Design of the UWB Fractal Antenna

7.1 Introduction

Fractal antennas are recognized as a good option to obtain miniaturization and multiband characteristics. These characteristics are achieved by unique features of fractal geometry such as self-similarity and space filling properties [123]-[126]. A self similar set is one that consists of its own scaled down copies. Each scaled down element of the antenna geometry generates a resonant frequency with the increase in electrical length of antenna. The self-similar property of fractal geometry and the self-similar current distribution on it facilitates antenna design to work for multiband characteristics [129], [131]. The space filling properties of higher order fractals are used to miniaturize the antenna size. Fractal geometries and iterated function system (IFS) based on the application of a series of affine transformation can be used to generate a fractal structure [127]-[128]. Fractal antennas are advantageous for wireless communication systems because of their small dimension and wideband operation.

The UWB fractal antennas demonstrated in [133]-[134], have very large physical dimension. Because of the coaxial feed and the large dimension, the fractal antennas reported [135]-[136] will not suit integration with MMIC. Fractal antennas are more susceptible to fabrication error due to critical iteration of the fractals used in the geometry [137]-[139].

In this chapter a novel design of a CPW fed fractal antenna is discussed for UWB operation. The band-notch characteristic is presented to minimize potential interference of existing narrow bands. The antenna design comprises of inscribed pentagonal fractals on the top and pentagonal parasitic patch on the bottom of the substrate. The parasitic patch acts as the filter element. The antenna is analysed and studied with respect to reflection coefficient, VSWR, -10 dB impedance bandwidth, gain, and radiation pattern. The designed novel antenna possesses the highly desirable attributes of compact size and broad bandwidth.
7.2 CPW fed Inscribed Pentagon Fractal Antenna (IPFA)

The base geometry of the fractal antenna (first iteration) is achieved by subtracting an inverted pentagon of side length 7.0534 mm from the pentagonal shaped radiating patch of side length 9.522 mm. In a similar manner the second and third iterations are designed by a scale down factor of 0.62. The three iterations of the UWB antenna are shown in Figure 7.1. While generating the iterations, the vertices of the inner pentagon (inverted) should be located at the mid of sides length of the pentagon from which it is substracted. The resonant modes are generated due to each iteration. These resonant modes overlap with each other to form a broad band.

7.2.1 Design and Configuration of the IPFA

The geometry of the IPFA is shown in Figure 7.2(a). The first iteration of the IPFA receives the signal through the CPW feedline. The black area represents a metallic conductor, while the white area represents the non metal part. The antenna is printed on the FR4 substrate of 1.6 mm thickness, dielectric constant 4.4 and loss tangent 0.02. The optimal parameters of IPFA are $W = 32$ mm, $L = 22$ mm, $h_1 = 4.5$ mm, $w_f = 3.0$ mm, $g = 0.5$ mm, $p = 1.446$ mm, $S = 9.522$ mm, $S_1 = 5.903$ mm and $S_2 = 3.658$. The antenna parameters such as the coupling gap $g$, the distance between the ground and patch $p$, feed width $w_f$ and side length of the iterations are tuned for impedance matching.

![Figure 7.1 Iteration elements of the CPW feed inscribed pentagon fractal antenna](image-url)
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Figure 7.2 Geometry and configuration of (a) CPW feed inscribed pentagon fractal antenna (IPFA) (b) Photograph of the fabricated antenna

Figure 7.3 Simulated reflection coefficient of the fractal antenna with 1\textsuperscript{st}, 2\textsuperscript{nd} and 3\textsuperscript{rd} iteration

The number of iterations increases the electrical length of the antenna. The presence of the triangular slots in the geometry acts as discontinuities in the path of the current. This specific slotted structure creates self reactance and traps to store the energy. In the simulation, the signal is connected to the antennas' radiating patch via a wave port. Photograph of the fabricated IPFA is shown in Figure 7.2(b).
7.2.2 Parametric Analysis of the IPFA

7.2.2.1 Effect of Iteration on the Bandwidth Enhancement

Figure 7.3 exhibits the reflection coefficient comparison of the IPFA with first, second and third iteration. Fractal antenna with the first iteration results in dual band with resonances in the vicinity of 3 GHz, 9 GHz and 10.5 GHz. The first band is centred at 3 GHz and is more dominant than the second band at 10.5 GHz. The lower edge frequency of first band is 2.7 GHz and the upper edge frequency of the second band is 10.8 GHz. This dual band characteristic is converted into UWB with the inclusion of the second iteration in the antenna geometry. The wideband is achieved by inclusion of second iteration and has three resonances at 3.2, 8.5 and 10.7 GHz. It is observed that the upper edge frequency increases due to the second iteration. The inclusion of the third iteration in the antenna geometry shifts the 8.5 GHz resonant mode to the lower frequency at 8.4 GHz and results in a wide bandwidth of 8.77 GHz (2.78–11.55). It is also found that by adding additional iterations, the bandwidth remains unchanged, hence, further scaling down of the geometry is not encouraged.

7.2.2.2 Effect of the Feed Width ($w_f$)

Figure 7.4 illustrates the effect of the variation in feed width on $S_{11}$ of antenna. The tuning of the feed width is very important to match the characteristics impedance of feed line to 50 ohm and hence the load impedance of the patch. It is found that maximum energy is radiated at feed width 2.8 mm as compared to 2.6 and 3 mm. But the optimum value of the feed width $w_f=3$ mm is chosen as it increases the bandwidth.

7.2.2.3 Effect of $h_1$ and $p$ on the impedance bandwidth

The variation in the coupling gap $p$ is responsible for good impedance matching over UWB spectrum as depicted in Figure 7.5. Poor impedance matching at $p=2.446$ mm and ground height $h_1=3.5$ mm is observed. From the comparative study shown in Figure 7.5(a) it is observed that by tuning the ground height, impedance matching is improved. This results in wide impedance bandwidth. At $p=0.446$ mm and $h_1=5.5$ mm a wide bandwidth of 4.758 GHz (2.94–7.698) with generation of centre resonance
at 3.5 GHz. The antenna design can be used for lower UWB applications. The parametric study shows that by tuning $p$, $g$, and $h_1$ parameters, good impedance matching is achieved over a wide bandwidth. At optimal values of $p = 1.446$ mm and $h_1 = 4.5$ mm, -10 dB impedance bandwidth of 8.73 GHz (2.78–11.51) and return loss of -43.3 dB is achieved. The measured 10 dB impedance bandwidth is in good agreement with the simulation. The impedance matching over the 8.73 GHz bandwidth is shown in Figure 7.5(b).

![Figure 7.4 Simulated reflection coefficient of the fractal antenna with variation in feed width](image1)

![Figure 7.5(a) Comparison of reflection coefficient with variation in coupling gap $p$ and ground plane height $h_1$](image2)
Figure 7.5(b) Simulated Smith Chart of IPFA

Figure 7.6 Simulated radiation patterns in the E- and H-plane at (a) 3.2 GHz and (b) 8.4 GHz and (c) 10.7 GHz
7.2.3 Radiation Pattern

The simulated co and cross polarised radiation patterns in the two principle planes, E- and H-plane, are shown in Figure 7.6. It is observed that the antenna radiates in omnidirectional pattern over the full UWB spectrum. At lower frequencies the radiation pattern in the E-plane is bidirectional with a figure of eight. In the frequency range of (2.78–9) GHz, the antenna radiates with almost constant gain. But at higher frequencies, beyond 9 GHz, the antenna generates minor side lobes. These minor lobes indicate that the radiation energy is degraded by lowering the antenna gain. The cross polarization levels are minimum in both the H- and E-plane as shown in Figure 7.6.

A comparison of the fractional bandwidth and the antenna dimension of the proposed IPFA and some previously published antennas are presented in Table 7.1. The physical size of the IPFA is very compact. The IPFA shows a size reduction of 76.65%, 83.23%, 20.72%, 90.22% and 76.85% as compared with [133], [134], and [137]-[139] respectively with respect to the substrate dimension.

Table 7.1 Parameters of some of the earlier published antennas in comparison with IPFA

<table>
<thead>
<tr>
<th>Some of the UWB Fractal Antenna Designs</th>
<th>FRB (%)</th>
<th>Dimension (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wideband fractal printed monopole antennas [133]</td>
<td>159.18</td>
<td>58 × 52 × 1.6</td>
</tr>
<tr>
<td>Novel wideband planar fractal monopole antenna [134]</td>
<td>155.55</td>
<td>45 × 45 × 1.5</td>
</tr>
<tr>
<td>Inscribed square circular fractal antenna [137]</td>
<td>133.14</td>
<td>37 × 24 × 1.53</td>
</tr>
<tr>
<td>On the design of wheel-shaped fractal antenna [138]</td>
<td>130.21</td>
<td>90 × 80 × 1.53</td>
</tr>
<tr>
<td>Pentagonal- cut UWB fractal antenna [139]</td>
<td>142.85</td>
<td>52.45 × 58 × 1.6</td>
</tr>
<tr>
<td>Inscribed Pentagon Fractal Antenna (IPFA) designed in this Chapter</td>
<td>122.18</td>
<td>32 × 22 × 1.6</td>
</tr>
</tbody>
</table>
7.3 Electromagnetically Coupled Band-Notch IPFA

The narrow band wireless communication systems, such as IEEE 802.11a WLAN, and HIPERLAN/2, operates from 5 GHz to 6 GHz. The ultra-wideband of the IPFA is achieved in section 7.2 and has potential interference from the existing narrow band applications. It is required that the UWB antenna must provide band-rejection characteristic to coexist with other narrow band devices and their services. Also, it is valuable to design a UWB antenna with wide band-notch characteristics to reject nearly all associated narrow bands. The investigation for a novel technique of electromagnetically coupled parasitic patch to achieve wide notch-band of bandwidth 1GHz is performed to minimize the interference of WLAN 802.11a.

7.3.1 Design Configuration of Band-Notch IPFA

The dimensions of the electromagnetically coupled IPFA are the same as designed in section 7.2 for obtaining band-notch characteristics. The electromagnetically coupled band-notched IPFA uses the top plane of the substrate to print the fractal geometry along with the CPW fed ground as shown in figure 7.7(a). The CPW feed is preferred because of its wide impedance bandwidth and good impedance matching characteristics [77], [138]. The wide impedance bandwidth is achieved by tuning various antenna parameters and is advantageous over the multilayer structure. The bottom plane of the substrate is used to print the pentagonal shape parasitic band-notch structure as shown in Figure 7.7(b). The pentagonal parasitic patch printed on the bottom of the substrate is electromagnetically coupled with the conducting fractal patch. Figure 7.7(c) illustrates the photograph of the fabricated electromagnetically coupled band-notched IPFA. The optimal parameters of the band-notched IPFA are: \( W = 32 \text{ mm}, L = 22 \text{ mm}, h_1 = 4.5 \text{ mm}, w_f = 3.0 \text{ mm}, g = 0.5 \text{ mm}, p = 1.446 \text{ mm}, S = 9.522 \text{ mm}, S_1 = 5.903 \text{ mm}, S_2 = 3.658 \text{ mm}, d = 3 \text{ mm}, p' = 1.113 \text{ mm}, \text{ and } S' = 8.699 \text{ mm}. \) The parameters \( p', d \) and \( S' \) decide the notch frequency and bandwidth across the UWB spectrum to avoid potential interference of the existing narrow bands. A pentagonal shaped parasitic band-notch structure is used to make the antenna design simple.
Study and Development of Compact Ultrawideband (UWB) Antenna for Wireless Communication System

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Figure 7.7 (a) Geometry and configuration of the CPW feed inscribed pentagon fractal radiating patch on the top
(b) Electromagnetically coupled parasitic element on the bottom of the substrate
(c) Photograph of the fabricated antenna

Figure 7.8 Simulated and Measured reflection coefficient of the band-notched fractal antenna
7.3.2 Performance of the Band-Notch Structure

The electromagnetically coupled parasitic patch has optimized side length $S' = 8.699$ mm, which is scaled down by 0.913 times the side length of the first iteration $S = 9.522$ mm. The side length of the parasitic patch is about quarter of the guided wavelength ($\lambda_g/4$) calculated at 5.24 GHz in the WLAN 802.11a band. In this design the guided wavelength is $\lambda_g = \lambda_0/\sqrt{\varepsilon_{\text{eff}}}$ and $\varepsilon_{\text{eff}} = (\varepsilon_r+1)/2$, where $\lambda_0$ is the free space wavelength.

7.3.2.1 Simulated and Experimental Reflection Coefficient Characteristics

Figure 7.8 exhibits the $S_{11}$ simulated and measured curves of the IPFA, with and without the band-notch structure. A wide bandwidth of the IPFA is segmented into multiband operation by embedding notch bands. The electromagnetic coupled parasitic patch does the segmentation of 8.73 GHz (2.78–11.51) bandwidth into three operating bands. The measured lower edge frequency of the first operating band is 2.81 GHz and the higher edge frequency of the third operating band is 10.6 GHz. The measured -10 dB impedance bandwidth of the three operating bands are 2.51 GHz (2.81–4.96), 2.71 GHz (6.07–8.78), and 0.94 GHz (9.67–10.61) respectively.

7.3.2.2 Simulated and Experimental VSWR Characteristics

Figure 7.9 shows simulated and measured VSWR $\leq 2$ curves of the band notched IPFA. The VSWR curves shows four notch bands, out of which two are generated across the UWB spectrum and other two, are beyond the UWB spectrum. The first notch band observed at 5.6 GHz is generated by a parasitic patch and the other three notch bands generated at 9.3 GHz, 12.5 GHz, and 17 GHz are called as spurious notch bands. The centre frequencies of the spurious notch bands are approximately harmonic multiples of the first notch band frequency [109].

Figure 7.10 exhibits the VSWR curves of the band notched antenna for various values of parameters $S'$, $p'$ and $d$, where $S'$ is the side length of parasitic patch, $p'$ is distance between the coplanar ground and the bottom edge of parasitic patch, and $d$ is the distance between the upper vertex of the parasitic patch and upper edge of the
substrate. From the VSWR curves it is observed that the notch frequency shifts towards the lower side with increase in the side length of the parasitic patch.

![Simulated and measured VSWR of the band-notched IPFA](image1)

**Figure 7.9 Simulated and measured VSWR of the band-notched IPFA**

![VSWR Comparison of the band-notched IPFA for various side lengths of the parasitic patch](image2)

**Figure 7.10 VSWR Comparison of the band-notched IPFA for various side lengths of the parasitic patch**

The increase in the side length $S'$ decreases both the $p'$ and $d$ parameters dimension. The increase in the side length of the parasitic patch fully covers the pentagonal fractal patch and overlaps with the CPW ground plane. This results in impedance mismatch of the CPW feed over the wideband. The optimizations are
performed in \( S', d \) and \( p' \) to control the position of the notch frequency. At an optimum value of \( S' = 8.699 \) mm, \( d = 3 \) mm, and \( p' = 1.113 \) mm, the VSWR > 2 notch bandwidth is 1.01 GHz (5.09–6.10), centred at 5.6 GHz. The pentagonal shaped parasitic patch does the role of filtering characteristics at these optimum values, because it adjusts the electromagnetic coupling effects between the fractal patch and the ground plane. The notch band rejects WLAN 802.11a band. The calculated centre rejection frequency is 5.24 GHz for \( S' = 8.699 \) mm, moreover by tuning the dimensions of \( d \) and \( p' \), the band-notch frequency shifts to 5.6 GHz. The notch-band centred at 9.3 GHz of bandwidth 0.82 GHz (8.82–9.64 GHz) rejects the lower spectrum of the X-band applications. The other spurious notch band generated at 12.5 GHz has rejection bandwidth 3 GHz (10.6–13.6). The VSWR ≤ 2 bandwidth for the three operating bands are 2.29 GHz (2.8–5.09), 2.72 GHz (6.10–8.82), and 0.92 GHz (9.64–10.56) respectively.

### 7.3.3 Current Distribution

The current distribution at various operating frequencies is shown in Figure 7.12. At 3.2 GHz and 6.8 GHz and most of the current is concentrated along the feed, ground surface near the feed and the lower part of the radiating patch. This indicates that at lower frequencies the ground acts as a capacitive load with maximum current on the feed coupling slot. As the frequency increases, at 10 GHz and 14 GHz, the maximum current accumulates on all the edges of the radiating patch iterations, ground plane and on the feed. The maximum current concentration along the edge of the fractals at higher frequency is the indication of an increase in the electrical length of the antenna with increase in the iterations. Figure 7.13 shows the current distribution on the bottom view of the IPFA at notch frequencies 5.6 GHz, and 9.3 GHz. It is found that the maximum current is accumulated on the side length of the parasitic patch.

### 7.3.4 Radiation Characteristics

The simulated gain of the band-notched IPFA is shown in Figure 7.11. It is found that the gain at notch bands decreases, which indicates poor radiation by the antenna over the notch bands. The maximum gain over the operating bands is 8 dBi and it reduces at notch frequencies. The radiation pattern in the E-plane and H-plane with co and cross polarization is shown in Figure 7.14 and 7.15 respectively. It is seen that the
antenna has bidirectional characteristics in the E-plane with lower cross polarization. At higher frequency, for 10 GHz and 15 GHz side lobes are generated, which indicates low radiation intensity in the broad side direction. This will reduce the antenna gain. The radiation pattern at 15 GHz shows that the antenna has good radiation and is tilted at $\phi = 0^0$ and $\theta = 30^0$. This directional characteristic could be due to the edge reflection. Figure 7.16 shows the H-plane radiation pattern, which are omnidirectional at lower as well as at higher frequencies. The measured and simulation results are found with good agreement. Table 7.2 shows the performance comparison of IPFA.

![Figure 7.11 Gain of band-notched IPFA](image)

### 7.3.5 Group Delay

Small variations of the group delay are important frequency domain characteristics for the UWB antennas. Constant group delay is required in the signal bandwidth to maintain signal integrity of the pulsed wideband signal. Constant group delay indicates that the phase is linear throughout the frequency range. The simulation results for the group delay of the fractal antenna are obtained by keeping a pair of identical antennas in the far field with face-to-face orientation. The two fractal antennas are separated by a distance of 30 cm. The simulation set up for face-to-face configuration is shown in Figure 16(a). Both the antennas are excited by a separate wave port. Figure 16(b) shows that stable group delay is achieved for the proposed fractal antennas. The group delay variation of the fractal antenna is less than 1ns over the operating band, except at the notch-band. It is seen that the group delay variation exceeds 3ns and 2ns at 5.6 GHz and 9.3 GHz notch-bands respectively, which indicates that the phase is not linear in the notch-band and pulse distortion can be caused.
Figure 7.12 Simulated Current distribution on the top view of the IPFA at (a) 3.2 GHz (b) 6.8 GHz (c) 10 GHz and (d) 14 GHz

Figure 7.13 Simulated current distribution on the bottom view of the IPFA at notch frequencies (a) 5.6 GHz and (b) 9.3 GHz
Figure 7.14 Simulated and measured radiation pattern in the E-plane at (a) 3.2GHz and (b) 7.1 GHz (c) 10 GHz and (d) 15 GHz of band notched fractal antenna

Figure 7.15 Simulated and measured radiation pattern in H-plane at (a) 3.2GHz and (b) 7.1 GHz (c) 10 GHz and (d) 15 GHz of the band notched fractal antenna
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Figure 7.16(a) Simulation set up for group delay (b) Simulated group delay of fractal antenna

Table 7.2 Performance comparison of the Inscribed Pentagonal Fractal Antenna (IPFA)

<table>
<thead>
<tr>
<th>Antennas Configuration and Operation</th>
<th>( f_c ) (GHz), BW (GHz), FRBW% (10 dB Impedance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPFA 22 x 32 mm(^2)</td>
<td>8.73 (2.78–11.51), 122.18%</td>
</tr>
<tr>
<td>Band-Notched IPFA 22 x 32 mm(^2)</td>
<td></td>
</tr>
<tr>
<td>Band 1 Simulated</td>
<td>2.29 (2.70–5.00), 59.67%</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>Band 2 Simulated</td>
<td>2.66 (6.14–8.8), 35.60%</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>Band 3 Simulated</td>
<td>0.86 (9.65–10.51), 8.53%</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>Notch Band 1</td>
<td>5.6, 1.11</td>
</tr>
</tbody>
</table>
7.4 Summary

The self similarity property of the fractals leads to multi resonance behaviour. A unique design of a CPW fed fractal antenna is discussed for UWB operation. The first iteration of the fractal antenna is achieved by subtracting an inverted pentagon from the pentagonal shaped radiating patch. The second and third iterations are designed by a scale down factor of 0.62. The iterations are generated, by locating the vertices of inner inverted pentagon at the mid of the side length of the outer pentagon from which it is substracted. These resonant modes generated due to each iteration overlap with each other to form a broad band. With the first iteration, the antenna operates in a single band of bandwidth 1.1 GHz. By deploying three iterations, the impedance bandwidth of the inscribed pentagonal fractal antenna (IPFA) is enhanced to 8.73 GHz (2.78–11.51) compared with first iteration. This enhanced bandwidth covers the FCC UWB spectrum of 7.5 GHz.

The wide 8.73 GHz bandwidth of the proposed IPFA is converted into multi-band operation by segmentation. The segmentation is done by an electromagnetically coupled pentagonal parasitic patch, which is used as the filter element. The electromagnetically coupled IPFA presents band-notch characteristic to minimize potential interference from the existing narrow bands. The antenna design comprises of inscribed pentagonal fractals on the top and pentagonal parasitic patch on the bottom of substrate. The antenna generates two notch bands at 5.6 GHz and 9.3 GHz in the UWB. The bandwidth of each segmented operating band is more than 500 MHz.

Omnidirectional radiation pattern is achieved over all the operating bands in the H-plane and in the bidirectional pattern in the E-plane. At higher frequency, the side lobes are observed indicating reduction in gain. The electromagnetically coupled IPFA shows size reduction of 76.65%, 83.23%, 20.72%, 90.22% and 76.85% as compared with [133], [134], and [137]-[139] respectively with respect to substrate dimension. The differences between measured and simulated values are due to fabrication error, variation in dielectric constant and thickness of the substrate.