Journal of Engineering Science and Technology
Vol. 19, No. 3 (2024) 966 - 976

PERFORMANCE COMPARISON INVESTIGATION OF THE WIDEBAND AND FRACTAL MULTIBAND BOWTIE ANTENNAS

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Abstract

In many applications, it is desirable to use a single antenna that can operate effectively at several tune frequencies instead of a several narrowband antennas. Fractal antennas have many advantages, and they are capable to fulfil these requirements. In this paper, the conventional bowtie antennas which are characterized as broadband antennas are redesigned to include the Sierpiniski fractal structures such that the required multiband operation can be fulfilled. The original bowtie antenna shape is repeated at different scales corresponding to the required frequency bands. Thus, the procedure for producing the modified fractal multiband bowtie antenna is simple. This simplicity in the configuration change makes the proposed fractal bowtie antenna very desirable in practice and it can used in the frequency-reconfiguration applications. Further, it can be precisely tuned to any number of frequency bands depending on the number of fractal growth. Three antennas are designed, and their performances are analysed. The first one is a simple narrowband dipole; the second one is a broadband bowtie, and the third one is a Sierpiniski fractal multiband bowtie antenna. Their performances in terms of return loss, radiated power, gain and the directivity are extensively studied and compared using both MATLAB simulation and CST full-wave modelling software. The designed second-stage fractal bowtie has multiple resonant frequencies at different scale copies of the structure at 2.4, 9.2 and 17.4 GHz.

Keywords: Bowtie antennas, Fractal multiband antennas, Narrowband antennas, Wideband antennas.

1. Introduction

The current evolution in the massive wireless communication technologies have been introduced great challenges and opportunities for antenna designers. Especial attention were paid toward techniques of interference and noise suppression [1-3] to improve the reliability, spectral efficiency, and the system's performance where advanced antenna technologies are used for beamforming to focus the signal on a desired direction only and reduces interfering signals in other directions [4-7]. As the demand for wireless communication continues to grow, the need for compact, high-performance, and effective antennas that are efficiently capable to operate in a wide range of applications becomes increasingly crucial. Some key aspects of this challenge includes: compactness and miniaturization, high performance, easy-to-fabricate, high radiation efficiency, multiband and wideband operations [8, 9]. Conventional antennas are often designed to operate within specific frequency bands, which can limit their versatility for multipurpose wireless applications. This limitation has led to the development of more advanced and flexible antenna designs to address the needs of modern wireless communication systems [10, 11].

Modern antenna systems are expected to support a wide range of wireless standards and frequencies by making them reconfigurable. Antenna designers are tasked to create single antenna systems that can operate efficiently across multiple frequency bands or provide wideband coverage to accommodate diverse communication standards. The use of fractal geometry in patch antennas is a fascinating and effective technique for achieving multiband performance and compact antenna designs [10-12]. Fractal antennas are characterized by their self-similar patterns, where smaller copies of the overall shape are repeated at different scales. This property allows fractal antennas to exhibit unique electromagnetic properties that can lead to improved performance and versatility [11].

Fractal geometry, as defined by Benoit Mandelbrot in 1975, offers unique properties that can enhance antenna performance and functionality. The concept of fractals involves self-similarity and recursive procedures, resulting in complex structures that exhibit certain properties, such as large surface area within limited space [11]. The snowflake curve, which was one of the first examples of a fractal presented by Mandelbrot, illustrates the intricate and self-repeating nature of fractal shapes. This property is what makes fractal patterns particularly interesting for antenna design, as it allows for the creation of compact structures with enhanced electromagnetic properties [12], the self-similarity inherent in fractal shapes can be harnessed by applying an infinite number of iterations, leading to the achievement of multiband characteristics in antennas.

This approach is a key feature that makes fractal geometry particularly advantageous for creating compact and multiband antennas [13]. The space-filling property of fractal geometries is a valuable tool that antenna designers use to decrease the size and achieve miniaturization of antennas. Fractal antennas take advantage of this property to create structures that efficiently utilize space, allowing for compact designs without sacrificing performance.

Fractal geometries come in various types and shapes, each with its unique characteristics and applications. Some common types of the fractal geometries that used in the antenna design are as follows: Koch Curve, Hilbert curve, Sierpinski carpet, Sierpinski gasket, Giusepe-piano, Koch snowflake and Minkowski loop [14].

The conventional bowtie antenna is a type of wideband antenna that derives its name from its distinctive bowtie-shaped radiating elements. It is known for its broadband performance, relatively simple design, and wide radiation pattern. Conventional Bowtie antennas are often used in applications that require wide frequency coverage and moderate gain. Some key characteristics and features of the bowtie antenna includes wideband performance that can cover a broad frequency range while maintaining relatively consistent radiation characteristics. This makes it well-suited for applications that require operation across multiple frequency bands. Its radiation pattern is usually bidirectional in the plane of the antenna. This means that the antenna radiates energy effectively in both forward and backward directions, making it suitable for various applications [15].

On the other hand, the simple dipole antenna is often associated with a single resonant frequency and omni-directional radiation pattern. It can be designed to operate in a narrow band of frequencies with careful design considerations. The dipole antenna can be tailored for narrowband operation; the physical length of a half-wave dipole antenna determines its resonant frequency. To make a dipole antenna operate in a narrow band, simply adjust its length to match the desired frequency range. However, this means sacrificing some of the inherent advantages of a dipole's simplicity and omni-directional radiation [16].

The used of fractal geometry arrangements for the design of planar antenna arrays with low side lobes. Iterated Function System (IFS) is used to generate the Sierpinski fractal antenna arrays using circular shapes. CST Microwave Studio EM Simulation software is used for design and simulation of these antenna arrays. In [17], the authors designed a fractal Sierpinski antenna that can operate at two resonant frequencies where its performance is examined experimentally. Such a behaviour is based on the self-similarity properties of the antenna's fractal shape, which might open an alternative way for designing new multiband and frequency independent antennas.

Franciscatto et al. [18] fabricated a Sierpinski fractal gasket with a height of 1.6 mm using a Fr4 substrate. The modified Sierpinski gasket has an increased in the bandwidth where in the first iteration, there are wide bands, and after cutting the slot in microstrip patch and get a wide bandwidth that covers applications in the frequency range of 4.8-5.9 GHz and two bands in the frequency range of 7.1-7.4 GHz and 8.2-8.9 GHz.

Yu et al. [19] designed and simulated various configurations of Koch snowflake fractal. It was identified that linear arrays have more gain than the corporate array. The simulation result has confirmed the gain enhancement in antenna as compared to single element antenna. Other antenna types have been proposed to enhance the bandwidth and gain [20, 21].

This paper presents design and performance investigation of three different antennas for applications that ranging from the second generation (2G), third generation (3G), fourth generation (4G), WLAN, fifth generation (5G), and the navigation wireless applications. First, a bowtie broadband antenna has been designed using microstrip technique and then its fractal counterpart has been derived from the original bowtie antenna for 5G applications. The performances of the conventional and the modified fractal bowtie antennas have been compared and verified using MATLAB simulation and CST full wave modelling software. The proposed fractal bowtie antenna structure is capable to provide a significant improvement in the performance with compared to its original bowtie antenna without fractal structure. The improvements include return loss, radiated power and some other radiation characteristics.

2. Microstrip Antenna Design

In this section, three different types of microstrip antennas are designed and simulated using both the MATLAB simulation and the CST full-wave modelling software where the narrowband dipole, broadband bowtie and the proposed fractal multiband bowtie antennas are considered.

The narrowband half-wavelength dipole antenna is a one of the most commonly used antennas in practice. Its radiation resistance is 73 ohms, which is very close to the 50 ohm or 75 ohm characteristic impedances of some transmission lines. A perfect matching to the line can be obtained at the resonance frequency. The length of the dipole is calculated from the following equation:

$$L = \lambda/2 \tag{1}$$

where $\lambda = C/f$, C is the speed of wave propagation in free space, f is the operating frequency. However, for the half-wavelength dipole the length for a wave travelling in free space is needed to be multiplied by a factor called "A" which is known as the end factor. Its value can be calculated according to Fig. 1 as follows

$$L_n = A \times L \tag{2}$$

where L_n is the new length which represents the physical effective length of the dipole. The radius of dipole is computed as $R = 0.001 \times \lambda$. Then the diameter of the dipole is $D = 2 \times R$. Then, the feeding gap at the centre of dipole is computed as

$$g = L_n/200 \tag{3}$$

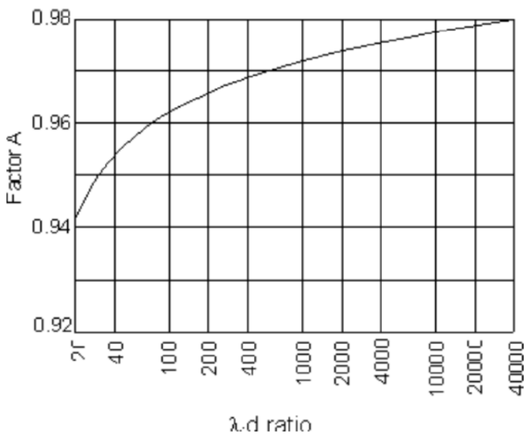


Fig. 1. The Multiplication factor "A" that used for calculating the physical length of the dipole.

This dipole antenna is designed at 2.4 GHz, as shown in Fig. 2. The length of this dipole is about 60.63 mm, the width of the strip is 0.13 mm and the distance between two dipole strip is 0.30 mm. The feeding point is placed at the origin. The performance of the designed dipole antenna in terms of return loss, radiated power and the gain will be analysed.

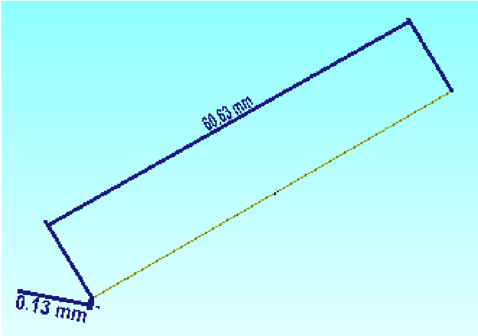


Fig. 2. Narrowband dipole antenna designed at 2.4 GHz using CST software.

A second design is the bowtie antenna, also it is known as a bow-tie antenna or butterfly antenna. It is a type of dipole antenna that resembles two bowtie-shaped elements facing each other. It is a popular design for wideband radio frequency (RF) and microwave applications, commonly used for television reception, wireless communication systems, and radars. This antenna is also designed at 2.4 GHz. Its height was about 22.06 mm, width=34.91 mm, flare angle =67.380 and distance between two triangles is about 1.82 mm as shown in Fig. 3. In general, this antenna can be designed as a function of the designed frequency, or the wavelength as follows:

$$\mathrm{BW} = 0.33\ \mathrm{f} \quad (4)$$

$$\mathrm{Width} = 0.375\ \lambda \times 1000\ \mathrm{mm} \quad (5)$$

$$\mathrm{Distance} = 0.02066\ \lambda \quad (6)$$

$$\mathrm{Hight} = 0.25\ \lambda \quad (7)$$

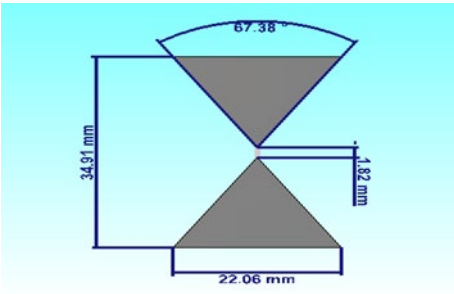


Fig. 3. Wideband bowtie antenna designed at 2.4 GHz using CST software.

The third designed antenna is the proposed Sierpiniski bowtie fractal antenna which is a direct modification from the conventional bowtie antenna. The proposed Sierpiński fractal bowtie is built using an equilateral triangle as its initial shape. The initial shape is bowtie construction itself the height, width and distance are equal to bowtie dimension, The basic construction rule is to divide the triangle into smaller equilateral triangles and then remove the middle triangle from each set of three. This process is repeated recursively on the remaining smaller triangles as infinitum. In this paper this process is repeated two times which corresponds to the second iteration fractal antenna as shown in Fig. 4, where the first one represents the original bowtie antenna without fractal structure while the second one represents the fractal bowtie at first iteration and the third one represents the fractal bowtie at the second iteration. It can be seen from Fig. 4 that the Sierpiński triangle exhibits self-similarity because each smaller copy of itself is similar to the overall structure.

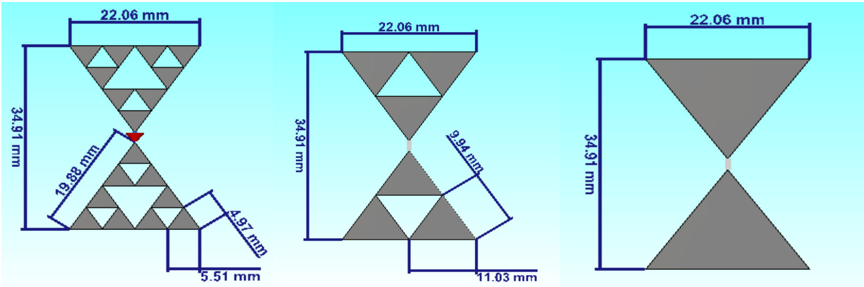
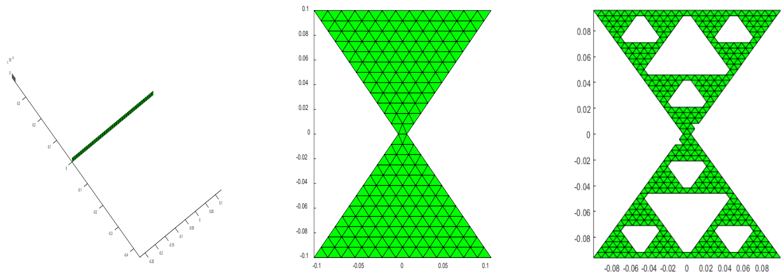


Fig. 4. Fractal multiband bowtie at various stages designed using CST software.

3. Simulation Results and Discussions

In this section, three different antenna structures are designed, and their performances are compared using two different simulations software namely MATLAB and CST. These antennas are the narrowband simple dipole antenna, broadband bowtie antenna and a fractal multiband bowtie antenna. They are all designed and simulated at two different frequencies, i.e., 0.4 GHz and 2.4 GHz. The CST designed structures of these three antennas at 2.4 GHz were shown in Figs. 2, 3 and 4 respectively, while the MATLAB designed structures of these three antennas at 0.4 GHz are shown in Figs. 5(a), (b), and (c) respectively.



(a) (b) (c)

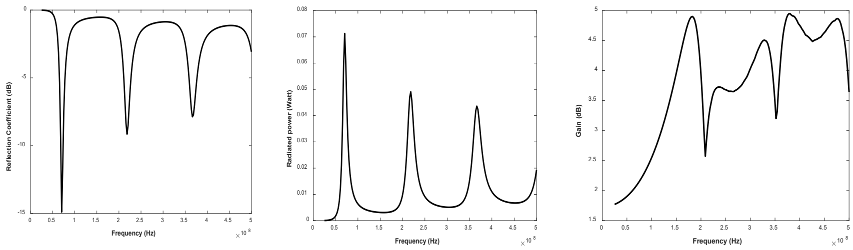
Fig. 5. Designed antennas using MATLAB simulation (a) Narrowband dipole, (b) Broadband bowtie, (c) Fractal multiband bowtie at second stage.

The feeding edge is always chosen to be at the origin. The method of moment is used to design these antennas in MATLAB which involves dividing the antenna's surface into a number of small triangular segments. For each segment, the electric and magnetic fields have been solved. Then, the antenna impedance and the current distribution on the overall antenna's surface is solved which is used to find the antenna's radiation pattern. The design specifications of the three structured antennas that were shown in Fig. 5 are listed in Table 1.

Table 1. The MATLAB design specifications of the constructed antennas.

Antenna Name	Design Specifications
Narrowband Dipole	2m total length, 0.02 wide strip.
Wideband Bowtie	0.2m total height and width with flare angle 90 deg.
Fractal Multiband Bowtie	0.2m length whereas the height is smaller 0.18m with second iteration

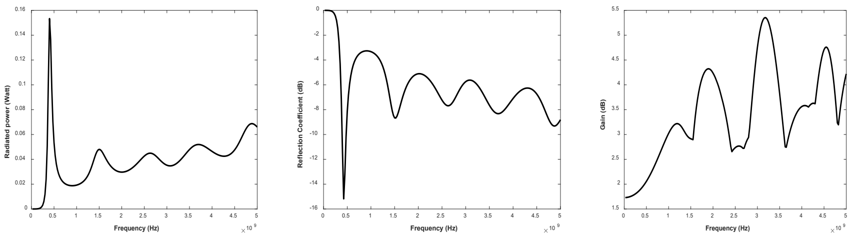
The simulated performance of the designed narrowband dipole antenna in terms of the reflection coefficient, radiated power, and the antenna gain as a function of the frequency are shown in Fig. 6. The MATLAB constructed half-wavelength dipole operates at the resonance frequency which is at 0.4 GHz. It is also observed that there is other two resonance frequencies appearing at multiple integers of the wavelength which are at 2.2 GHz and 3.7 GHz respectively.



(a) (b) (c)

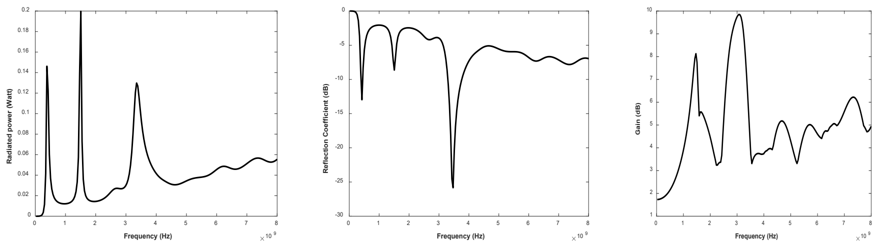
Fig. 6. Performance of the constructed dipole antenna using MATLAB (a) Reflection coefficient, (b) Radiated power, (c) Gain.

The first resonance frequency is at 0.4 GHz which corresponds to the original bowtie antenna, and it does not rely on the fractal structures. The second resonance is at 1.48 GHz which corresponds to the first iteration fractal structure, while the third one is at 3.35 GHz which corresponds to the second iteration fractal structure. The MATLAB results of the constructed broadband bowtie antenna are shown in Fig. 7 in which its resonance frequency is at 0.4 GHz, while the MATLAB results of the fractal bowtie antenna are shown in Fig. 8.



(a) (b) (c)

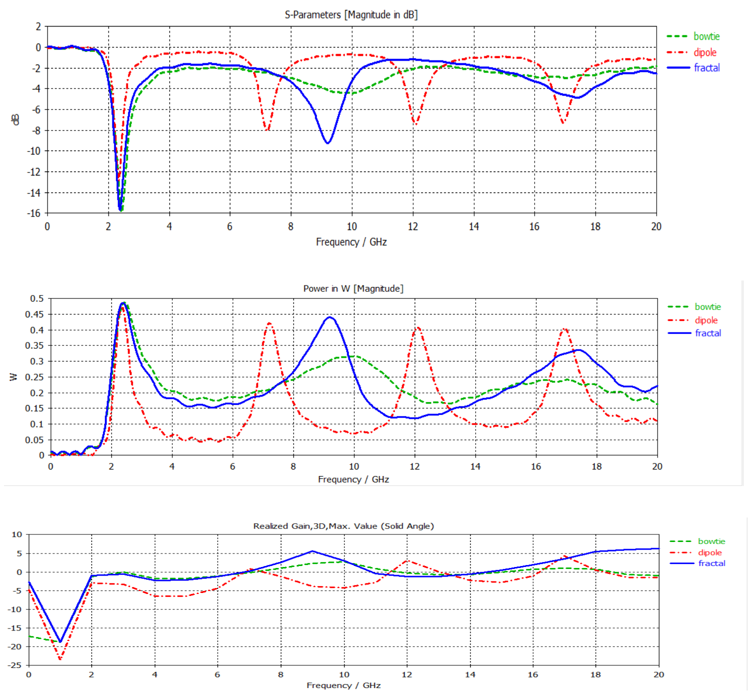
Fig. 7. Performance of the constructed bowtie antenna using MATLAB (a) Reflection coefficient, (b) Radiated power, (c) Gain.



(a) (b) (c)

Fig. 8. Performance of the constructed fractal bowtie antenna using MATLAB (a) Reflection coefficient, (b) Radiated power, (c) Gain.

Generally, from the results of Figs. 6, 7, and 8, it can be seen that the dipole itself is not a broadband but a narrow band antenna. The bowtie antenna is a broadband antenna (its bandwidth can be simply changed by changing the flare angle). The fractal bowtie antenna is also not a broadband but rather a multiband antenna. Also, they are performing very well at the designed frequency. Next, the CST full-wave modelling is used to construct these threes antennas at the designed frequency of 2.4 GHz. The CST is more powerful than the MATLAB and its results are more accurate. The reflection coefficient, radiated power, and the gain as a function of frequency for the dipole, bowtie, and the fractal bowtie antennas are shown in Fig. 9.



(a)

(b)

(c)

Fig. 9. Performances of the constructed three antennas using CST (a) Reflection coefficients, (b) Radiated powers, (c) Gains.

From the results of c), it can be observed that the dipole antenna is a narrow band antenna, and it has a fine tune at the resonance frequency of 2.4 GHz. Also note that there are other resonance frequencies at 7.3 GHz, 12.0 GHz and 17.0 GHz due to the dipole behaviour repeating at the multiple integers. The slope of the power curve becomes smoother when one increases the dipole thickness. Thus, the dipole is treated as a typical resonant antenna. It has strongly oscillated gain that exhibit peak at each multiple integers of the resonance frequency and it cannot be treated as a broadband antenna. From Fig. 9(b), it can be observed that only one power resonance can be identified for the constructed bowtie antenna with flare angle at 67.380 degree. This resonance occurs when the antenna length/wavelength ratio is slightly smaller than 1:3. As expected, the first resonance of the fractal bowtie antenna is fine-tuned at 2.4 GHz which is strongly coincidence with that of the original bowtie antenna and its output power peak of about 0.48W is observed at the resonance.

The antenna size at the second iteration of the fractal bowtie antenna is approximately equal to the size of the original bowtie antenna where the width is same 34.91 mm whereas the height is 22.06 mm. The frequency band is chosen to cover the range from 0 to 20 GHz. The radiated power of the fractal bowtie antenna (blue colour) clearly shows its effectiveness in radiating the wanted powers at the three multiband frequencies. The designed fractal bowtie antenna at the growth stage of 2 has three resonance bands at 2.4 GHz, 9.2 GHz, and 17.4 GHz respectively. The first resonance corresponds to that of the original bowtie antenna which is f_1=2.4 GHz. This resonance always occurs whether or not the fractal structure is present. The second resonance at f_2=9.2 GHz corresponds to the first fractal iteration, and the third resonance at f_3=17.4 GHz corresponds to the second fractal iteration. Moreover, the radiation patterns of the constructed fractal bowtie in Fairfield at different frequency values are shown in Fig. 10.

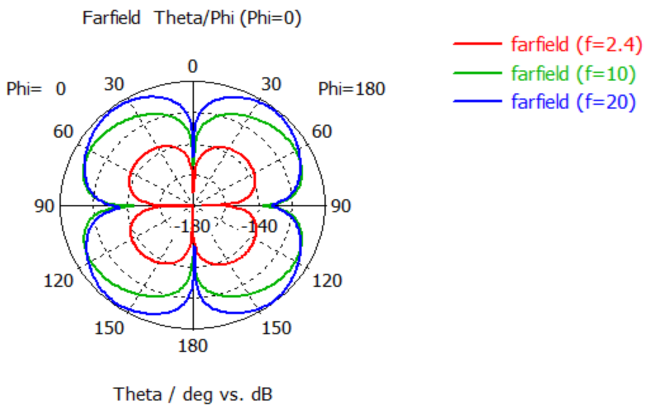


Fig. 10. Radiation pattern of the fractal bowtie antenna.

Finally, Table 2 summarizes and compares between the performances of the three constructed antennas under study.

Table 2. Performance comparison of the three constructed antennas.

Performance Measure	At resonance frequency band		
	Dipole	Bowtie	Fractal
Return loss (dB)	-12.865	-15.77	-15.23
Gain (dB)	1.778	1.639	1.6
Radiated power (Watt)	0.47	0.486	0.48

4. Conclusion

Three different antennas namely narrowband, wideband and multiband have been constructed and analysed using both the method of moment in MATLAB and the full-wave modelling in CST to verify their performances. In both simulation methods, an original bowtie antenna was designed and then efficiently and simply modified to obtain multiband fractal bowtie properties. By applying the fractal structures on the original broadband bowtie antenna, a multiband behaviour can be obtained, and the total number of the tuned frequency depends directly on the number of the formed fractal structures. Thus, the proposed fractal bowtie can be considered as a reconfigurable antenna according to the desired multiband operation.

In this study, second iteration stage of growth was applied, thus, two extra resonance frequencies were obtained as well as the original tuned frequency. Results of the constructed fractal bowtie shows that it has three frequency bands at 2.4 GHz, 9.2 GHz and 17.4 GHz. The use of the fractal structures with the bowtie antenna provides the ability to precisely control the spacing of operating frequencies, achieving repeated resonances between bands. Thus, the proposed fractal antenna offers many advantages in terms of bandwidth utilization, multiband operation, and maintaining a consistent radiation pattern across frequencies.

The proposed fractal antenna can be effectively used in the applications that span different frequency ranges in which stable performance characteristics are needed.

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