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MULTIBAND FRACTAL-LIKE ANTENNAS

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Abstract—In this paper, new multiband fractal-like antennas are proposed. The proposed multiband antenna design is based on a methodology that utilizes the self transformation principle of fractal-like rectangular profiles to generate multiband operation. The proposed monopole-type antennas are built on a partial ground plane and fed through a microstrip feed line. The analytical design procedures are straightforward and can be applied to any practical antenna structure to operate at multiple preselected bands. The developed methodology has been used to design antennas operating at three, four, and five preselected practical bands. Numerical simulations are utilized to verify the simple design procedures of the proposed multiband antenna structures. The triple-band and the quad-band structures have been realized on FR4 substrate to prove the concept. Simulation and experimental results are in good agreement and demonstrate the performance of the design methodology and the proposed antenna structures.

1. INTRODUCTION

Immense growth in wireless communication system demands more complex and sophisticated systems along with more operating bands. In mobile communication systems many different frequency bands are needed such as global system for mobile communication (GSM800/900), digital communication system (DCS), personal communication system (PCS), universal mobile telecommunication system (UMTS) and the industrial scientific and medical (ISM) band [1]. Multiband antennas are also very attractive candidates for application in communication devices for global positioning system

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(GPS) and Bluetooth and Wireless Local Area Network-WLAN 802.11b/g system bands.

To satisfy these demands, antenna designers try to achieve small, light weight, and low profile multiband antennas [2]. Fractal antennas have received much attention from antenna designers to make multiband antennas because they are light-weight, low profile, conformal and easy to combine with other circuit structures. Several fractal configurations have been suggested for GSM/DCS/WLAN, 900/1800/2450 MHz bands in recent publications as the fractal shapes consists of self-similarity and can be applied to design multiband antennas. It has been demonstrated that fractal shapes [3, 4] are suitable solutions for both miniaturization [5, 6] and multi-band operation [7, 8]. Fractal geometries are fragmented geometries that can be subdivided in parts, each of which is a reduced copy of the whole. Fractals are generally self similar and independent of scale. Self-similarity is probably one of the most important characteristics of fractal profiles. It means the same geometry repeats with different length and width scales. The Sierpinski gasket monopole antenna has been designed by decomposition method [9], through three iterations. In decomposition method, the original gasket is constructed which is an equilateral triangle by subtracting a central inverted triangle from the main triangle. Remaining three equal triangles are half scaled from each other. The same decomposition method is repeated for the remaining three triangles, if the iteration taken place an infinite times then an ideal Sierpinski gasket is obtained. In such an ideal structure, each main part is exactly equal to the whole object, but scale by a given factor. Due to this particular similarity property, it is said that the Sierpinski gasket is a self-similar structure.

A modified Sierpinski fractal broadband antenna for multiband application was proposed in [10], the perturbed fractal patch and modified partial ground plane are employed to obtain wider bandwidth at resonance frequencies. Another Sierpinski fractal antenna designed through three iterations displays a multiband behaviour with three bands that are log periodically spaced by a factor of 2; the same scale factor that defines the geometrical self-similarity of the Sierpinski fractal [11]. A Modified configuration of Sierpinski gasket monopole antenna is proposed in [12]. The motivation for the modified configuration originated from the fact that at, the first band of the Sierpinski monopole gasket, the similarity and periodicity is lost due to the truncation effect of the finite number of iterations. Since the similarity is lost one can take the advantage of it by altering the geometry of the upper subscale in an effort to change the electromagnetic behaviour and control the spacing between the first two bands. Furthermore, the modification maintains the symmetry of the upper bands and ground plane dimensions which are the controlling parameters of the antenna affecting both the spacing factor and the bandwidth of the operational bands. A triple band planner antenna working in the GSM and UMTS frequency bands was presented in [13]. A hybrid pre-fractal shape has been adopted by integrating a Sierpinski and a Meander-line structure. The synthesis of the antenna has been performed by optimizing the descriptive geometrical parameters of the reference shape by means of a customized particle swarm strategy to comply with the electrical and geometrical requirements. In [14], a simple microstrip-line-fed monopole antenna for triple band wireless applications was designed. By properly loading folded strips along the edges of a stair patch, the designed antenna with a moderate ground plane can have good impedance matching in triple-bands covering DMB (or L-band DVB-H) and 2.4/5.2/5.8 GHz WLAN operations. Basically, most of the above described contributions and other published work are based, generally, on experience intuition and trial and error schemes [15–18].

In this paper, fractal-like geometrical structures with self transformation property have been investigated for multiband wireless communications antenna applications. A simple design methodology based on the self transformation of fractal-like multi-rectangular-slot geometries has been developed and elucidated in the next section. This systematic approach can be applied to design multiband antennas operating at predetermined multiple bands on suitable substrates with partial ground plane ensuing wide operating bandwidths. Based on that, novel triple-band, quad-band, and pent-band fractal-like antennas have been designed and presented in this paper. The effect of the geometrical iterations and the self-transformation factors on locating the operating-bands is investigated as well. The introduced rectangular-slot-based fractal-like microstrip antenna geometries are not only simpler than the classical complex triangular fractal geometries but they, also, have more controllable and flexible superior multiband operation. Numerical simulations, using full wave electromagnetic (EM) MoM-based IE3D simulator, are used to verify the systematic design approach. Two triple-band and quad-band antenna structures have been realized on FR4 dielectric substrate material with 4.7 relative permittivity and 0.78 mm thickness. Simulation and experimental results express the good matching and radiation performance of the designed multiband antennas without an extended ground plane.

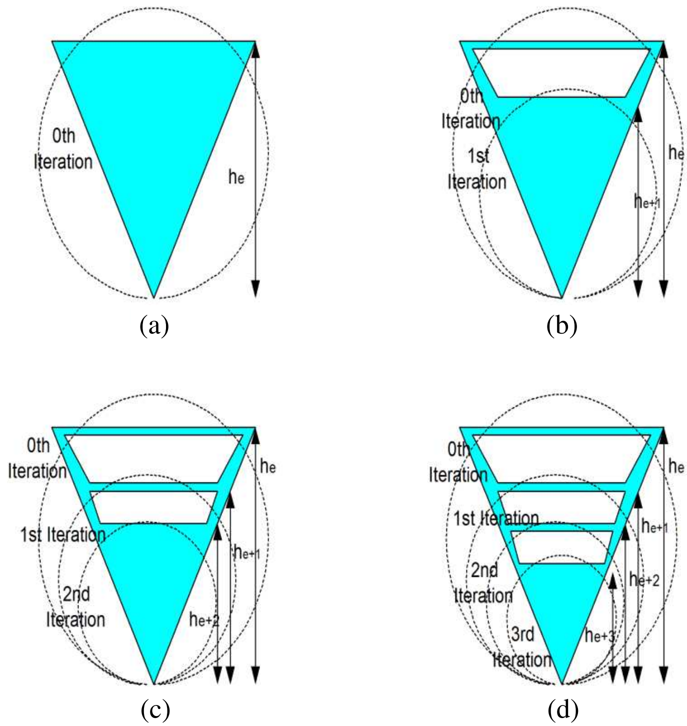


Figure 1. Generation of multiband fractal-like geometries.

2. MULTIBAND FRACTAL-LIKE ANTENNAS

The proposed fractal-like antenna is shown in Figure 1. This fractal-like antenna has repeated (iterated) simple rectangular slots instead of the standard multiple isosceles triangles. Such fractal-like antennas can operate at multiband depending on their geometries. The proposed multiband antenna is constructed by applying a geometric transformation on the triangular base-region of the bowtie monopole antenna of Figure 1(a). Subtracting the inverted gasket triangle to the rectangular shape, the fractal-like monopole in Figure 1(b) is obtained. Repeating the procedure more than one time, results in the fractal like monopoles shown in Figures 1(c) and 1(d). The first band of such structures corresponds to the fundamental frequency of the bowtie monopole [11] and can be approximated by,

$$f_o \approx \frac{c}{2L_e\sqrt{\varepsilon_r}} \qquad (1)$$

where, c is the speed of light in vacuum, L_e is the effective length which is the sum of strip feed line and length of the triangle, i.e.,

$$L_e = L + p \tag{2}$$

where, L and p are the lengths of the triangle and the strip line indicated in Figure 2.

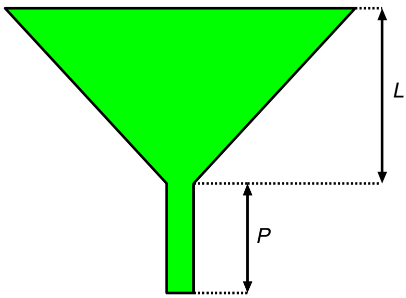


Figure 2. Triangular shape indicating lengths of the triangle and strip line.

The second and higher bands are log-periodically spaced by a ratio which is determined by the iterative construction procedure and the self transformation factor or space factor. It can be calculated as [11];

$$\psi = \frac{h_e}{h_{e+1}} \tag{3}$$

where, ψ and h are the self transformation factor and height of the gasket, respectively. The second band is analogous to that of classical Sierpinski fractal shape [11] and can be calculated approximately using an empirical relation developed from [9] and given as;

$$f_2 \approx 0.52 \frac{c}{L_e} \tag{4}$$

where, c is the speed of light in vacuum, L_e is the effective length of the largest gasket. Higher bands are, then, calculated simply from the self transformation (space) factor of the structure. The number of the antenna's operating-bands is determined by the number of geometric iterations and it is equal to the number of iterations. The number of the generated rectangular slots in the geometry is one less the number of the operating bands of the antenna. The proposed multiband fractal-like monopoles possess good matching performance with compact partial-ground plane unlike classical fractal structures presented in [11] and [12].

2.1. Triple-band Fractal-like Antennas

The triple-band fractal-like antenna is designed by performing three iterations to operate at three preselected frequencies. Simple antennas designs on FR4 dielectric substrate with thickness, $q = 0.78\,\text{mm}$ and relative permittivity, $\varepsilon_r = 4.7$ are used to demonstrate the design concept. The fractal-like antenna with a total dimension of $62 \times 89.6 \times 0.78\,\text{mm}^3$, is fed by a microstrip line placed at the centre axes of the dielectric substrate as shown in Figure 3. The partial ground plane which is on the other side is only $62 \times 24\,\text{mm}^2$. The

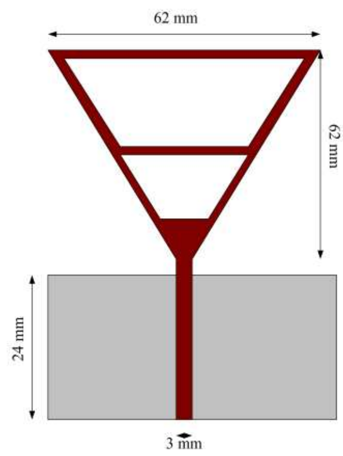


Figure 3. Triple band fractal-like antenna with $\psi = 2$.

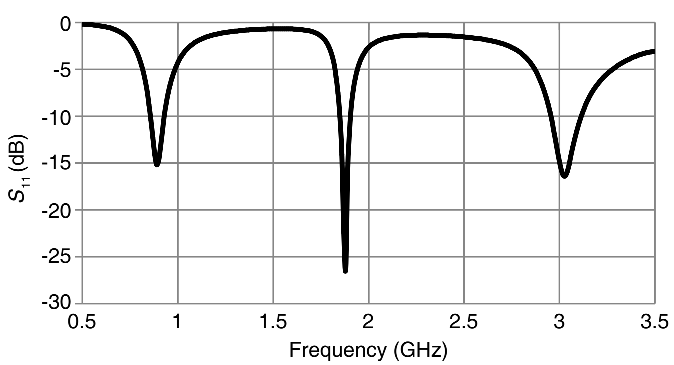


Figure 4. Computed S_{11} of triple band fractal-like antenna with $\psi = 2$.

width and length of the strip line is 3 mm and 27.6 mm, respectively. Triple band fractal-like antenna design with self transformation factor of 2 has bands which are log-periodically spaced by a factor of 2 except the first band.

The 50 Ω return loss of the triple band fractal-like antenna in Figure 4 shows that the second and third bands are spaced by a scale factor of 2. The first resonance occurs at $f_1 = 890$ MHz, the second resonance occurs at $f_2 = 1720$ MHz, and the third resonance occurs at $f_3 = 3000$ MHz.

The effect of the transformation (space) factor on controlling the locations of the higher bands is investigated by two additional triple-band examples. The second triple-band fractal-like antenna is similar to the previous one but with a self transformation factor of 1.5 which produces smaller rectangular slots. The antenna consisted of an open triangular gasket with a partial ground plane is depicted in Figure 5.

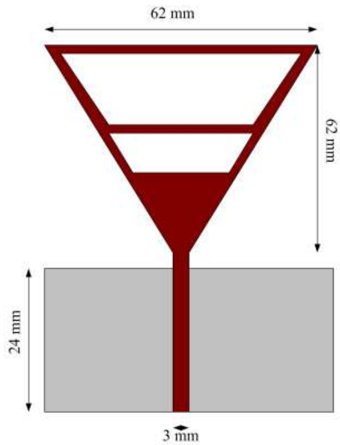


Figure 5. Triple band fractal-like antenna with $\psi = 1.5$.

The return loss plot of this triple band fractal-like antenna in Figure 6 shows that the second and the third bands are equally spaced by a periodicity factor of 1.5. Also, investigating the resonance frequencies of the designed antenna of Figure 5, it is noticed that the third band moves closer to the second band. This is due to the smaller self transformation factor. The first band occurs at $f_1 = 890$ MHz, second resonance occurs at $f_2 = 1770$ MHz, and the third resonance occurs at $f_3 = 2600$ MHz. These bands are practically wide bands and located at the GSM800/900, DCS and 3GPP Long Term Evolution bands.

The third triple-band fractal-like antenna is similar to the previous ones but with a scale factor of 1.25 which produces smaller rectangular slots than the above examples. The designed antenna is shown in Figure 7 with the partial ground plane and microstrip feed line.

Figure 8 shows the return loss graph of the last triple band fractal-like antenna. It can be observed that using 1.25 self transformation factor makes an important effect to shift the resonant frequencies closer to the lower frequency direction where all the three bands befall closer to each others. Furthermore, good matching among the bands

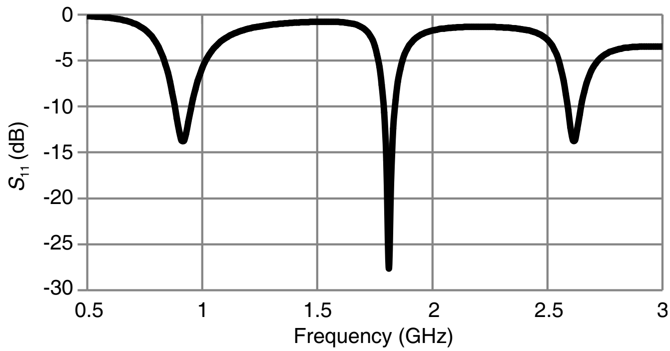


Figure 6. Computed S_{11} of triple band fractal-like antenna with $\psi = 1.5$.

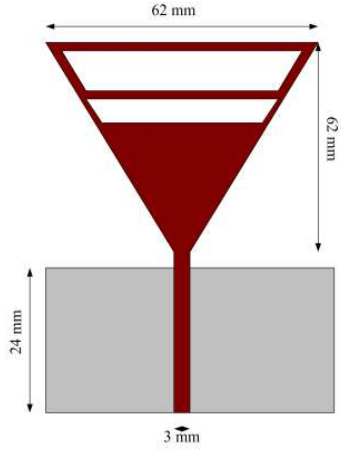


Figure 7. Triple band fractal-like antenna with $\psi = 1.25$.

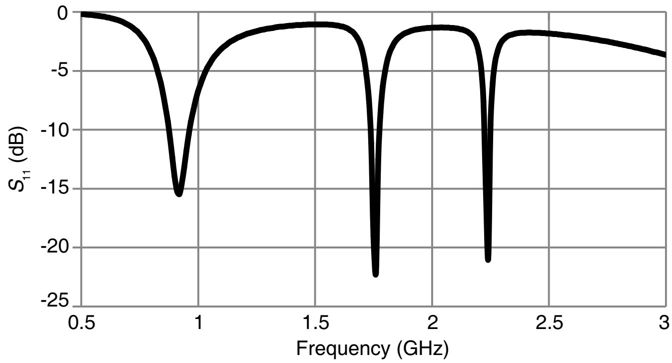


Figure 8. Computed S_{11} of triple band fractal-like antenna with $\psi = 1.25$.

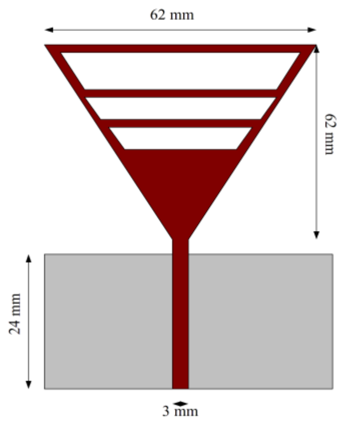


Figure 9. Quad band fractal-like antenna with $\psi = 1.25$.

can be seen in the return loss plot. S_{11} plot shows that the first resonance frequency is at $f_1 = 890\,\text{MHz}$, the second resonance occurs at $f_2 = 1710\,\text{MHz}$, and the third resonance occurs at $f_3 = 2200\,\text{MHz}$. The bands cover the practical operating frequencies of GSM, DCS and IMT-2000.

2.2. Quad-band Fractal-like Antenna

The quad band fractal-like antenna presented here consists of a partial ground plane and microstrip feed line whose three rectangular-slot geometry is shown in Figure 9. The dimension of the proposed quad-band fractal-like antenna is same as the previous examples. Four iterations have taken place to get the four resonance frequencies on 1.25 self transformation factor using Equation (3). The first two resonance frequencies approximated by Equations (2) and (3), and the 1.25 periodicity behaviour among the second, third and fourth bands are revealed in the respective return loss plot shown in Figure 10.

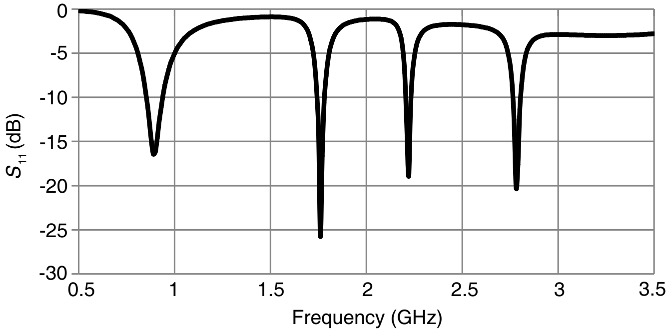


Figure 10. Computed S_{11} of quad band fractal-like antenna with $\psi = 1.25$.

Return loss plot shows that the first resonance frequency occurs at $f_1 = 890\,\text{MHz}$, second resonance occurs at $f_2 = 1710\,\text{MHz}$, the third resonance occurs at $f_3 = 2200\,\text{MHz}$ and the fourth resonance occurs at $f_4 = 2700\,\text{MHz}$. These bands cover the operating frequencies of GSM, DCS, IMT-2000, and WiMAX allocated bands.

2.3. Pent-band Fractal-like Antenna

An Antenna design with five-band operation is accomplished by performing five iterations on the fractal-like structure. A 1.25 self transformation factor is applied to the fractal-like partially ground plane antenna to control the operating five bands. The five bands fractal-like antenna is shown in Figure 11 which has the same dimensions as the previous examples. This structure has four rectangular slots with dimensions determined by the chosen space factor. Figure 12 illustrates the 1.25 periodicity behaviour among the second, third, fourth and fifth bands.

The S_{11} plot shows that the first resonance frequency occurs at $f_1 = 890\,\text{MHz}$, second resonance occurs at $f_2 = 1710\,\text{MHz}$, the third resonance occurs at $f_3 = 2200\,\text{MHz}$, the fourth resonance occurs at $f_4 = 2700\,\text{MHz}$, and fifth resonance occurs at $f_5 = 3500\,\text{MHz}$. These are practical bands that cover the operating frequencies of GSM, DCS, IMT-2000, and WiMAX allocated bands.

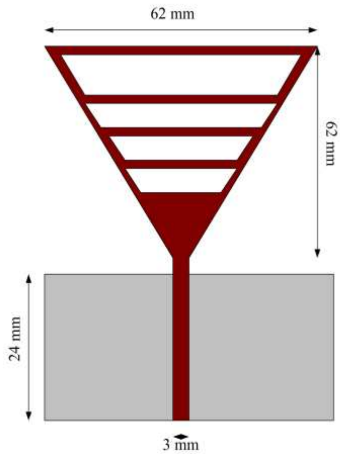


Figure 11. Pent-band fractal-like antenna with $\psi = 1.25$.

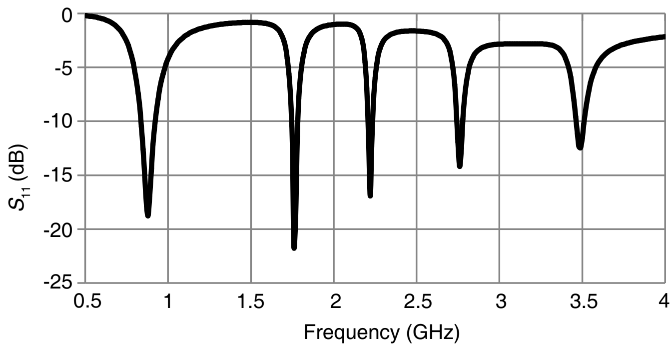


Figure 12. Computed S_{11} of pent-band fractal-like antenna with $\psi = 1.25$.

In the proposed multi-band fractal-like antennas the resonance frequencies are generated and controlled by applying fractal iterations and geometry transformation. Performing iterations (with rectangular-shape slots) in the basic antenna gasket leads the antenna to function at different preselected controllable bands. As compared to classical fractal monopoles, rectangular slot-based fractal-like geometries provide more capability in controlling the number of operating frequencies and in locating them much closer to each others. For example, the proposed quad-band antenna has all of the bands within 2 GHz as compared to 8 GHz in the classical fractal antenna shapes [9–11]. Besides that, the proposed rectangular-slot geometries give at least 31% direct-size reduction as compare to the conventional fractal antennas in addition to a remarkably more compact partial ground plane [9–11].

3. RADIATION CHARACTERISTICS

To examine the radiation of the multiband fractal-like antenna structures, the computed radiation patterns of the quad band fractal-

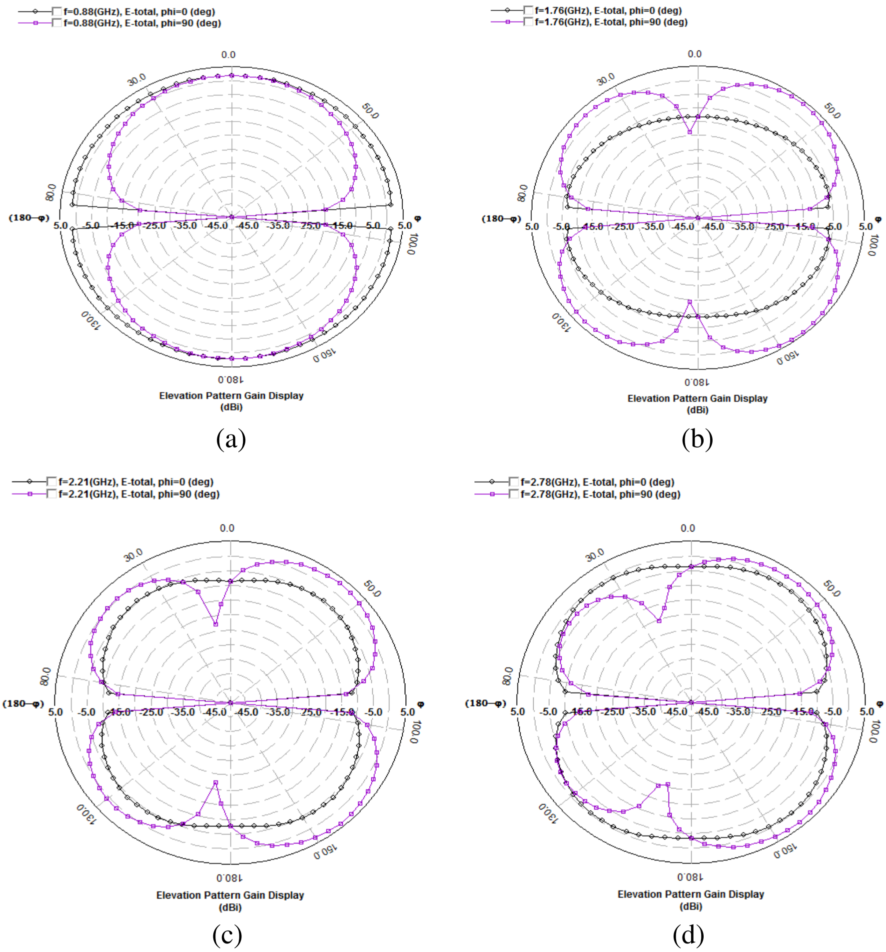


Figure 13. Computed radiation patterns of the proposed quad-band fractal-like antenna at (a) 0.88 GHz, (b) 1.76 GHz, (c) 2.21 GHz, (d) 2.78 GHz.

like antenna of Figure 9 are depicted in Figure 13. The radiation patterns of the total radiated field at two orthogonal planes; $\phi = 0°$ and $\phi = 90°$, at the four resonance frequencies; 0.88 GHz, 1.76 GHz, 2.21 GHz and 2.78 GHz are shown in the figure. The antenna confers a dipole like patterns with an omnidirectional behaviour at $\phi = 0°$ plane. The antenna radiation characteristics at the first band are very similar to that of the basic bow-tie monopole at its resonance frequency. The gain of the antenna at the four bands is between 1 dB at the lower band and 4 dB at the higher band as expected for microstrip monopole structures. The computed radiation efficiencies of the quad-band antenna are in the range of 90% at the first band and decreases to 62% at the fourth-band.

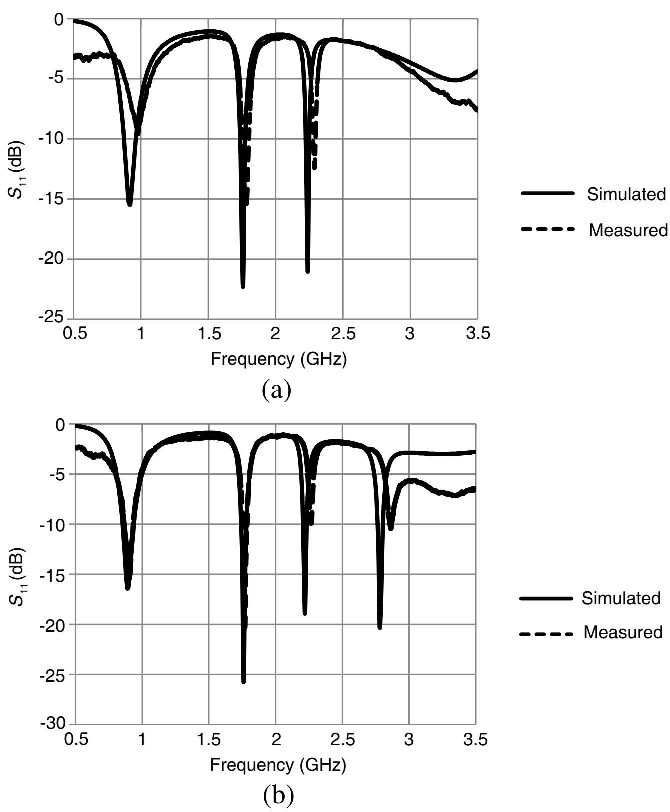
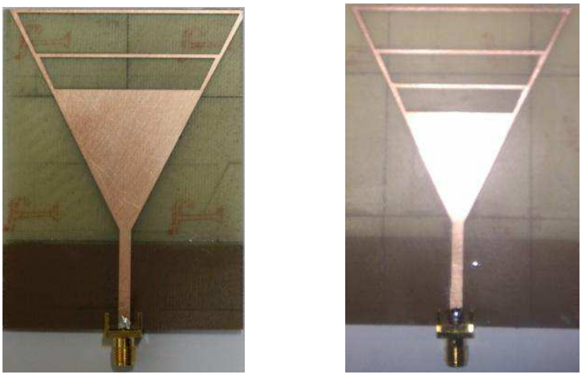


Figure 14. Simulated and measured S_{11} of the proposed (a) triple band fractal-like antenna, (b) quad band fractal-like antenna.



(a) (b)

Figure 15. Photographs of the fabricated (a) triple band fractal-like antenna and (b) quad band fractal-like antenna.

4. FABRICATIONS AND MEASUREMENTS

The triple-band and the quad-band fractal-like antennas shown in Figure 7 and in Figure 9 have been implemented on the same FR4 substrate used in the theoretical study. The measured return loss as compared to the simulated one is plotted in Figures 14(a) and 14(b) for the triple band and the quad band antenna structures, respectively. The fabricated antennas are photographed in Figure 15 as well.

Good agreement between the simulated and the measured results is observed. The measured resonance frequencies for the triple-band antenna are 895 MHz, 1720 MHz, and 2230 MHz. Similarly, the measured resonance frequencies for the quad-band antenna are at 880 MHz, 1760 MHz, 2220 MHz and 2800 MHz, respectively.

5. CONCLUSIONS

Fractal-like geometrical structures with self transformation property have been investigated for multiband wireless communications antenna applications. A simple design methodology based on the self transformation property of fractal-like geometries has been developed. This systematic approach can be applied to design multiband antennas operating at predetermined multiple practical bands on suitable substrates. Accordingly, new multiband fractal-like antennas have been designed and proposed in this paper. The proposed antennas are with simple multi-rectangular slot geometry and built on a partial ground plane fed through a microstrip feed line. The control of the locations of the antenna multiple operating-bands by the space factor has been demonstrated as well. The designed antennas are simulated using a full wave electromagnetic (EM) simulator and then two triple and quad-band antenna structures were realized on FR4 dielectric substrate material with relative permittivity of 4.7 and thickness of 0.78 mm. Simulations and experimental results are in good agreement and reveal the matching and the radiation performance of the proposed compact ground-plane fractal-like multiband antennas.

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