5.1 INTRODUCTION

Apart from having many advantages, microstrip antennas have some disadvantages. One disadvantage is the excitation of surface waves in the substrate layer. Surface waves are undesired because when a patch antenna radiates, a portion of total available radiated power becomes trapped along the surface of the substrate. It can extract total available power for radiation to space wave. Therefore, surface wave can reduce the antenna efficiency, gain and bandwidth. In general, the bandwidth of simple patch antenna geometries of regular shape is very poor (1 to 2%) and their gain is also very low [12], [242-243]. Recently, there has been an increasing interest in the applications of defected ground structure (DGS) in microwave and millimeter wave applications. The microstrip antennas can show wide-band characteristics while introducing defects in the ground plane. DGS is realized by etching a defected pattern in the ground plane, this etched pattern interferes with the shield current distribution in the ground plane which affects the characteristics of the antenna. This disturbance creates beneficial capacitance and inductance effect on the structure. It affects the input impedance and provides band rejection characteristics from the resonance property. It can also control the excitation and the electromagnetic waves propagating through the substrate layers, which results in slow wave effect of radiation [137], [218], [244-245].

Many shapes of DGS have been studied such as concentric ring, circle, spiral, dumbbells, elliptical and U- and V-slots. Each DGS shape can be represented as an equivalent circuit consisting of inductance and capacitance, which leads to a certain frequency band gap determined by the shape, dimension and position of the defect. DGS gives an extra degree of freedom in microwave circuit design and can be used for a wide range of applications. Several types of slots and defects are trenched in the ground of the microstrip antenna so that the size could be reduced and impedance bandwidth and gain can be enhanced [62],
The DGSs have been successively introduced to control and improve the radiation properties of the microstrip antennas. The defects introduced in the ground plane leads to the suppression of the cross-polarized radiations, reduction of the mutual coupling between the microstrip array elements and elimination of scan blindness of microstrip phased arrays [176], [178], [180-181], [187], [250-251].

A method based on Fuzzy Inference Systems (FIS) has been successfully implemented for the synthesis of various antenna parameters. The FIS is a popular computing framework based on the concept of fuzzy set theory, fuzzy if-then rules and fuzzy reasoning. It is very powerful approach for building complex and non-linear relation between a set of input and output data. The FIS model has been used to determine the physical dimensions of the patch and feed point location. [252-253].

In the previous chapter we have studied the effect of the DGS on the performance of a stacked ring antenna. In our investigations we found that the impedance bandwidth of the stacked antennas can be furthered by introducing the defects in the ground plane. Also we observed an improvement in the gain of the antenna.

In this chapter, we will examine a circular ring antenna with a different defected ground structure. A circular ring sector shape DGS is proposed in the ground plane of the ring antenna. We will discuss the influence of circular ring sector shape DGS towards the improvement of the radiation properties of the circular ring antenna. By adding the DGS, therefore, will suppress surface wave propagation in the dielectric layer, which affects the resonance properties of the structure. The intended DGS has direct effect on the resonant frequency, bandwidth, side lobe level and cross polar radiations of the antenna. The Fuzzy Inference System (FIS) is deployed to obtain the optimized position of the defect to have the highest return loss. The antenna with DGS shows enhanced bandwidth in X-
band. The DGS also improves the gain of the ring antenna and suppresses the cross polar radiations to higher level. The solution to the transcendental equation for a circular ring antenna of outer to inner radii ratio 3 has been derived. Then the expression for resonant frequency of the antenna has been discussed.

5.2 THEORY

In this section, the theory of circular ring microstrip antenna is discussed. A circular ring microstrip antenna comprises a ring shaped conductor on one side of the substrate and a metal ground plane on the other side. For a circular ring antenna, the cavity model provides the general solution of the wave equation

\[(\nabla^2 + k^2)\vec{E} = 0,\]

\[k = \frac{2\pi\sqrt{\varepsilon_r}}{\lambda_0}\]  \hspace{1cm} (5.1)

in cylindrical coordinates is given as:

\[E_z = E_0[I_n(k\rho)Y_n'(ka) - J_n'(ka)Y_n(k\rho)] \cos n\phi\]

\[H_\rho = \frac{j}{\omega\mu_0} \frac{\partial E_z}{\partial \phi},\] \[H_\phi = \frac{-j}{\omega\mu_0} \frac{\partial E_z}{\partial \rho}\]  \hspace{1cm} (5.2)

where \(J_n(\cdot)\) and \(Y_n(\cdot)\) are the Bessel functions of first and second kind of order \(n\), and \(a\) is the inner radius of the ring respectively [17]. The other field components are zero inside the cavity. The surface current on the lower surface of the ring metallization is given by

\[\vec{J}_s = -\hat{z} \times \vec{H} = -\hat{\phi} H_\rho + \hat{\rho} H_\phi\]

Or
\[ J_\phi = \frac{jnE_0}{\omega \mu \rho} [J_n'(k\rho)Y_n'(k\rho) - J_n'(k\rho)Y_n'(k\rho)] \sin n\phi \]

\[ J_\rho = -\frac{jkE_0}{\omega \mu} [J_n'(k\rho)Y_n'(k\rho) - J_n'(k\rho)Y_n'(k\rho)] \cos n\phi \]  
(5.3)

The radial component of the surface current must vanish along the edges at the \( \rho = a \) and \( \rho = b \) to satisfy the magnetic wall boundary conditions. This leads to

\[ J_\rho(\rho = a, b) = H_\phi(\rho = a, b) = 0 \]  
(5.4)

where \( a \) and \( b \) are the inner and outer radii of the circular ring antenna [12].

Application of this boundary condition leads to the well-known characteristic equation for the resonant modes

\[ J_n'(kb)Y_n'(ka) - J_n'(ka)Y_n'(kb) = 0 \]  
(5.5)

For the given values of \( a, b, \varepsilon_r, \) and \( n \), the frequency is varied and the roots of equation (5.5) are determined. If we denote these roots by \( k_{nm} \) for the resonant \( T_{nm} \) modes and form \( X_{nm} \) such that \( X_{nm} = k_{nm}a \). The integer \( n \) denotes the azimuthal variation as \( \cos n\phi \), while the integer \( m \) represents the \( m^{th} \) zero of equation (5.5) and denotes the variation of fields across the width of the ring [12].

The resonant frequency of the circular ring antenna is obtained by setting

\[ k_{nm} = \frac{X_{nm}}{a}, \quad f_{nm} = \frac{X_{nm}c}{2\pi a\sqrt{\varepsilon_{re}}} \]  
(5.6)

where \( c \) is the velocity of light in space, \( \varepsilon_{re} \) is the effective dielectric constant respectively.

The roots \( X_{nm} \) of the characteristic equation \( J_n'(kb)Y_n'(ka) - J_n'(ka)Y_n'(kb) = 0 \) for \( b = 3a \) are given in Table 5.1.
Table 5.1: Roots $X_{nm}$ of the characteristic equation $J_n'(3X_{nm})Y_n'(X_{nm}) - J_n'(X_{nm})Y_n'(3X_{nm}) = 0$

<table>
<thead>
<tr>
<th>m → n ↓</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>1.6356</td>
<td>3.1788</td>
<td>4.7381</td>
</tr>
<tr>
<td>1</td>
<td>0.5136</td>
<td>1.7578</td>
<td>3.2361</td>
<td>4.7749</td>
</tr>
<tr>
<td>2</td>
<td>0.9775</td>
<td>2.0901</td>
<td>3.4067</td>
<td>4.5851</td>
</tr>
<tr>
<td>3</td>
<td>1.3880</td>
<td>2.5422</td>
<td>3.6872</td>
<td>5.0676</td>
</tr>
<tr>
<td>4</td>
<td>1.7692</td>
<td>3.0197</td>
<td>4.0681</td>
<td>5.3223</td>
</tr>
<tr>
<td>5</td>
<td>2.1377</td>
<td>3.4738</td>
<td>4.5207</td>
<td>5.6497</td>
</tr>
</tbody>
</table>

5.3 ANTEenna DESIGN AND FUZZY APPROACH

The results of the development design of a compact wideband defected ground antenna using Fuzzy approach for use in communications applications are presented in this section. Bandwidth is specified as the frequency bandwidth in which the return loss is above 10 dB.

5.3.1 GEOMETRY

The circular ring antenna of inner radius $a$ and outer radius $b$ is considered. The outer radius is three times the inner radius ($b = 3a$) of the proposed ring antenna. The design consists of a circular ring microstrip antenna with a defected ground shown in figure 5.1. Figure 5.1(a) and 5.1(b) shows the top and bottom views of the antenna with purported defect respectively. The circular patch antenna with DGS is designed on a commercially available FR-4 substrate of dielectric constant 4.4 and height 1.59 mm respectively. A circular annular ring of inner radius, $a = 5$ mm and outer radius, $b = 15$ mm is printed over the substrate material. The ground plane of 50 mm x 50 mm is defected by introducing four circular ring sectors. The angular width of each sector is selected to be
75° about the center of the ground plane. A gap of 15° (2.8 mm) about the center is present between the two adjacent ring sectors. The antenna is fed by a coaxial probe at 7 mm from the center of the ring. The configuration for the circular ring microstrip antenna without defected ground is same as for defected ground antenna except for the ground plane. Each ring sector has 9 mm and 10 mm as inner and outer radii respectively. These values for the position of the defect are obtained from the FIS model optimization which is discussed in the next section.
Figure 5.1: Design of defected ground circular patch microstrip antenna
(a) top view (b) bottom view.

5.3.2 FUZZY INFERENCE SYSTEM MODEL

A new modeling approach by using fuzzy inference system (FIS) for computing various parameters of the microstrip antenna like input impedance, resonant frequency and back scattering response has been studied earlier [254-256]. The fuzzy inference system (FIS) is a popular computing structure based on the concept of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. With crisp inputs and outputs, a fuzzy inference system implements a nonlinear mapping from its input space to output space. The MATLAB Fuzzy Logic Toolbox was used for FIS development [257].
In the present study, FIS model is used to optimize the position of the defect in the ground plane so as to obtain the highest return loss in X-band. The Mamdani fuzzy inference system is used for the optimization purpose. The inputs to the FIS system are feed position, substrate and position of the defect in the ground plane. The input parameter values are the crisp numbers obtained from a data set generated from simulations. The feed point location is 7 mm, substrate used is FR-4 having $\varepsilon_r = 4.3$ and the outer radius of the defect (circular ring sectors) is varied from 6 mm to 19.5 mm with a step height of 1.5 mm respectively. The width of the defect is kept constant (i.e. 1 mm) during the entire variation. The output of the FIS model represents the return loss and operating frequency parameters of the proposed antenna. The return loss ranges from 0 to 30 dB and frequency lies in the X-band. The proposed Fuzzy Inference System model using MATLAB is given in Appendix A.

The results obtained from the fuzzy model are compared with the simulated results obtained by Ansoft HFSS and are shown in Table 5.2 (for test data). From the results, it is clear that outcomes for frequency and return loss are in good agreement with each other with a marginal difference. The position of the defect with maximum return loss comes at 10 mm (at the 3rd row in Table 5.2) for both simulated and FIS model results. Hence, this optimized value is used for the outer radius of the defect for both simulation and experimental design of the antenna. The surface plots for the variation of frequency and return loss with feed location and defect position are shown in figure 5.2. The design layout of the proposed DGS antenna with optimized defect position is shown in figure 5.3.
<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Position of Defect (in mm)</th>
<th>Simulated Results (HFSS)</th>
<th>FIS Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (GHz)</td>
<td>Return Loss(dB)</td>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>1.</td>
<td>9.8</td>
<td>11.2997</td>
<td>16.3309</td>
</tr>
<tr>
<td>2.</td>
<td>9.9</td>
<td>11.4396</td>
<td>22.7070</td>
</tr>
<tr>
<td>3.</td>
<td>10</td>
<td>11.2918</td>
<td>25.6347</td>
</tr>
<tr>
<td>4.</td>
<td>10.1</td>
<td>11.1227</td>
<td>22.6383</td>
</tr>
<tr>
<td>5.</td>
<td>10.2</td>
<td>11.0544</td>
<td>20.1780</td>
</tr>
<tr>
<td>6.</td>
<td>10.3</td>
<td>11.1211</td>
<td>15.9104</td>
</tr>
<tr>
<td>7.</td>
<td>10.4</td>
<td>11.1544</td>
<td>13.7171</td>
</tr>
<tr>
<td>8.</td>
<td>10.5</td>
<td>11.1644</td>
<td>12.4568</td>
</tr>
</tbody>
</table>

![Graph](image_url)

(a)
Figure 5.2: Surface plot for the variation of feed location and position of defect with
(a) frequency (b) return loss.
Figure 5.3: Design of proposed DGS circular patch microstrip antenna with optimized defect position (a) top view (b) bottom view.

5.3.3 PROTOTYPE OF THE PROPOSED STRUCTURE

The parameters like return loss, input impedance, bandwidth, gain and radiation patterns and VSWR are studied for the proposed geometry by using commercially available Ansoft HFSS simulation software. For the experimental verification of the simulated results, the prototype of the proposed antenna has been manufactured and tested on R & S ZVL Vector network analyzer. The figure 5.4 shows the top and bottom sides of the prototype of the proposed design.
Figure 5.4: Prototype of defected ground circular patch microstrip antenna
(b) top view (b) bottom view.
5.4 SIMULATED AND EXPERIMENTAL RESULTS

In this section, the wide-band defected ground ring antenna is studied in detail. The antenna with and without DGS were simulated and verified by measurement results. Parameters such as return loss, input impedance, bandwidth, voltage standing wave ratio (VSWR) for the cases are measured and calculated. The simulated radiation pattern is also presented for the defected ground antenna structure.

When the ground plane for the proposed antenna is not defected and covers whole of the substrate, the variation of reflection coefficient and input impedance (real) with frequency for simulated and measured values is shown in figure 5.5. The reflection coefficient is shown for the X-band. The antenna with no DGS resonates for TM_{32} mode at 11.70 GHz as calculated for \( b = 3a \) from eq. (5.6) above. The antenna is fed at 7 mm from the center. From the graph, it is clear that both simulated and experimental results are in good agreement. The simulated results shows TM_{32} resonating mode at 11.80 GHz with a return loss of 4.38 dB while the experimental value appears at 11.61 GHz with a return loss of 4.75 dB. It is obvious from the results that antenna does not show wideband characteristics.

![Graph showing simulated and experimental reflection coefficient and input impedance](image.png)

**Figure 5.5:** Simulated and experimental variation of reflection coefficient and input impedance (real) with frequency (without DGS).
The input impedance is also about 15 ohms for both results. The low value of return loss and low impedance could be due to the unmatched feed point location. A proper choice of feed point location will result in good return loss and impedance matching at resonant frequency.

When the circular ring sector defect is introduced in the ground plane, the antenna shows a wide band in the X-band. The simulated and measured values of reflection coefficient are reported in figure 5.6. From this figure, we can see that the antenna shows a wideband in the frequency range of 8 – 12 GHz with reduction of overall antenna size. Both experimental and simulated results are in good agreement. The antenna with DGS is again fed at 7 mm to excite the higher TM$_{32}$ mode. The simulated results show that the antenna resonates at 11.29 GHz with a return loss of 25.95 dB. The simulated bandwidth is 1.33 GHz which is 11.78% about the center frequency of 11.29 GHz. The DGS antenna structure is then experimentally tested and the measured return loss is 20.51 dB at the frequency of 11.27 GHz. The return loss above 10 dB impedance bandwidth has a range of 1.2 GHz which is about 10.65% at the center frequency of 11.27 GHz. When no defect was introduced in the antenna, its simulated TM$_{32}$ mode was at 11.8 GHz. But due to the presence of defect in the ground plane, the same resonant mode is shifted towards the lower side at 11.29 GHz. Figure 5.7 shows the simulated TM$_{32}$ resonant mode at the frequency 11.29 GHz. Thus the defect also reduces the overall size of the antenna.

The experimental and simulated input impedance is reported in figure 5.8. It is evident from the results that experimental and simulated values are in good agreement. The DGS antenna shows a wide band in X-band and input impedance of nearly 50 ohm is achieved over the entire frequency range. The voltage standing wave ratio (VSWR) calculated from simulated and experimental results for the defected ground plane antenna is reported in figure 5.9. The simulated bandwidth calculated is about 1.2 GHz while experimentally measured bandwidth is about 0.8 GHz for VSWR<2. The comparison of the simulated and experimental results for resonant frequency, return loss and bandwidth (without DGS and with DGS) is given in Table 5.3.
Figure 5.6: Simulated and experimental variation of reflection coefficient with frequency (with DGS).

Figure 5.7: TM$_{32}$ mode of the DGS antenna at frequency 11.29 GHz (simulated).
Figure 5.8: Simulated and experimental variation of impedance with frequency (with DGS).

(a) real part        (b) imaginary part.
Figure 5.9: Simulated and experimental variation of VSWR with frequency (with DGS).

Table 5.3: Comparison of simulated and experimental results for resonant frequency, return loss and bandwidth (without DGS and with DGS).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Without DGS</th>
<th></th>
<th>With DGS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulated</td>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Experimental</td>
<td></td>
<td>Experimental</td>
</tr>
<tr>
<td>Resonant Frequency (GHz)</td>
<td>11.80</td>
<td>11.61</td>
<td></td>
<td>11.29</td>
</tr>
<tr>
<td>Return Loss (dB)</td>
<td>4.38</td>
<td>4.75</td>
<td></td>
<td>25.95</td>
</tr>
<tr>
<td>Bandwidth (%)</td>
<td>---</td>
<td></td>
<td></td>
<td>11.78</td>
</tr>
</tbody>
</table>
The simulated radiation patterns of E-plane and H-plane for the antenna structure with defected ground at frequency 11.29 GHz are shown in figure 5.10. For E-plane (\(\phi = 0^0\)), the gain of the DGS antenna is 6.43 dB at \(-4^0\). The side lobe level is 2.75 dB below the main beam direction and the 3 dB beam width is 26.2^0 respectively. It is also clear from the graph that there is an isolation of 20.19 dB between co-polar and cross-polar radiations. The main beam shows a gain of 5.99 dB at 0^0 with side lobe level of -10.56 dB for H-plane (\(\phi = 90^0\)). The 3dB beam width of about 60^0 is obtained for H-plane radiations. Also the cross-polar radiations are suppressed by 5.96 dB. The E-plane and H-plane radiation patterns show that a good antenna gain is achieved with suppressed cross-polar radiations.
It is apparent from all the results discussed above that the suggested DGS antenna shows an increased bandwidth with good impedance matching. The DGS also reduces the overall size of the antenna structure and suppresses the undesired cross-polar radiations from the main beam. In addition to this, the radiation properties of the defected ground antenna structure are also improved to a very good extent as compared to the normal antenna structure.

5.5 CONCLUSIONS

In this chapter, we have investigated a low-profile circular ring DGS patch antenna with wideband width and low level cross-polar radiations. Measured results on fabricated antenna were used to confirm the simulation results. The proposed DGS antenna with
wideband width was optimized using MATLAB FIS based on fuzzy decision-making. The fuzzy logic approach has been successfully implemented for the antenna parameter optimization. It has been observed that using the defected ground geometry and optimizing antenna parameter results in good impedance matching with high impedance bandwidth. The designed antenna operates in X-band giving a wide impedance bandwidth. It is also observed that a good antenna gain of 6.43 dB for E-plane, 5.99 dB for H-plane and low level cross-polar radiations are obtained by introducing the circular ring sector defect in the ground plane. The cross polar radiations are suppressed by 20.19 dB for E-plane and 5.96 dB for H-plane. The measured results are in good agreement with the experimental results. At the end, 10.65% bandwidth (measured) circular ring DGS patch antenna is designed, measured, and characterized in detail, which can be applied to modern wireless communication frequencies of X-band.