A Circular Cantor Fractal Based Printed Slot Antenna for Triple and Dual-band Wireless Applications

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Abstract – Fractal based structure are found attractive for antenna designers to produce a compact size and multi-band antenna because of their unique properties; space-filling and self-similarity. In this paper, a new printed fractal based slot antenna is presented. The slot structure of the proposed antenna is extracted by applying Cantor fractal geometry to a circular shape as an initiator. The Cantor based slot structure has to be etched on the ground plane of a substrate with relative permittivity of 4.4 and 1.6 mm thickness. A 50 ohm microstrip feed line has been etched on the other side of the substrate. Modeling and performance evaluation of the proposed antenna have been carried out using the commercially available EM simulator HFSS, from Ansoft corporation. A parametric study carried out to explore the effects of feed line length on the antenna performance show that is possesses a triple band behavior with reasonable radiation characteristics. Simulation results show that the variation of the antenna aspect ratio results in return loss responses with tri-band behavior covering a wide variety of wireless communication applications below 6 GHz. Furthermore, it has been found that, the modification of the antenna slot structure results in return loss responses with dual-band resonances. The proposed antenna provides the antenna designer with a high degree of freedom.

Keywords – Cantor Fractal Geometry, Microstrip-Fed Antenna, Multiband Antenna, Printed Antenna, Slot Antenna.

I. INTRODUCTION

Recently, intensive research work has been devoted to the design of antennas satisfying the requirements of the increasing number of communication services, such as PCS, WiBro, WiMAX, and wireless LAN, that have become available below 6 GHz in the last decade. In this frequency range multiple frequencies have been allocated for the development of high-speed mobile information and communication systems. This has triggered the research to design compact and multiband antennas that can transmit and receive of more than one frequency signal [1].

In this context, microstrip and printed antennas are promising candidates for this design due to their low profile, low-weight, and ease of fabrication [2]. Furthermore, various fractal geometries have found their way to be used in the antenna design to produce compact and multiband antennas benefiting from their unique properties; space filling and self similarity respectively. In the other hand, to provide bandwidth enhancement of the resonant bands, fractal based slot structures are widely used in the design of multiband printed antennas.

In this respect, Koch, Cantor, Hilbert, Sierpinski, Minkowski and other fractal geometries have been successfully used to produce dual-band and multiband printed slot antennas for various wireless applications [3]–[21]. In these reported works, it has been concluded that the application of fractal geometries in the design of slot printed antennas can be classified into two categories [3]. In the first category, direct application of fractal geometries has been adopted [4]–[13]. In such a case, the fractal geometries constitute the whole antenna slot structures. The multiband behavior of such antennas has been extracted almost directly without the need of any tuning elements or slot shape modification. However, in the second category, the slot structure is a combination of Euclidian structures, such as triangle, square, rectangle and other polygons, and fractal geometries superimposed on these structures, where each line segment is replaced by fractal curve with certain iteration level [14]–[21]. In this case, the multiband behavior has been reached in different techniques. These include the addition of tuning stubs to the feed line and modification of the slot structures by rotating it around the antenna axis.

In this paper, a printed slot antenna with its slot structure being modified to take the shape of Cantor fractal geometry of the second iteration is presented as a candidate for use in triple band / dual-band wireless applications. The antenna has been fed with a 50 Ω microstrip line etched on the reverse side of the ground plane on which the slot structure is to be etched. Results show that, the aspect ratio of this antenna plays a considerable role on its performance. Variation of the antenna aspect ratio results in return loss responses with tri-band behavior covering a wide variety of wireless communication applications below 6 GHz. Furthermore, the modification of the antenna slot structure results in return loss responses with dual-band resonances.

II. THE ANTENNA STRUCTURE

The Cantor fractal based on circular structure is adopted to create the slot structure of the proposed antenna presented in this paper. The circular Cantor fractal is a version of Cantor set but based on circles instead of lines. Here, the generation process of this fractal involves starting with a circle, dividing it into three circles with the ratio of one third in terms of the outer circle diameter, cutting the middle one and keeping the other two. The subsequent iterations can be derived by applying the same idea to the previous structure. For the 2nd iteration, the diameters of the embedded circles inside the resulting structure are multiples of one ninths the outer circle diameters. Fig. 1 depicts the generation process of the
Cantor circle fractal structure up to the 2nd iteration. The first step to extract the proposed antenna structure a circle as shown in Fig. 1(a). Applying the concept of generation of the Cantor fractal geometry on this structure, results in the first iteration, Fig. 1(b). The second iteration is obtained by applying the Cantor concept on the structure depicted in Fig. 1(c).

Fig. 1. The steps of growth of the proposed circular Cantor fractal geometry up to the 2nd iteration.

III. THE ANTENNA DESIGN

The structure depicted in Fig.1(c) has been modeled using an FR4 substrate with a relative dielectric constant of 4.4 and thickness of 1.6 mm. Figure 2(a) shows the top view of the modeled antenna, where the Cantor based slot structure is etched on the ground plane. The bottom view is shown in Fig. 2(b), where the 50 microstrip line has been etched on the reverse side of the substrate beneath the slot structure.

Fig. 2. The layout of the modeled antenna with respect to the coordinate system : (a) Top view, and (b) Bottom view.

After several trials, an initial design of the proposed antenna has been modeled with a square ground plane such that the lowest resonant frequency is positioned at 1.8 GHz. Table I summarizes the detailed dimensions of this antenna. Performance evaluation of the modeled antenna has carried out using the commercially available EM simulator, HFSS, from Ansoft Inc. [22].

Table I. The modeled antenna dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_1 )</td>
<td>40</td>
<td>( L_f )</td>
<td>25.00</td>
</tr>
<tr>
<td>( L = W )</td>
<td>50.00</td>
<td>( w_f )</td>
<td>3.05</td>
</tr>
</tbody>
</table>

IV. PERFORMANCE EVALUATION

The performance of the proposed antenna with the structure depicted in Fig. 2 and the dimensions summarized in Table I has been evaluated in terms of the return loss response within a swept frequency range from 1 to 7 GHz. Fig. 3 demonstrates the resulting antenna return loss responses with the feed line length as a parameter. It is clear that the antenna possesses a triple band behavior throughout the specified swept frequency range with \( f_1 \) at 1.80 GHz, \( f_2 \) at 3.70 GHz, and \( f_3 \) at 5.50 GHz and corresponding −10 dB fractional bandwidths of 18.87, 5.90, and 11.80% respectively. Here, the microstrip feed line length is varied from 22 to 26 mm in steps of 2 mm. This, of course, does not prevent the possibility of the existence of other resonant bands outside this frequency range.

As the results in Fig. 3 imply, the impact of the variation of the feed line is only to enhance the coupling of resonant bands. However, the variation of the feed line length has no impact on the positions of the first and the second resonant bands, while it has a little impact on the position of the third resonant band.

Fig.3. The simulated return loss responses of the modeled antenna, depicted in Fig. 2, with the feed line length as a parameter.

It has been found that the diameter of the external antenna slot, \( d_1 \), plays a dominant role in determining the lowest resonant frequency \( f_1 \). In terms of the guided wavelength, \( \lambda_g \):

\[
\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_r}}
\]

(1)

The lowest resonant frequency, \( f_1 \), is given as:

\[
f_1 = \frac{12.5 \ c}{9 \ \pi \ n \ \sqrt{\varepsilon_{rs}}}
\]

(2)

where \( \varepsilon_{rs} \) is the effective dielectric constant, calculated at the lowest resonant frequency for the given substrate parameters, and \( c \) is the speed of light. In this context, most of the recently available EM simulators provide direct calculation of the effective dielectric constant based on the mentioned parameters.

V. PARAMETRIC STUDY

An interesting feature, the proposed antenna offers, is that its performance is considerably affected by the variation of its aspect ratio. For this purpose, we will...
define the aspect ratio of the proposed antenna as the ratio of the antenna ground plane width, \( W \), to its length, \( L \). In the subsequent investigation, the different values of the antenna aspect ratio are the results of varying the ground plane width and keeping its length constant.

Fig. 4 demonstrates the simulated return loss responses of the proposed antenna with its aspect ratio as a parameter and a feed line length of 25 mm.

Fig. 4 demonstrates the simulated return loss responses of the proposed antenna, depicted in Fig. 2, with the aspect ratio as a parameter. The aspect ratio has been varied from 0.75 to 1.5 in steps of 0.25, while the feed line length is maintained constant at 25 mm. It is clear from the results shown in Fig. 4 that the variation of the antenna aspect ratio has different impacts on the resulting resonant bands. As the aspect ratio has increased, all the resonant frequencies decrease but with different rates. The lowest resonant frequency, \( f_1 \), has been the least affected as compared with the second and the third resonant frequencies. More details concerning the variation of these frequencies with the antenna aspect ratio have been depicted in Fig. 5, where the aspect ratio has been varied in the range from 0.8 to 1.6 in steps of 0.2. However, below some value of the aspect ratio, the lowest resonant band starts to be diminished. Furthermore, for some value of the aspect ratio, the antenna possesses additional resonant band.

In summary, from the simulation results presented in Figs. 4 and 5, together with appropriate dimension scaling, the proposed antenna offers tri-band responses covering a wide variety of communication applications below 6 GHz, including GSM1800 (1710-1820 MHz), DCS (1.71-1.88 GHz), 2.4 GHz WLAN band (2.4–2.483 GHz), 2.50 GHz mobile WiMAX operating band (2.5–2.7 GHz), U-NII mid-band (5.47–5.725 GHz), U-NII high-band (5.725–5.875 GHz) and many others.

Fig. 6 demonstrates the current distribution on the surface of the modeled antenna at the three resonant frequencies. At the lowest resonant frequency, 1.80 GHz, the current path is concentrated on the outer circle and partially on the middle ring, while the inner circle contributes little in this respect. At the second resonant frequency, 3.70 GHz, the current path is partially concentrated on both the outer circle and the middle ring, while almost no current pass through the inner circle. At the third resonant frequency, 5.50 GHz, less current is concentrated on the outer circle and partially on the middle ring and the inner circle. In summary, shorter current path results in higher resonance and vice versa.

The far field patterns at the three resonant frequencies have been depicted in Fig. 7. It is clear that the proposed antenna offers almost monopole like radiation characteristics at all these resonances, where a figure eight-like radiation pattern in the XY plane and an approximately omnidirectional in the XZ plane. Fig. 8 has confirmed these facts, where the 3D E-field radiation patterns at centers of the three resonant bands have been demonstrated.

Fig. 5. The variation of the resonant frequencies as a result of varying the antenna aspect ratio, \( W/L \), and a feed line length of 25 mm.

Fig. 6. Simulated current distributions on the surface of the modeled antenna at: (a). 1.80 GHz, (b). 3.70 GHz and (c) 5.50 GHz.

Fig. 7. Simulated far field radiation patterns of the proposed antenna at (a). 1.80 GHz, (b). 3.70 GHz and (c) 5.50 GHz.
Another feature, the proposed antenna could offer, is that a dual-band response can be extracted within the same swept frequency as well. This can be achieved modifying the substructures that are embedded in the antenna slot structure. Recalling Figs. 1 and 2, the antenna slot structure is composed of three concentric substructures; a circular substructure with the least diameter at the center of the slot and two other annular rings with different diameters. It has been found that each of these substructures contributes differently to the resulting antenna performance.

Fig. 9 shows the return loss response of the proposed antenna, as depicted in Fig. 2, but with the smallest inner circle being removed leaving only the two concentric annular rings. Examining Fig. 9, where still three resonant bands occupy the same specified swept frequency range, the removal of this circle causes the antenna to produce resonances at three bands centered at about 1.80, 3.80 and 5.60 GHz respectively. The corresponding resonances produced by the original antenna structure, depicted in Fig. 3, take place at 1.80, 3.70 and 5.50 GHz respectively. This means that the removal of the inner circle has no effect on the position of the first resonant frequency, while slightly shifts the other two.

Fig. 8. Simulated 3D E-field radiation patterns of the proposed antenna at: (a) 1.80 GHz, (b) 3.70 GHz and (c) 5.50 GHz.

As it is implied in Fig. 10, the antenna with the modified slot structure offers an interesting dual-band resonant behavior. It is obvious that the removal of this ring acts like a band reject filter of the middle resonant band. On the other hand, it is clear that the lower resonant frequency is maintained at 1.80 GHz, since it is determined by the diameter of the external circle according to Equ. 2, while the upper resonant frequency is slightly shifted to the right. Then, the resonant bands offered by this antenna are shown to be positioned around 1.80 and 5.80 GHz with fractional bandwidths of about 17.3 and 7.75 % respectively. This makes this antenna a suitable candidate for use in dual-band wireless applications incorporating the GSM1800 (1710-1820 MHz), DCS (1.71-1.88 GHz), U-NII mid-band (5.47–5.725 GHz), and U-NII high-band (5.725–5.875 GHz) services. The current distributions on the surface of this antenna at 1.8 and 5.8 GHz have been depicted in Fig. 11.
A further parametric study has been conducted to explore the effect of the inner ring dimensions of the antenna slot structure, depicted in Fig. 10, on the resulting antenna dual-band response within the specified frequency range. For this purpose the inner ring diameter and its width have been scaled by a factor ranging from 0.9 to 1.1 in steps of 0.05. Again, as shown in Fig. 12, the modified antenna is still with dual-band resonant behavior, and the inner ring acts like a tuning element to allocate the two resonant bands. However, the ring scaling has larger impact on the higher resonant band as compared with that on the lower one.

VI. CONCLUSION

The Cantor fractal based circular printed slot antenna has been suggested in this paper for use in tri-band and dual-band wireless applications. A parametric study carried out on this antenna reveals that the antenna aspect ratio has a considerable effect on its return loss response. Simulation results show that for a certain range of the aspect ratios, the antenna is capable to offer return loss responses covering almost most of the recently available communication services below 6 GHz. Furthermore, it has been found that the proposed antenna can offer a dual-band resonance by modifying its slot structure without varying its dimensions. A design example presented for 1.8/5.8 GHz dual-band applications, shows that the antenna exhibits a dual-band behavior with the two resonant bands centered at 1.8 and 5.8 GHz and the corresponding fractional bandwidths are sufficient for such an application. The compact size of the proposed antenna, together with the reasonable radiation characteristics, make it suitable for a wide variety of the recently available triple band / dual-band wireless applications operating within the specified frequency range.

REFERENCES


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