Chapter 5. **Helical Antenna in a Cylindrical Cavity**
5.1 Introduction

In most cases, helical antennas are mounted over a ground plane. The length of the helical element is one wavelength or greater. The ground plane is a circular or square metal sheet whose cross dimension measures at least $3\lambda/4$. The length of the helix and the size of ground plane is the main problem in making the helical antenna compact and conformal. When the helical antenna needs to be used for aircrafts, the shape and size of the antenna affects the aerodynamic property of the aircraft and to solve this problem the helical antenna is loaded in a cavity. The main challenge in designing is to reduce the size of the helix and making it to the conformable shape.

In this chapter, a helical antenna of 1.64 turns is loaded in a cavity for 2.4 GHz frequency, which reduces the size and makes it conformal. This type of antenna is designed for use with an unbalanced feed line such as the coaxial cable. The centre conductor of the cable is connected to the helical element, and the shield of the cable is connected to the ground plane. 3-D modelling and simulation is done by the SINGULA simulation software by Integrated Engineering Software. The antenna is fabricated in an aluminium cavity with copper helix.

The antenna can be considered as the band pass filter, the concept of helical resonator filter [64] is used for designing of helical loaded cavity backed antenna to reduce the size. A helical resonator is a passive electrical component that is used as a filter. Physically a helical resonator is a wire helix surrounded by a square or cylindrical conductive shield like cavity resonators.

5.2 Helical Loaded Cavity Backed Antenna

The helix is enclosed in a highly conductive shield of circular cross section [64] as shown in Fig. 5.1. One lead of the helical winding is connected directly to the transmission line and the other end is open circuited. The design is done by considering the helical resonator as a quarter-wavelength section of helical transmission line, and by the equivalent formulation for inductance ($L$) and capacitance ($C$).
The inductance per unit length is derived from the well known Nagaoka equation for the inductance of a single layer solenoid. The expression is modified for the cavity [65] which gives the result.

\[ L = 0.025n^2d^2[1 - (d/D)^2] \quad \text{μH per axial inch} \]  \hspace{1cm} (5.1)

where

- \( L \) is the equivalent inductance of the resonator in μH per axial inch.
- \( d \) is the mean diameter of helix in inches.
- \( D \) is the inside diameter of the shield in inches.
- \( n = 1/\tau \) is the number of turns per inch.
- \( \tau \) is the pitch of the winding in inches.

The capacitance per unit length (\( C \)) for air dielectric is empirical and only valid for the case \( b/d = 1.5 \). It is similar to the capacitance for a normal coaxial line and is given by

\[ C = \frac{0.75}{\log_{10}(D/d)} \text{ pF per axial inch} \]  \hspace{1cm} (5.2)
The expression (5.2) takes no account of the self capacitance of the helix. The self capacitance is the capacitance that exists between the turns of the helix. The axial length of the helix \( b \) is a quarter wavelength long. However, empirically the length is approximately 6% less due to the fringing and self capacitance of the coil, the capacitance that exists between the turns of the helix. Thus, axial length of the helix \( b \) is given by (5.3)

\[
b = \frac{0.235v}{f \times 10^{-6}} \text{ inch} \tag{5.3}
\]

Where \( v = 1/(LC)^{1/2} \text{ inch/second} \)

This equation (5.1), (5.2) and (5.3) are only valid for the following condition:

\[
1.0 < b/d < 4.0 \tag{5.4}
\]

\[
0.45 < d/D < 0.6
\]

\[
0.4 < d_0/\tau < 0.6 \text{ at } b/d = 1.5
\]

\[
0.5 < d_0/\tau < 0.7 \text{ at } b/d = 4.0
\]

\[
\tau < d/2
\]

Where \( d_0 \) is the diameter of the conductor in inches.

The number of turns per inch obtained by substituting equations (5.1) and (5.2) into (5.3).

\[
\frac{1}{\tau} = n = \frac{1720}{f_0 D^2 (b/d)(d/D)^2} \left( \log_{10}(D/d) \right)^{1/2} \text{ turns per inch} \tag{5.5}
\]

The total number of turns \( N \) given by

\[
N = nb = \frac{1720}{f_0 D(d/D)} \left[ \log_{10}(D/d) \right]^{1/2} \text{ turns} \tag{5.6}
\]
Table 5.1 Design parameters of the helical loaded cavity backed antenna for 2.4 GHz frequency.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Dimension in $\lambda$</th>
<th>Dimension in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Helix axial length ($b$)</td>
<td>0.240 $\lambda$</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Mean diameter of helix ($d$)</td>
<td>0.064 $\lambda$</td>
<td>08</td>
</tr>
<tr>
<td>3</td>
<td>Internal diameter of cavity ($D$)</td>
<td>0.136 $\lambda$</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>Inner height of cavity ($H$)</td>
<td>0.328 $\lambda$</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>Pitch of the helix ($\tau = 1/n$)</td>
<td>0.144 $\lambda$</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Diameter of the conductor of helix ($d_0 = 0.4 \tau$)</td>
<td>0.0712 $\lambda$</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Using (5.6), the number of turns for the helix is 1.64 for 2.4 GHz frequency, number of turns per millimetre is 0.0547. External height of the antenna including both the cavities is 59 mm. Using (5.3) (5.4) and (5.5), design parameters of the helical loaded cavity backed antenna is calculated, which is shown in Table 5.1. As the diameter of the conductor of helix ($d_0$) is 8.9 mm and mean diameter of helix ($d$) is 8 mm, it is not possible to design a helix mean diameter of 8 mm with 8.9 mm thick wire conductor. To solve this problem, instead of cylindrical wire conductor, a copper strip conductor is used. The circumference of the conductor is 28 mm ($8.9 \times \pi$); the strip weight of 11 mm and thickness of 3 mm (11+11+3+3=28 mm) is used. The strip conductor improves the bandwidth of the antenna. The helical loaded cavity backed antenna is designed with a copper strip conductor and an aluminium cavity for 2.4 GHz frequency as shown in Fig. 5.2.

![Fig. 5.2 Schematic of the helical loaded cavity backed antenna.](image)
5.2.1 3-D Modelling and Simulation

The 3-D modelling and simulation of the various helical antennas are done by using the SINGULA simulation software. Initially a copper strip helical antenna of 1.64 turns with ground plane of 0.75λ diameter is simulated, which is shown in Fig. 5.3. It is simulated for comparison with the helical loaded cavity backed antennas. Then the helical loaded cavity backed antenna of 1.64 turns copper strip helix in aluminium cavity is simulated. The design parameters of the helical loaded cavity backed antenna are as shown in Table 5.1.

The parametric design does not take care of impedance matching of antenna with 50 Ω SMA connector. Copper strip transmission line quarter wave transformer was used for impedance matching. It is a section of one-quarter wavelength long transmission line. There can be multiple design variations to incorporate the quarter wave transformer for helical loaded cavity backed antenna. Three different designs are simulated, the design parameters for all three designs are the same as in Table 5.1, only additional cavity shape and size is changed to incorporate the quarter wave transformer. Design-1 is circular base of 32 mm diameter bottom cavity, Design-2 is circular base of 60 mm diameter bottom cavity and Design-3 is a rectangular base of 60 mm bottom cavity. These three designs are shown in Fig. 5.4 that are designed for 2.4 GHz frequency. The variation in these designs was to achieve better results with respect to bandwidth and gain.

![Fig. 5.3 Helical antennas of 1.64 turns with 0.75λ (93.75 mm) diameter ground plane.](image)
5.2.2 Radiation Pattern

Radiation pattern of 0.75λ diameter ground plane helical antenna is as shown in Fig 5.5. The circumference of the helix is 0.2λ which is less than the wavelength. Radiation pattern is normal to the axis of helix. Radiation pattern of Design-1 is an axial mode radiation pattern with strong back lobe as shown in Fig. 5.6. Radiation pattern of Design-2 is an axial mode radiation pattern with back lobe as shown in Fig. 5.7. Radiation pattern of Design-3 is an axial mode radiation pattern with back lobe as shown in Fig. 5.8. Although Design-1 is a compact design, it has a strong back lobe.
Bothe Design-2 and Design-3 have back lobes but Design-3 has more directive radiation pattern along the axis as compared with Design-2.

Fig. 5.5 Radiation pattern of the helical antenna of 1.64 turns with 0.75 \( \lambda \) (93.75 mm) diameter ground plane.

Fig. 5.6 Radiation pattern of Design-1, helical loaded cavity backed antenna with 32 mm diameter circular base.
Fig. 5.7 Radiation pattern of Design-2, helical loaded cavity backed antenna with 60 mm diameter circular base.

Fig. 5.8 Radiation pattern of Design-3, helical loaded cavity backed antenna with 60 mm rectangular base.
According to the classical design method [56] for axial mode operation, the helical antenna operates in the axial mode, where circumference of the helix to wavelength of operation ratio should be in the range of \((0.8 < \frac{C}{\lambda} < 1.2)\). For wavelength of 125 mm, the circumference of the helix should be 100 mm < \(C < 150\) mm for axial mode radiation, but the circumference of the helix is 25.13 mm i.e. 25% of minimum requirement. For such smaller circumference of the helix, the antenna operates in the axial mode. The same helical antenna with \(0.75\lambda\) diameter ground plane radiates in normal mode, as shown in Fig 5.5. With reference to the above discussion, by loading helical antenna in a cavity, the mode of radiation changes from normal mode to axial mode.

### 5.2.3 Bandwidth Analysis

The bandwidth is the major parameter for antenna design. The simulation bandwidth of helical antenna and the three designs of helical loaded cavity back antenna are discussed here. The reflection coefficient of 1.64 turn helical antenna with \(0.75\lambda\) diameter ground plane is shown in Fig 5.9. The bandwidth of Design-1 is 160 MHz (2.31 GHz to 2.47 GHz) which is shown in Fig. 5.10. The bandwidth of Design-2 is 187 MHz (2.355 GHz to 2.542 GHz) is shown in Fig. 5.11. The bandwidth of Design-3 is 250 MHz (2.26 GHz to 2.51 GHz) which is shown in Fig. 5.12.

![Reflection coefficient (dB) of the helical antenna of 1.64 turns with 0.75 \(\lambda\) (93.75 mm) diameter ground plane](image-url)
Fig. 5.10 Reflection coefficient (dB) of Design-1, helical loaded cavity backed antenna with 32 mm diameter circular base.

Fig. 5.11 Reflection coefficient (dB) Design-2, helical loaded cavity backed antenna with 60 mm diameter circular base.
Fig. 5.12 Reflection coefficient (dB) of Design-3, helical loaded cavity backed antenna with 60 mm rectangular base.

Fig. 5.13 Design-3, helical loaded cavity backed antenna with 60 mm rectangular base.
Fig. 5.14 Measured reflection coefficient (dB) of Design-3, helical loaded cavity backed antenna with 60 mm rectangular base.

Design-3 has the highest simulation bandwidth and therefore; it is fabricated for copper helix in aluminium cavity as shown in Fig 5.13. Rohde & Schwarz FSH6 spectrum analyser range of 100 kHz to 3 GHz is used for reflection coefficient measurement. Measured bandwidth of Design-3 is 120 MHz (2.05 GHz to 2.17 GHz) which is shown in Fig 5.14.

5.2.4 Gain Analysis

The simulation gain of 1.64 turn helical antenna with 0.75λ diameter ground plane is 1.41 dB that is shown in Fig 5.15. The simulation gain of Design-1 is 5.1 dB at 2.4 GHz frequency. At the same frequency, Design-2 and Design-3 have a gain of 5.6 dB and 5.55 dB respectively. All three designs have the same upper cavity and helix dimensions as mentioned in Table 5.1. There is a variation in the bottom cavity dimensions only for impedance matching. Bottom cavity diameter in Design-1 is 32 mm so it reduces the gain. The bottom cavity diameter of Design-2 and bottom cavity side length of Design-3 is the same of 60 mm, so the gain of both the designs is comparable. The gain of all three designs is moderate because the number of turns is only 1.64. Gain can be increased by increasing the number of turns of helical antenna. The gain plot of Design-3 at 2.4 GHz frequency is shown in Fig. 5.16.
Fig. 5.15 Gain (dB) of 1.64 turn helical antenna with 0.75\(\lambda\) diameter ground plane at 2.4 GHz.

Fig. 5.16 Gain (dB) of Design-3, helical loaded cavity backed antenna with 60 mm diameter rectangular base at 2.4GHz.
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Antenna Structure</th>
<th>Centre Freq.</th>
<th>Freq. Range</th>
<th>Band Width</th>
<th>Gain</th>
<th>Height</th>
<th>λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design-1: circular base of 32 mm diameter bottom cavity (simulation)</td>
<td>2.4</td>
<td>2.310 to 2.470</td>
<td>160</td>
<td>6.67</td>
<td>5.1</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>Design-2: circular base of 60 mm diameter bottom cavity (simulation)</td>
<td>2.4</td>
<td>2.355 to 2.542</td>
<td>187</td>
<td>7.79</td>
<td>5.6</td>
<td>59</td>
</tr>
<tr>
<td>3</td>
<td>Design-3: rectangular base of 60 mm bottom cavity (simulation)</td>
<td>2.4</td>
<td>2.260 to 2.510</td>
<td>250</td>
<td>10.42</td>
<td>5.55</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>Design-3: rectangular base of 60 mm bottom cavity (fabricated)</td>
<td>2.4</td>
<td>2.050 to 2.170</td>
<td>120</td>
<td>5.00</td>
<td>-</td>
<td>59</td>
</tr>
</tbody>
</table>
5.3 Results and Discussion

The important results of helical loaded cavity backed antenna are summarized in Table 5.2. Three different antennas were simulated and the highest simulation bandwidth of Design-3 is fabricated and tested. This antenna has only 1.64 turns, which is unlike the conventional concepts of helical antenna. The measured reflection coefficient for Design-3 is -15.30 dB and the measured bandwidth of the antenna is 120 MHz (2.05 GHz to 2.17 GHz). The directive gain of 5.55 dB is achieved.

The helix of 25.13 mm circumference simulated with 0.75 λ ground conductor radiates in the normal mode. By loading the helix in a cavity, the antenna radiation pattern changes from normal mode to axial mode radiation. According to classical design data, the helical antenna operates in the axial mode in the frequency band where \(0.8 \leq C/\lambda \leq 1.2\). For the centre frequency of 2.4 GHz and wavelength of (\(\lambda=125\) mm), the circumference of the helix should be 100 mm \(\leq C \leq 150\) mm but the circumference in this design is 25.13 mm, which is 25.13% of the minimum requirement. For such smaller circumference, the antenna operates in the axial mode. It is concluded by loading the helix in a cavity, the mode of operation changes from normal mode to axial mode radiation.

This antenna addresses the conformability issue. Unlike conventional helical antenna by loading the helix in a cavity, the antenna becomes conformal. The compact size and low fabrication cost makes this antenna very attractive for satellite communications and aerospace applications.

Table 5.3 Comparison of Design-3 with cavity backed helical antenna [63]

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Fabricated Design-3</th>
<th>Cavity Backed Helical Antenna [63]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Helix turns</td>
<td>1.64</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Frequency of operation</td>
<td>2.4 GHz</td>
<td>1.5 GHz</td>
</tr>
<tr>
<td>3</td>
<td>Bandwidth</td>
<td>120 MHz</td>
<td>60 MHz</td>
</tr>
<tr>
<td>4</td>
<td>Gain</td>
<td>5.55 dB</td>
<td>8.5 dB</td>
</tr>
<tr>
<td>5</td>
<td>Mean diameter of helix ((d))</td>
<td>0.064(\lambda)</td>
<td>0.32(\lambda)</td>
</tr>
<tr>
<td>6</td>
<td>Internal diameter of cavity ((D))</td>
<td>0.136(\lambda)</td>
<td>0.5(\lambda)</td>
</tr>
<tr>
<td>7</td>
<td>Inner height of cavity ((H))</td>
<td>0.328(\lambda)</td>
<td>0.5(\lambda)</td>
</tr>
</tbody>
</table>
A comparison between the fabricated Design-3 and cavity backed helical antenna [63] is shown in Table 5.3. The frequency of operation is 2.4 GHz and 1.5 GHz for Design-3 and cavity backed helical antenna respectively. The bandwidth of Design-3 is 120 MHz as compared with 60 MHz bandwidth of the cavity backed helical antenna. In Design-3, mean diameter of the helix is reduced from 0.32 λ to 0.064 λ; it is reduced by five times. The internal diameter of the cavity is also reduced from 0.5 λ to 0.136 λ; it is reduced by around four times. The internal height of the cavity is reduced from 0.5 λ to 0.328 λ; which is also reduced more than 1.5 times. The overall reduction in the volume of the cavity of Design-3 is more than 20 times the volume of the cavity backed helical antenna.

The volume reduction of antenna Design-3 has adverse effect on gain. The gain of Design-3 is reduced to 5.55 dB as compared with 8.5 dB in cavity backed helical antenna. Design-3 has excellent performance as compared with cavity backed helical antenna for all the parameters except gain. The enhancement of gain is focused in the next chapter by using a square cavity and hybrid square cavity with detailed analysis.

5.4 Summary

This antenna design is a novel antenna that produces moderate gain and a broad bandwidth. This new antenna occupies a much smaller volume. The volume of the proposed antenna is reduced by a factor of 20 compared with the volume of the cavity backed helical antenna referred in the literature survey. The circumference of the helix is only 25.13% of the classical helix design. The cavity diameter is 53.4% of classical helix design. Axial mode radiation for C/λ = 0.2 is achieved. It is conformal antenna with miniaturized size with comparative high power handling. Measured Bandwidth of antenna of 120 MHz and gain of 5.5 dB is achieved. There is scope for bandwidth and gain enhancement. The circular cavity can be replaced by rectangular or square cavity and the optimum shape and size can be found out. In the next chapter partial rectangular cavity and complete rectangular cavity is discussed.