be determined using the design procedure [6] as

$$a \text{ (in cm)} = 4.7713 \times \text{Re}(k_0a)/f_r \text{ (in GHz)}$$ (4)

where, $f_r = 0.5(f_1 + f_2)$. Re($k_0a$) is the real part of $k_0a$ and is expressed as a function of $\varepsilon_r$ [6]. Table 3.1 provides some useful values for a set of $\varepsilon_r$'s. A designer, therefore, enjoys freedom to choose $\varepsilon_r$ to realize an antenna, but values above 20 do not present a suitable choice. Higher $\varepsilon_r$ causes higher $Q$ for TM$_{101}$ mode, which in turn degrade the antenna performance in terms of bandwidth as well as radiation.

Height of CoDRR: $h = a$ (5)
TABLE 3.1
Re($k_o \alpha$) OF THE TM$_{10i}$ MODE OF A HEMISPHERICAL DRA

<table>
<thead>
<tr>
<th>$\varepsilon_r$</th>
<th>Re($k_o \alpha$)</th>
<th>$\varepsilon_r$</th>
<th>Re($k_o \alpha$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.18200</td>
<td>45</td>
<td>0.64943</td>
</tr>
<tr>
<td>4</td>
<td>2.24670</td>
<td>50</td>
<td>0.61845</td>
</tr>
<tr>
<td>6</td>
<td>1.83440</td>
<td>55</td>
<td>0.59143</td>
</tr>
<tr>
<td>8</td>
<td>1.58870</td>
<td>60</td>
<td>0.56762</td>
</tr>
<tr>
<td>10</td>
<td>1.42090</td>
<td>65</td>
<td>0.54645</td>
</tr>
<tr>
<td>15</td>
<td>1.16020</td>
<td>70</td>
<td>0.52745</td>
</tr>
<tr>
<td>20</td>
<td>0.92278</td>
<td>75</td>
<td>0.51030</td>
</tr>
<tr>
<td>25</td>
<td>0.84240</td>
<td>80</td>
<td>0.49470</td>
</tr>
<tr>
<td>30</td>
<td>0.77926</td>
<td>85</td>
<td>0.48044</td>
</tr>
<tr>
<td>35</td>
<td>0.72803</td>
<td>90</td>
<td>0.46733</td>
</tr>
<tr>
<td>40</td>
<td>0.68547</td>
<td>95</td>
<td>0.45524</td>
</tr>
</tbody>
</table>

VERIFICATIONS

The above guideline is followed to determine the antenna parameters for different frequency ranges for a test. They are furnished in Table 3.2 for both HDRR and CoDRR loaded monopoles and are implemented through the simulation tool [5]. Resulting $S_{11}$ versus frequency plot is shown in Fig. 3.23. The plots are self explanatory and confirm the reliability of the proposed design. However, design #2 in Fig. 3.23(b) needs further optimization since $S_{11}$ value overshoots $S_{11} < -10$ dB limit by about 1.0 to 1.5 dB over a small range of frequency 18-21.5 GHz.

TABLE 3.2
HDRA / CoDRA PARAMETERS DETERMINED USING DESIGN GUIDELINES
$\varepsilon_r=10$, $h = a$ for CoDRR, ground plane radius $= \lambda_4/3$

<table>
<thead>
<tr>
<th>Design Freq. $f_1 - f_2$ (GHz)</th>
<th>$\lambda_i$ (cm)</th>
<th>Antenna Parameters (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$l$</td>
</tr>
<tr>
<td>#1: 4-16</td>
<td>6.00</td>
<td>15.0</td>
</tr>
<tr>
<td>#2: 5.6-22.4</td>
<td>4.29</td>
<td>10.7</td>
</tr>
</tbody>
</table>
Chapter 3: On Some Novel Wideband and Ultra Wideband...

Fig. 3.23 (a). Theoretical designs provided in Table 3.2 verified using simulated $S_{11}$ values. (a) hybrid monopole using HDRA; (b) hybrid monopole using CoDRR.
3.6 CONCLUSION

The configurations of monopole-DRA, explored in this chapter, are improved ones in terms of the operating bandwidth, ease of designing and fabrication. Two DRA shapes and their designs have been discussed. Either of the geometries can be used, but the feasibility in terms of their machining may be another aspect to choose the DRA shape. Both are equally suitable for their considerable fabrication tolerance. Surface finish of both the dielectric and metal bodies should be taken care of, particularly if the design frequency goes beyond X-band. A considerably compact monopole having nearly 126% or 4:1 operating bandwidth with average 4 dBi peak gain should find a wide range of applications starting from wideband EM sensor to UWB communications. The provided design guidelines should be useful in yielding easy designs for various applications.

REFERENCES


