Research Article

A Stacked Microstrip Antenna Array with Fractal Patches

Xueyao Ren, Xing Chen, Yufeng Liu, Wei Jin, and Kama Huang

College of Electronics and Information, Sichuan University, Chengdu 610064, China

Correspondence should be addressed to Xing Chen; chenxingscu@163.com

A novel microstrip antenna array, which utilizes Giuseppe Peano fractal shaped patches as its radiation elements and adopts a two-layer stacked structure for achieving both wideband and high-gain properties, is proposed. Parametric study estimates that the proposed antenna's size can be arbitrarily adjusted by changing the fractal proportion while high aperture efficiency is maintained. Two prototypes with 2×2 and 4×4 fractal patches, respectively, on each layer are designed, fabricated, and measured. Both simulation and measurement results demonstrate that the proposed antenna possesses encouraging performances of wideband, high directivity, and high aperture efficiency simultaneously; for example, for the two prototypes, their $S_{11} < -10$ dB impedance bandwidths are 23.49% and 18.49%, respectively; at the working frequency of 5.8 GHz, their directivities are 12.2 dBi and 18.2 dBi, and their corresponding aperture efficiencies are up to 91.0% and 90.5%, respectively.

1. Introduction

Directional antennas with high radiation gain are key devices in many practical applications such as the remote wireless communication. Due to their attractive features like low weight, low profile, small size, and being easy to manufacture, employing microstrip antennas to form array is a widely adopted method to design directional antennas with high gain. However, it is well known that microstrip antennas have an intrinsically narrow bandwidth [1], typically a small percent of the center frequency. In view of the explosive growth of the wireless system and the booming demand for a variety of new wireless applications, it is important to design directional antennas with both wideband and high gain to cover a wide frequency range. Indeed, there are countless researches proposed in the literature to design microstrip antennas with high gain or wide bandwidth, but few of them are for both properties together.

To tackle the narrow bandwidth problem of microstrip antennas, various techniques have been proposed. Among them is stacking one or several parasitic layers on a microstrip antenna [2], and various methods have been widely used. For example, the 8-layer stacked patch unit assembly allows for great bandwidth which is more than 50% of the center frequency [3] and the use of high dielectric constant substrate

for the driven layer and low dielectric constant substrate for the superstrate can offer more than 25% on bandwidth [4, 5]. The intrinsic properties of fractal geometries are conducive to the miniaturization of antenna size and realization of multiband or broadband characteristics [6, 7]; L-shape slot loaded broadband patch antenna for enhancing the gain without affecting the broadband impedance matching characteristics [8]; the artificial magnetic conductor structures are employed as the antenna magnetic ground plane for bandwidth enhancement and radiation gain improvement of patch antenna [9]. A dipole antenna with a double electromagnetic band gap (EBG) reflector is presented for wide operating bandwidth and high gain [10]. However, there are some defects in the designs. Some of them have high profile; some of them require special materials and increase the production costs; some of them have complex structures, which increase the difficulty in manufacture. More details are shown in Table 1.

In this work, a novel microstrip antenna array, which employs a two-layer stacked structure and Giuseppe Peano fractal shaped patches for realizing both wideband and high gain properties, is proposed, analyzed, and measured. The remainder of the paper is organized as follows. Section 2 introduces the configuration of the proposed antenna array. A parametric study is presented in Section 3. Simulated and

TABLE 1: Detailed data of the antennas mentioned previously.

Literature number	Number of layer	Number of array elements	Gain (dBi)	Bandwidth	Profile	Manufacture difficulty	Cost
[3]	8	1	7.4	52%	High	Hard	High
[4]	2	4	12.4	25.6%	Low	Easy	High
[5]	2	1	—	35%	Low	Easy	High
[8]	2	1	8.3	20%	Low	Easy	Low
[9]	4	4	15.95	20.45%	High	Hard	High
[10]	4	1	8.5	44.4%	High	Easy	Low

measured properties of two prototypes with 2×2 and 4×4 fractal patches, respectively, on each layer are given in Section 4. Conclusions are stated in Section 5.

2. Antenna Configuration

Fractals are geometrical shapes, which are self-similar, repeating themselves at different scales. With the development of the fractal theory, the nature of fractal geometries has been exploited in many fields of engineering and science, including antenna design. The utilization of fractal geometries in antenna design has led to the evolution of a new class of antennas called fractal shaped antennas.

The Giuseppe Peano fractal is a class of fractal geometries. Its recursive procedure is shown in Figure 1. A Giuseppe Peano starts from a segment with length f_2 and allows its central part with length f_1 to break into two zigzag sections; it is constructed iteratively by growing new zigzag sections that have a specific length ratio $n = f_2/f_1$ with respect to their parent section.

As depicted in Figure 2, when the Giuseppe Peano fractal is applied to the edges of the square patch, this fractal patch with different sections resonates at different frequencies which together to form a wide working frequency band.

The configuration of the proposed microstrip antenna array is illustrated in Figure 3. This antenna utilizes a two-layer stacked structure, containing a radiation layer and a parasitic layer. Each layer is printed on a PCB (printed circuit board) with relative permittivity $\varepsilon_r = 2.55$ and thickness $h = 1$ mm. The two layers are separated by air with distance of $h_z = 3.2$ mm.

On the top surface of the radiation layer, some Giuseppe Peano fractal shaped patches are etched periodically. They act as radiators and are connected to a microstrip corporate feeding network to form an array. On the bottom surface of the parasitic layer, the same patches as that on the radiation layer are also etched. Those patches are parasitic elements for enhancing the bandwidth and gain of the antenna array.

This antenna is fed from a $50\,\Omega$ coaxial connector. The microstrip corporate feeding network consists of a serial of T-junctions to deliver electromagnetic energy uniformly and multiple-section quarter-wavelength impedance transformers to achieve impedance match and is used to provide equal amplitude and in-phase excitation to all fractal shaped patches.

From Figure 3, we can see that $Ls = 2 \times (D + L)$, $X = (D - L0 - W1)/2$ $Lt = (D + L - W2)/2$, and $L3 = (D + L) -$

$2 \times (L1 + L2) - W1$. Finally, the structural parameters of this antenna are optimized by Genetic Algorithm (GA) [11, 12] as follows: $D = 16.46$ mm, $L = 14.71$ mm, $Lr = 16.06$ mm, $W1 = 2.27$ mm, $W2 = 2.07$ mm, $W3 = 1.77$ mm, $L0 = 1.38$ mm, $L1 = 3.66$ mm, $L2 = 8.20$ mm, and $h_z = 3.19$ mm. The total area of the antenna is 62.34×62.34 mm^2.

3. Parametric Study

Here, we investigate the effect of the antenna's parameters on its performance characteristics. In this section, the proposed antenna works at 5.8 GHz, has 2×2 and fractal 4×4 patches on the radiation and parasitic layers, respectively, and adopts second iteration Giuseppe Peano fractal patches.

3.1. Effect of the Fractal Proportion. The Fractal proportion n is defined as

$$n = \frac{f_2}{f_1}, \tag{1}$$

which can be seen from Figure 1. The greater the n is, the closer to square patch the Peano fractal radiator is.

The 2×2 square patches antenna array which works at the same frequency of 5.8 GHz is illustrated in Figure 4. Each layer is printed on a PCB with relative permittivity $\varepsilon_r = 2.55$ and thickness $h = 1$ mm, the same as the fractal ones.

The structural parameters of this antenna which is optimized by GA are as follows: $D = 29.50$ mm, $L = 15.02$ mm, $Lr = 17.30$ mm, $W1 = 3.72$ mm, $W2 = 2.78$ mm, $W3 = 2.18$ mm, $L0 = 1.52$ mm, $L1 = 3.40$ mm, $L2 = 13.27$ mm, and $h_z = 3.48$ mm. The simulated reflection coefficient and simulated directivity are given by Figures 5 and 6, respectively.

It is obvious that the $S_{11} < -10$ dB impedance bandwidth is about 14.02% (from 5.37 GHz to 6.18 GHz). At its working frequency of 5.8 GHz, the antenna has an input reflection coefficient of -22.65 dB, which estimates that a good impedance match has been achieved.

Different 2×2 array antennas of different fractal proportion ($n = 2$, $n = 2.5$, $n = 3$, $n = 3.5$, $n = 4$, and $n = 4.5$) which are also working at 5.8 GHz are optimized by GA. Figure 7 reveals the simulated reflection coefficient of different fractal proportion antenna arrays and Figure 8 reveals the simulated directivity.

From Table 2, one can observe that the fractal proportion has a great influence on the antenna performance. As fractal proportion n increases, the aperture area of the proposed
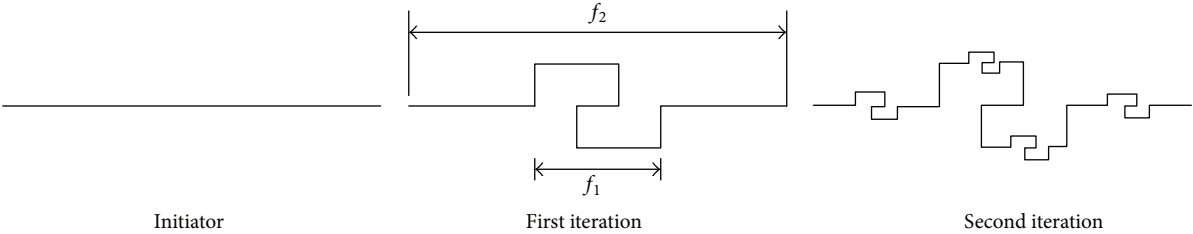
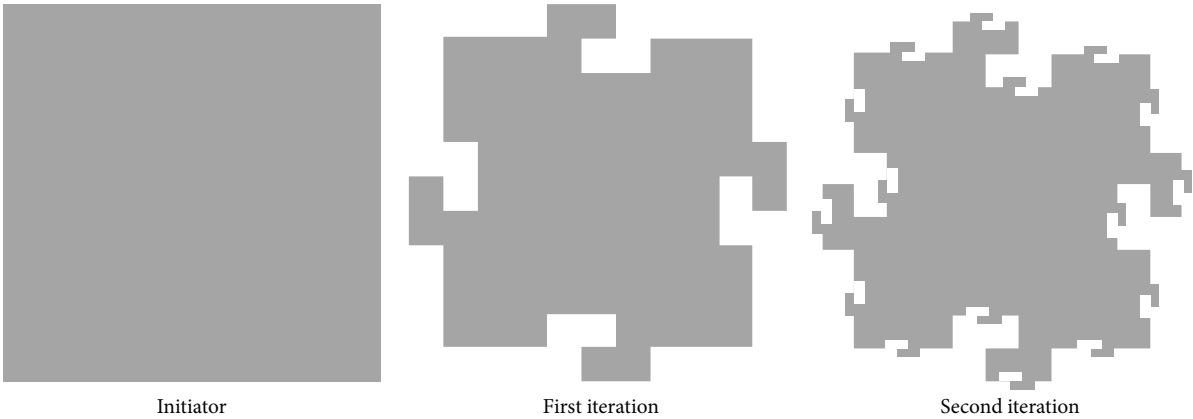Figure 1: The recursive procedure of the Giuseppe Peano fractal.
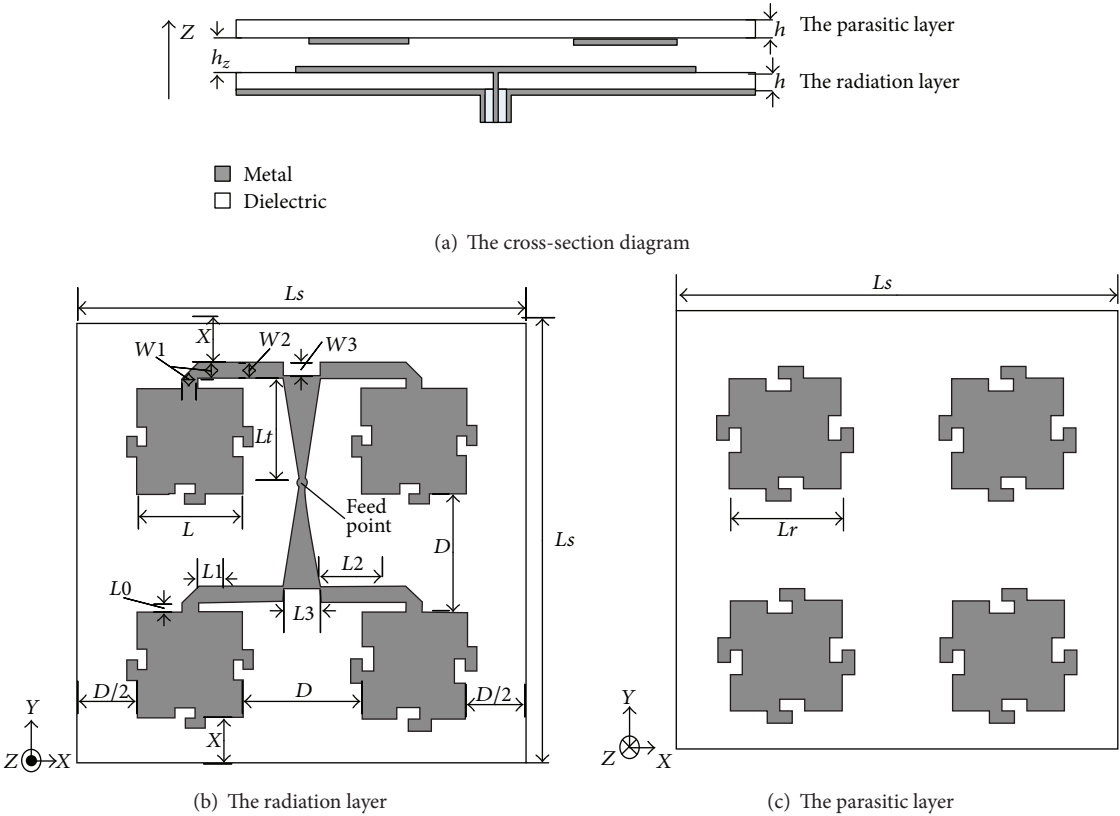

Figure 2: The Giuseppe Peano fractal patch.

(a) The cross-section diagram

(b) The radiation layer

(c) The parasitic layer

Figure 3: Configuration of the proposed microstrip antenna array.

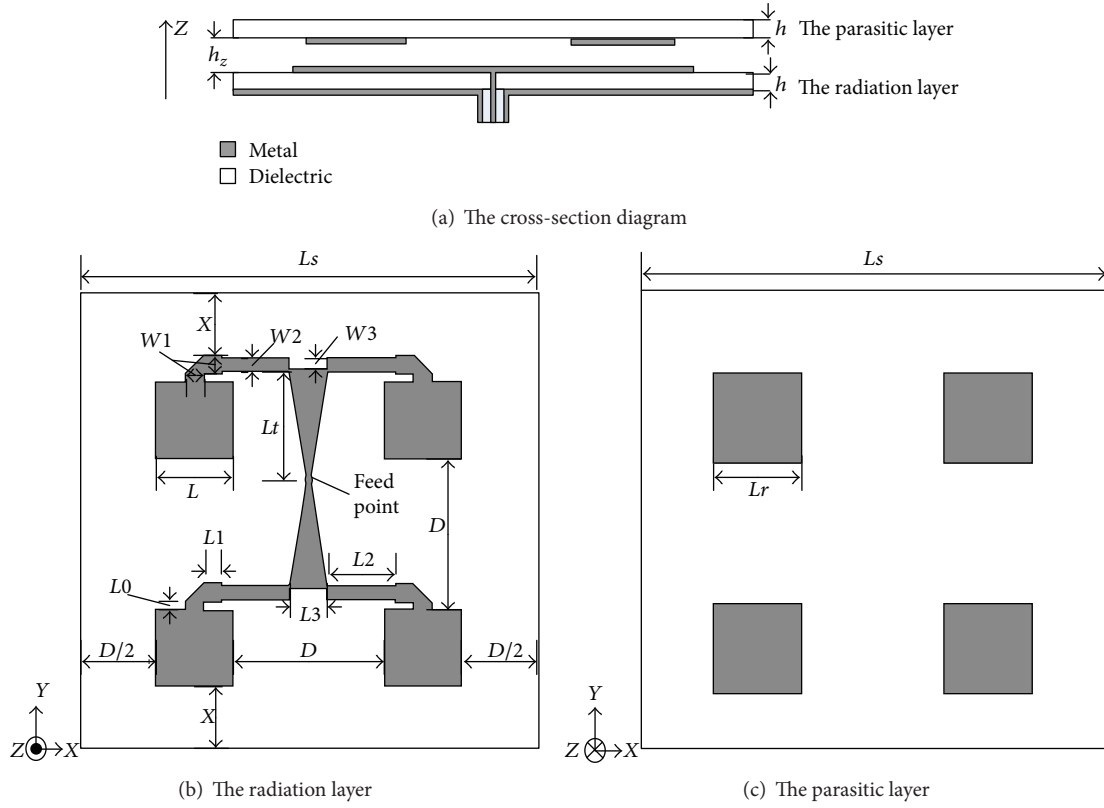(a) The cross-section diagram
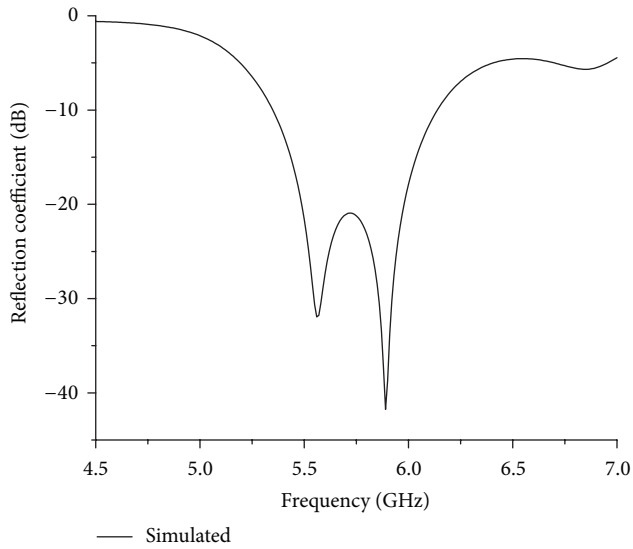

(b) The radiation layer

(c) The parasitic layer

FIGURE 4: The configuration of the two-layer square patches 2×2 antenna array.

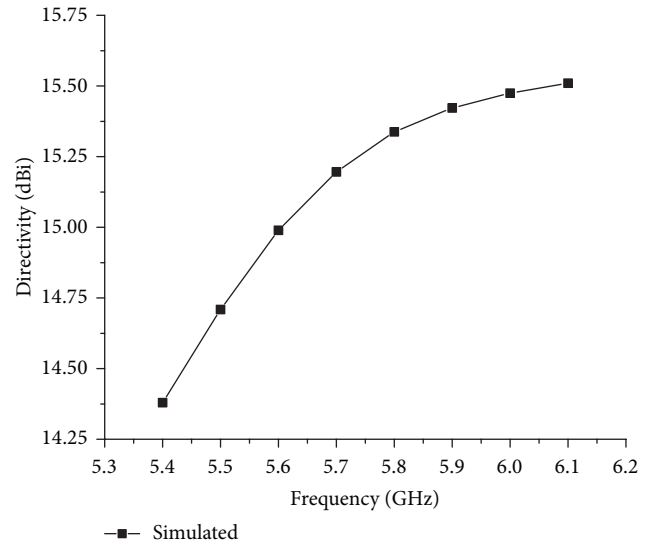FIGURE 5: The simulated reflection coefficient of the square antenna array.

FIGURE 6: The simulated directivity as a function of frequency for the square patches antenna array.

antenna must increase for maintaining the same working frequency of 5.8 GHz. When the fractal proportion $n = 3.5$, the $S_{11} < -10$ dB impendence bandwidth reaches 23.49% versus 14.02% of the square antenna array working at the same

frequency, the aperture area of proposed antenna is only 49% of the square patches antenna array's.

Another interesting observation worthwhile pointing out is the attainable aperture efficiency calculated only by the
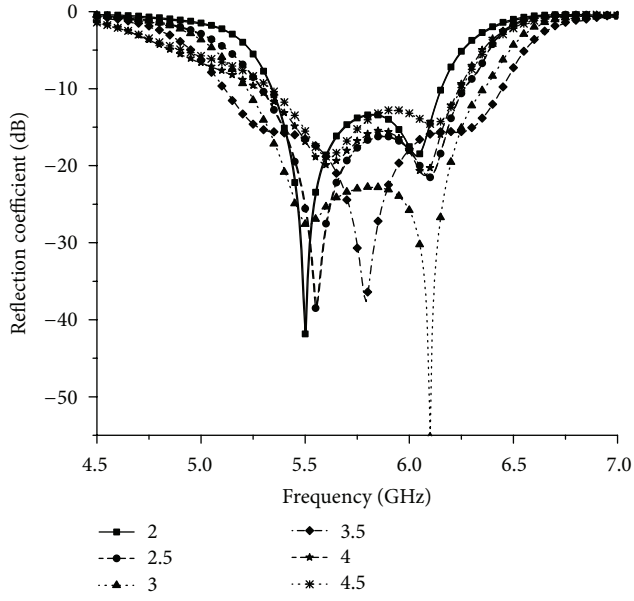
FIGURE 7: The simulated reflection coefficient of the different fractal proportion.
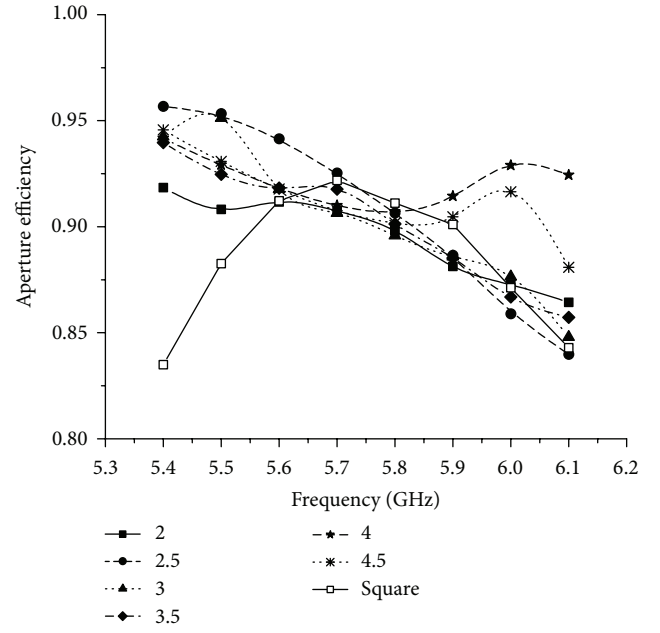

FIGURE 9: The simulated aperture efficiency of the different fractal proportion antenna array.
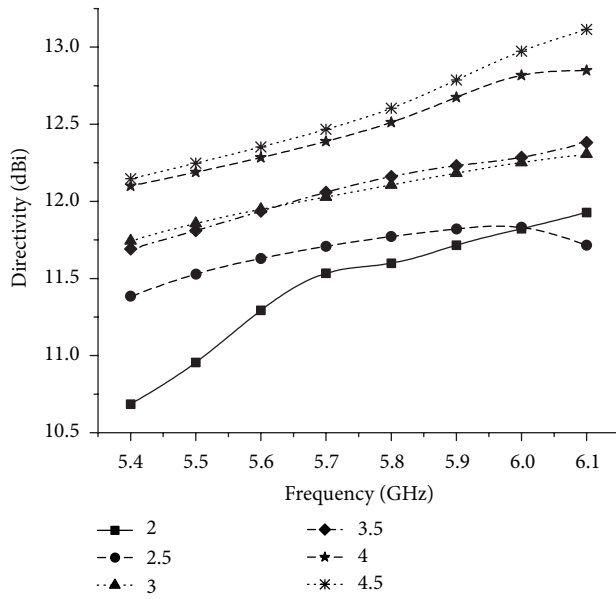

FIGURE 8: The simulated directivity as a function of frequency for the different fractal proportion.

FIGURE 10: Comparison of the simulated reflection coefficient of the 1st iteration and 2nd iteration.

directivity, shown in Figure 9. The vast majority of them are more than 85%. The average aperture efficiency (from 5.4 GHz to 6.1 GHz) is shown in Table 3.

Table 3 demonstrates that the average aperture efficiency of the Peano fractal antenna array is higher than that of the square antenna in the same working band. The maximum value of average aperture efficiency is obtained when the fractal proportion $n = 4$.
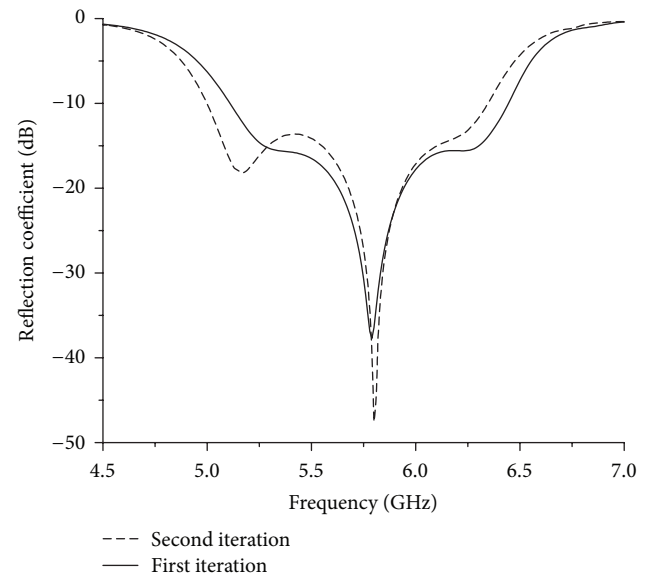
3.2. Effect of Fractal Iteration. First and second iteration are relatively applied to the edges of the square patch. All the parameters of the second iteration antenna array are set to be the same as the first one. The comparison of the reflection coefficient of these two antennas is drawn in Figure 10.

One can observe that the impedance bandwidth for $S_{11} <$ -10 dB is 24.18% (from 4.98 GHz to 6.35 GHz), which is much wider than that of square patches antenna array and slightly larger than that achieved in first iteration of the fractal patches antenna array. As the iteration of fractal geometry increases,
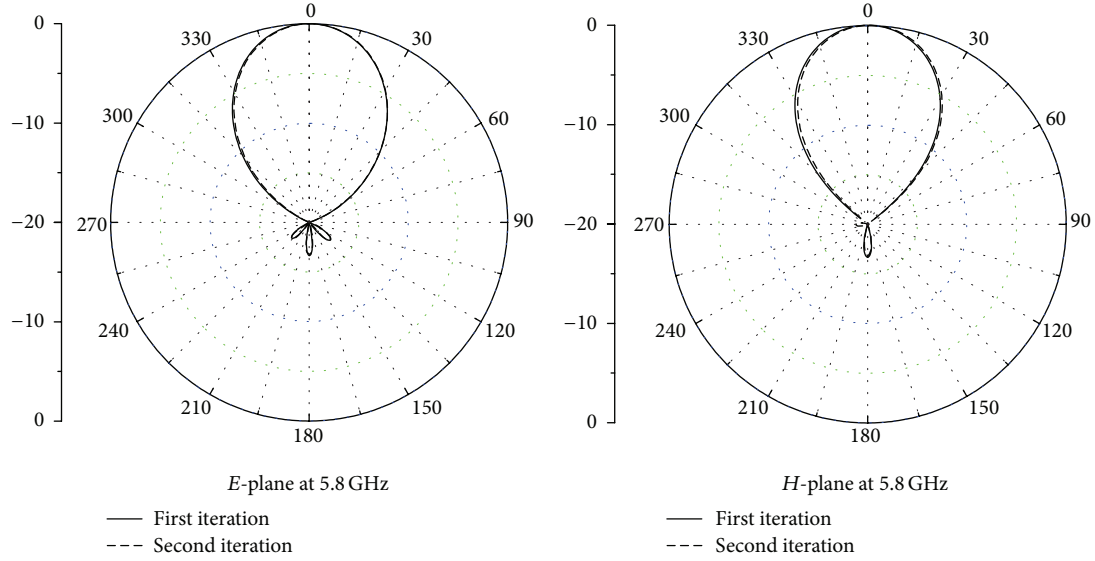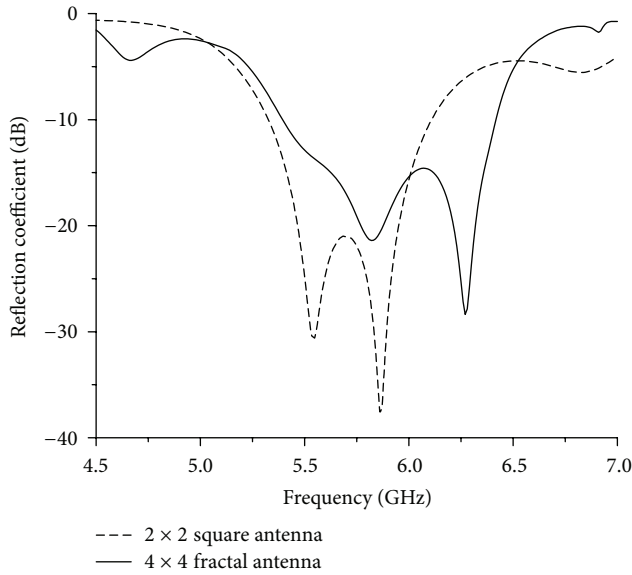
E-plane at 5.8 GHz

—— First iteration
--- Second iteration

H-plane at 5.8 GHz

—— First iteration
--- Second iteration

FIGURE 11: Comparison of the radiation patterns of the fractal iterations, 1st and 2nd.

--- 2 × 2 square antenna
—— 4 × 4 fractal antenna

FIGURE 12: Comparison of the simulated reflection coefficient of the 2 × 2 square patch antenna and the 4 × 4 Giuseppe Peano fractal antenna.

TABLE 2: Details of different antennas.

n	f_L (GHz)	f_H (GHz)	f_M (GHz)	$f_\%$	L_s (cm)
2	5.33	6.23	5.78	15.57%	56.68
2.5	5.29	6.27	5.78	16.98%	59.43
3	5.21	6.37	5.79	20.03%	62.12
3.5	5.07	6.42	5.78	23.49%	62.34
4	5.28	6.30	5.79	17.62%	64.90
4.5	5.33	6.25	5.79	15.89%	65.40
Square	5.37	6.18	5.78	14.02%	89

TABLE 3

Fractal proportion n	Average aperture efficiency
2	89.53%
2.5	90.86%
3	90.30%
3.5	91%
4	92.18%
4.5	91.32%
Square	88.48%

its resonance frequency decreases, which may lead to an effective antenna miniaturization. However, for iterations higher than the second iteration, the antenna design becomes quite complicated and its fabrication becomes difficult. The comparison of simulated radiation patterns in the E-plane and H-plane of these two antennas is shown in Figure 11.

The comparison indicates that the influence of radiation patterns that comes from the fractal iteration is almost negligible.

3.3. Effect of Array Elements Number. In this part, a proposed antenna with 4 × 4 Giuseppe Peano fractal radiated elements and working at 5.8 GHz is also optimized by GA.

Figure 12 compares the simulated reflection coefficient of the 2 × 2 square patch antenna and that of the 4 × 4 Giuseppe Peano fractal antenna. As known to all, when the number of array elements increases, the impedance bandwidth of the antenna array decreases because of the mutual coupling between the array elements [13, 14]. Although the element number of fractal antenna array is four times that in the square antenna, the impedance bandwidth for $S_{11} < -10$ dB
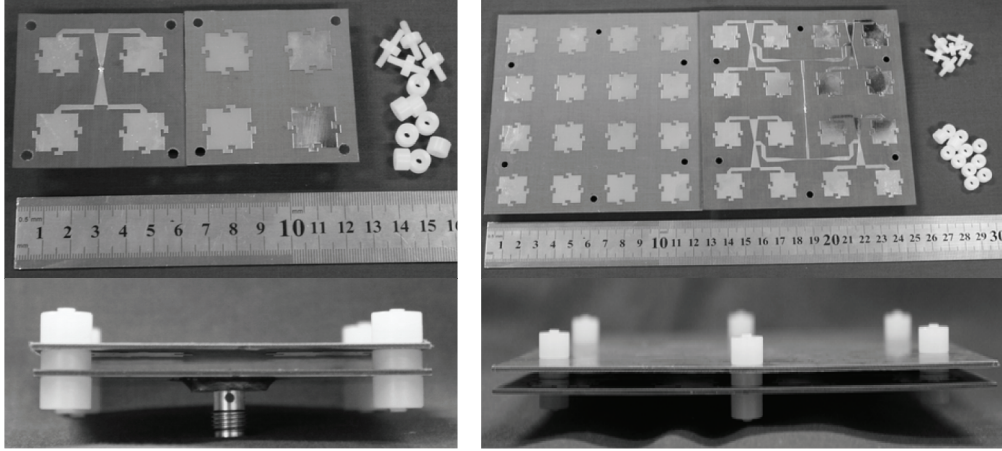
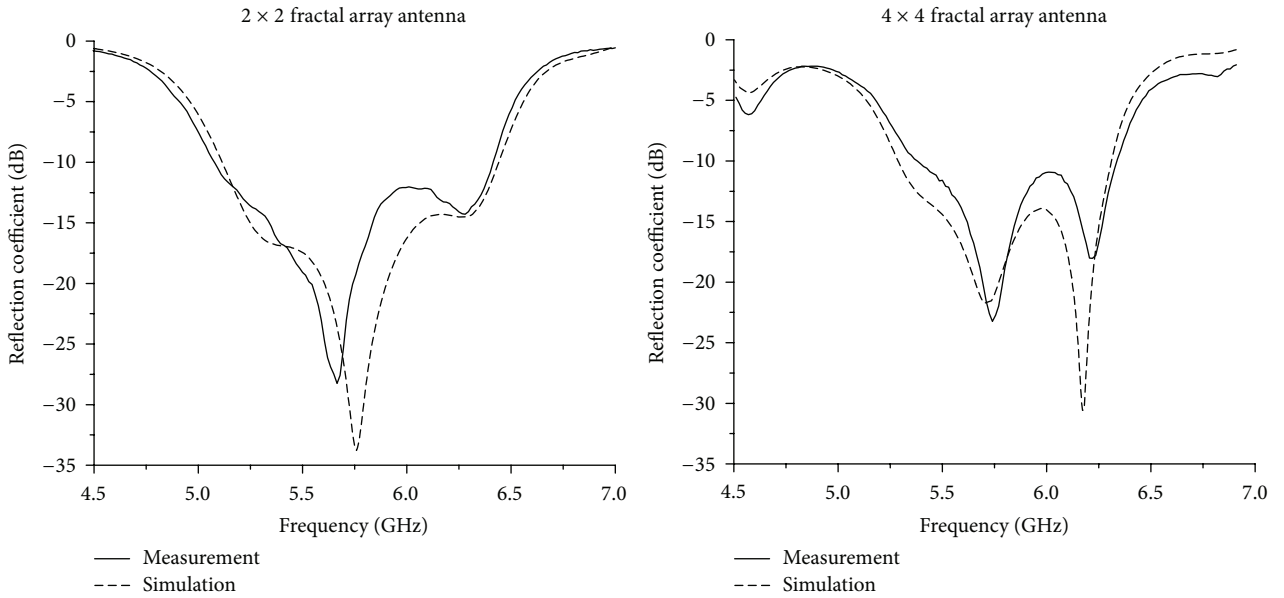FIGURE 13: The both layers of the fabricated prototype antennas.

FIGURE 14: The measured and simulated reflection coefficients of the prototype antenna.

is 18.43% (from 5.32 GHz to 6.40 GHz), which is much wider than that of square patches antenna array introduced previously.

4. Experimental Results

Two prototype antennas with 2×2 and 4×4 radiations elements, respectively, have been fabricated and measured, which are shown in Figure 13. Some glass sticks with a diameter of 5 mm are used for propping them up.

Figure 14 is the comparison of the measured and reflection coefficient of the prototype antennas, respectively.

The measured and simulated results are in good agreement. From the measurement, the $S_{11} < -10$ dB impedance bandwidth of the antenna is about 23.49% (from 5.07 GHz to 6.42 GHz) for 2×2 fractal array antenna and 18.19% (from 5.34 GHz to 6.41 GHz) for 4×4 fractal array antenna,

respectively. At its working frequency of 5.8 GHz, the antenna has an input reflection coefficient of -16.95 dB and -18.81 dB, respectively, which estimates that a good impedance match has been achieved. Figures 15 and 16 depict the simulated and the measured radiation patterns at different frequencies within the effective frequency band.

5. Conclusion

A novel Giuseppe Peano fractal antenna array is presented. Structural parameters of the proposed antenna are optimized by a parallel GA to achieve both high gain and wideband properties over a desirable frequency band with the center of 5.8 GHz. Two prototype antennas were fabricated and measured. The measurement results and the simulation results agree well and show that the optimized antenna array possess some encouraging properties.
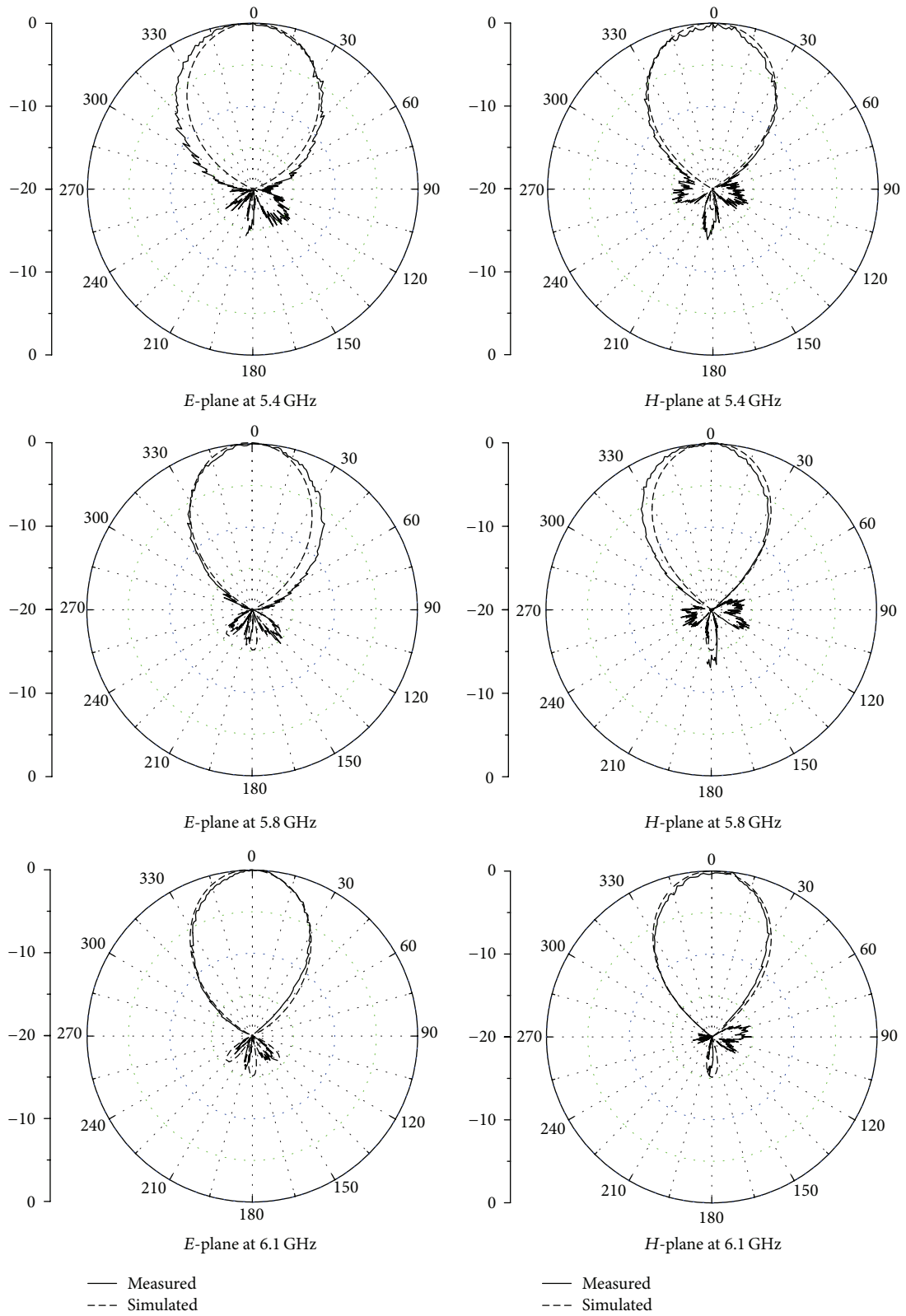
E-plane at 5.4 GHz

H-plane at 5.4 GHz

E-plane at 5.8 GHz

H-plane at 5.8 GHz

E-plane at 6.1 GHz

H-plane at 6.1 GHz

—— Measured
--- Simulated

—— Measured
--- Simulated

FIGURE 15: Measured and simulated radiation patterns on the E-plane and the H-plane at different frequencies of the 2 × 2 fractal antenna array.
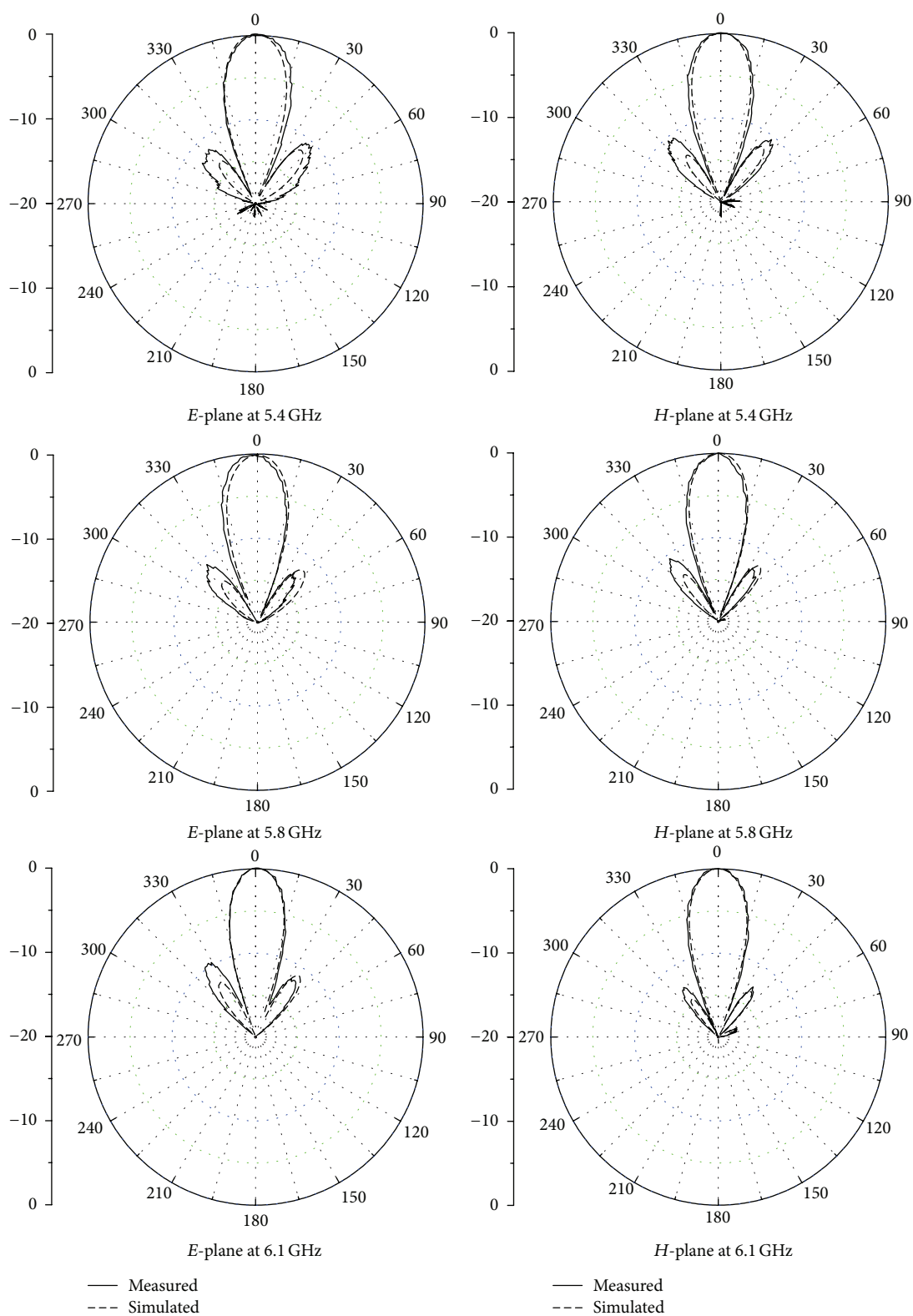
FIGURE 16: Measured and simulated radiation patterns on the E-plane and the H-plane at different frequencies of the 4 × 4 fractal antenna array.

By comparing the proposed antenna with the square patches one, the important conclusions resulting from this study are as follows.

(1) The Giuseppe Peano fractal configuration provides extremely high flexibility to achieve broadband performance while maintaining higher average aperture efficiency in the operating frequency band. Fractal proportion can be selected according to design requirements; for example, if the impedance bandwidth is a major consideration in design, the fractal proportion n close to 3.5 is comparatively suitable; if the design requires making full use of the high aperture efficiency to maintain the high directivity over the bandwidth, the value n approximating 4 is more reasonable.

(2) In the case of the same number of array elements and the working frequency, the Giuseppe Peano fractal antenna array can more effectively reduce the required aperture area (reduce 51%) than the traditional square patches antenna array. As the iteration of fractal geometry increases, its resonance frequency decreases; this may lead to an effective miniaturization of antenna. At the same time, the radiation pattern is essentially unchanged.

(3) Although the element number of fractal antenna array is four times that in square antenna, the impedance bandwidth for $S_{11} < -10$ dB is 18.43% (from 5.32 GHz to 6.40 GHz), which is still much wider than that of square array antennas introduced previously (which is about 14.02% from 5.37 GHz to 6.18 GHz). This clearly showed that the introduction of fractal radiation unit can reduce the mutual coupling between the antenna elements.

Given the conclusion above, the merits of wideband and high aperture efficiency make the proposed antenna a good candidate for various applications.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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