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A NOVEL TWO-LAYER STACKED MICROSTRIP ANTENNA ARRAY USING CROSS SNOWFLAKE FRACTAL PATCHES

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Abstract—In this paper, a novel approach was used to design two-layer stacked high-gain microstrip antenna array with improved bandwidth and high aperture efficiency. Cross Snowflake fractal microstrip patches were employed as radiation elements. Varieties of antenna arrays with different fractal iterations were optimized by using the Genetic Algorithm (GA) associated with 3D full-wave Finite Element Method (FEM) in order to investigate the influence of the Cross Snowflake fractal radiators. As compared with the conventional square patches, the Cross Snowflake fractal configuration provides extremely high flexibility to achieve a wideband performance and maintains higher aperture efficiency at operating frequency band. A prototype antenna with 2×2 Cross Snowflake radiators was fabricated and measured. Both simulated and measured results show that the proposed antenna has some promising performances to be more specially, the measured impedance bandwidth is 22.9% (from 5.18 GHz to 6.52 GHz) when $S_{11} < -10$ dB; the simulated gain is 12.0 dBi and its corresponding aperture efficiency is up to 87.4% at the working frequency 5.8 GHz.

1. INTRODUCTION

Recently, wireless communication has become more and more widespread. Meanwhile, compact wireless communication system is much more important in our lives than before. So miniaturization and high-gain performance for antennas need to be promoted.

To overcome an inherent weakness of microstrip antennas with a narrow impedance bandwidth will be a major challenge for upgrading

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antennas miniaturization and high-gain performance. Techniques for bandwidth enhancement have been intensively studied in past decades. There are different methods proposed to solve the problem such as narrow bandwidth and the low gain limitations. Therefore, wideband antenna with high-gain performance has drawn much attention during the latest years.

Microstrip antennas are widely used for their lightweight, low profile and low cost. However, it is well known that the two microstrip antennas has an intrinsically narrow bandwidth [1], typically a few percent of the center frequency and a 5–8 dBi low operating gain.

Several techniques have been formulated to improve the performance of the bandwidth and the gain of microstrip antennas. It is well known that by stacking a parasitic patch on a fed patch, an antenna with wideband and high gain can be realized easily.

Electromagnetically coupled feed and aperture coupled feed can be used for antennas usually to achieve improved impedance bandwidth [2–11]. One of the popular techniques is the use of a multilayer structure which is consisting of several parasitic radiating elements to increase the impedance bandwidth, for example, by assembling the aperture coupling and especially the 8 layers stacked patch unit allows a great bandwidth which more than 50% of the center frequency [12]; another popular technique is the use of high dielectric constant substrate for the driven layer which prevents the unwanted radiation as well as low dielectric constant substrate is used for the superstrate, the structure can offer more than 25% bandwidth for one patch unit than the original design [13].

The term "fractal electrodynamics", which describes a family of complex shapes that possess an inherent self-similarity or self-affinity in their geometrical structure, has been widely used for the purpose of investigating a new class of radiation, propagation and scattering problems. The intrinsic properties of fractal geometries are conducive to the miniaturization of antenna size and the realization of multiband or broadband characteristics [14–20].

In this paper, a new design approach of a two-layer stacked microstrip antenna array with improved bandwidth and higher aperture efficiency is proposed. This design is implemented by using the Cross Snowflake fractal microstrip patches to replace the square patches for the radiating elements. Section 2 describes the design of the square and the Cross Snowflake fractal antenna array. Section 3 includes numerical results and discussions, which are simulated by 3D full-wave Finite Element Method (FEM). To verify the antenna performance, experimental results are also involved and discussed in Section 4. The conclusion is in Section 5.

2. ANTENNA ARRAY DESIGN

Besides feeding techniques, the geometry of stacked patch element like square, rectangular, circular and other shapes were used and some of their characteristics have been discovered. The experimental results data for different geometry stacked two-layer antenna arrays are given in Table 1 [21].

Table 1. Experimental results for different geometry stacked two-layer antennas.

Antenna geometry	Polarization	Bandwidth	Gain (dBi)
Square	linear	9%	7
Rectangular	linear	9%	7.4
Circular disc	linear	15%	7.9
Circular annular disc	linear	11.5%	6.6

The geometry of patches described above is the most suitable for using as radiating element. The feeding elements may be etched jointly with the power dividing network as an integrated structure, leading to a very compact, lightweight and low loss design.

The configuration of the 2×2 two-layer square patch antenna array is illustrated in Fig. 1. It consists of two layers, they are the parasitic layer and the corporate feeding layer. Layers are printed on a PCB (printed circuit board) with permittivity $\varepsilon_r = 2.55$ and thickness $h = 1\,\mathrm{mm}$, the two layers are separated by air h_z, and some glass sticks are used for propping them up.

On the parasitic layer of the PCB, 2×2 square parasitic patches act as radiators, which couple electromagnetic energy from the bottom patches and radiate energy out forming a directional radiation pattern with high gain. This antenna is directly fed from a $50\,\Omega$ coaxial line via an SMA connector. The outer conductor of the SMA connector is connected to the ground plane while the inner conductor penetrates the PCB and connected with the feed network at feed point. A parallel and series hybrid power divider is printed on the bottom layer to provide equal amplitude and phase excitation to all the elements.

First, a two-layer stacked square patch antenna array with 2×2 radiators working at 5.8 GHz is optimized by GA. The GA is a powerful and efficient optimization technique and has been widely applied to the optimization of various applications [22–26]. From the Fig. 1, the

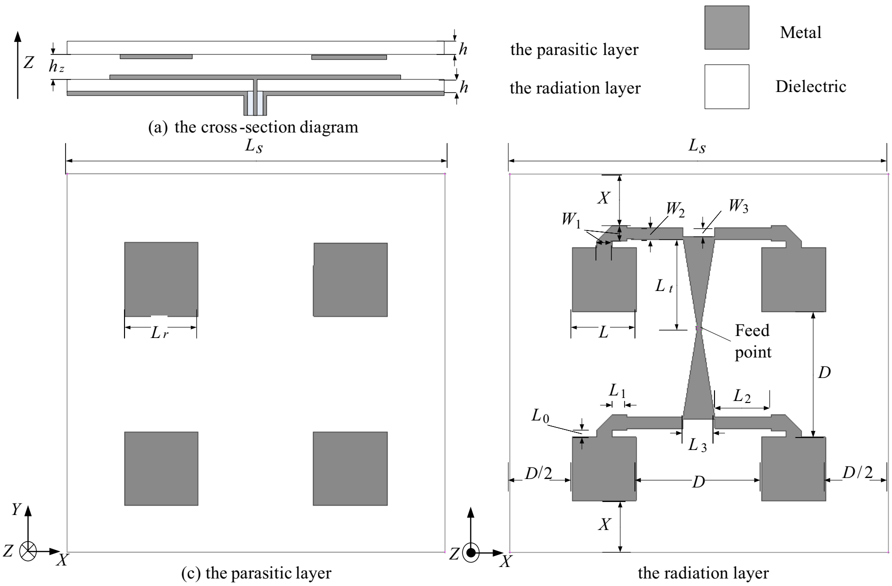

Figure 1. The configuration of the 2 × 2 two-layer square patches antenna array.

dimension of this design is listed below:

$$\begin{aligned} L_s &= 2 \times (D + L); \\ X &= (D - L_0 - W_1)/2; \\ L_t &= (D + L - W_2)/2; \\ L_3 &= (D + L) - 2 \times (L_1 + L_2) - W_1. \end{aligned}$$

There are other 10 structural parameters, i.e., D, L, L_r, W_1, W_2, W_3, L_0, L_1, L_2, h_z, the initial size L of the single element square patch is obtained by using the well know design equation [27]:

$$L \approx \frac{\lambda_o}{2\sqrt{\varepsilon_r}} = \frac{c}{2f_0\sqrt{\varepsilon_r}} \tag{1}$$

where λ_o is the free-space wavelength, c the velocity of light in free space, and ε_r the relative dielectric constant of the substrate, f_0 is the working frequency of the antenna. L_r is slightly larger than L.

The characteristics of the stacked microstrip antennas depend on the distance between the feed patch and the parasitic patch. When the wide bandwidth and gain enhancement can be obtained, the distances between the feed patch and parasitic patch are short ($h_z < 0.1\lambda_0$) and half a wavelength ($0.45\lambda_0 < h_z < 0.55\lambda_0$), respectively. So the parameters h_z is confined within the range of 1.5 mm $\sim$ 5 mm (about $0.03 \sim 0.1\lambda_0$) in order to achieve a wideband antenna array. The traditional T-network is used as our feed network, the groove and the transition structure as shown in Fig. 1 below are used to achieve the impedance matching between the patches and input impedance.

The structural parameters of this antenna optimized by GA are as shown in Table 2.

Table 2. Optimized parameters for square patch.

Parameters	Value (mm)
D	29.50
L	15.02
L_r	17.30
W_1	3.72
W_2	2.73
W_3	2.12
L_0	1.52
L_1	3.40
L_2	17.71
L_t	20.90
L_s	89.00
h_z	3.48

The simulated reflection coefficient is shown in Fig. 2. The aperture area of the Square patches 2×2 antenna is $89 \times 89\,\text{mm}^2$. Simulated directivity in the 5.4 GHz–6.1 GHz is shown in Fig. 3.

From Fig. 2, it can be observed that the impedance bandwidth of the antenna is about 14.02% when $S_{11} < -10$ dB (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 shows that a good impedance match has been achieved. If we defined the bandwidth is below 1.5 dB to the maximum directivity as the directivity-band, then the whole $S_{11} < -10$ dB impedance bandwidth satisfies this condition.

The proposed antenna in our project is an improvement of the work mentioned above. The idea of this method comes from fractal geometries which are composed of copies of themselves at different scales. These abnormal properties make them widely utilized in antenna design. So far in the large number of previous researches,

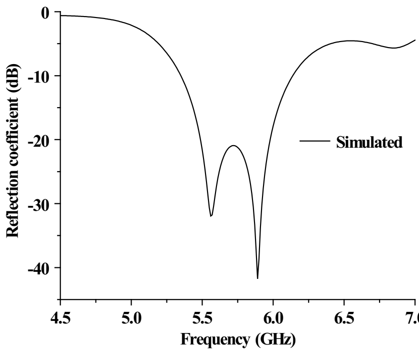

Figure 2. The simulated reflection coefficient of the square antenna array.

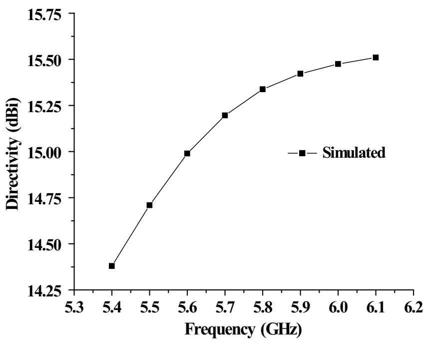

Figure 3. The simulated directivity of the square antenna array.

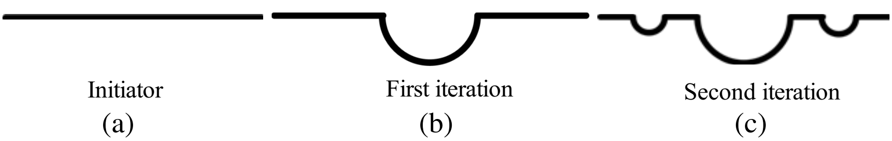

Figure 4. The recursive procedure of the Cross Snowflake fractal.

fractal geometry is applied to reduce electrical size of antennas by the good filling property itself or design as a radiator of the monopole antenna to obtain multiband or wideband performance. Quite different from those existing methods, the work utilizes a novel fractal structure-the Cross Snowflake fractal geometry. The recursive procedure of the Cross Snowflake fractal is shown in Fig. 4, it is constructed iteratively by growing new half-circle sections that have the diameter of 1/3 with respect to their parent section. The configuration of radiators in a two-layer stacked microstrip antenna array is to improve its impedance bandwidth and maintain the high aperture efficiency.

When the Cross Snowflake fractal is applied to the edges of the square patch, this fractal patch with different sections that resonate at different frequencies together forms a wide working frequency band. The square patch up to the second iteration as depicted in Fig. 5.

As illustrated in Fig. 6, the proposed first iteration 2×2 two-layer stacked microstrip antenna array is obtained by using the Cross Snowflake fractal radiators to replace the square patches.

The structural parameters of this antenna are optimized by Genetic Algorithm (GA) as follow as Table 3 shows, the aperture area of the Square patches 2×2 antenna is about $62 \times 62\,\mathrm{mm}^2$.

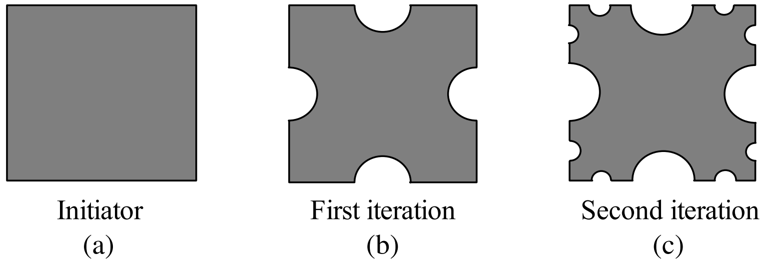

Figure 5. The Cross Snowflake fractal patch.

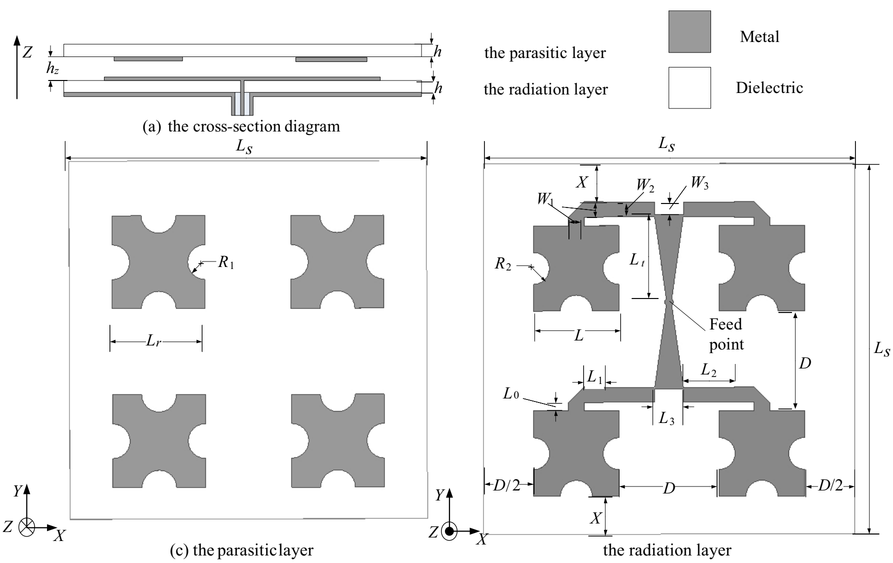

Figure 6. The configuration of the first iteration proposed two-layer Cross Snowflake patch 2×2 antenna array.

The current distributions on the initial and the first iteration antenna patches are shown in Fig. 7. It can be observed that the current focuses on the center of the square patches in the initial antenna arrays while on the fractal regions of the first iteration antenna arrays at the same surface current phase. The actual bandwidth of the first iteration antenna arrays contains two parts, the bandwidth supported by the concentrated current on the fractal regions, and the bandwidth provided by the patches originally. Therefore, the superposition of these bandwidths will boost the operating bandwidth. Meanwhile, a longer path of current reduces the center frequency, thus a smaller

Table 3. Optimized parameters for 1st Cross Snowflake patch.

Parameters	Value (mm)
D	16.75
L	14.32
L_r	16.14
W_1	2.61
W_2	2.39
W_3	2.09
L_0	1.41
L_1	3.28
L_2	8.54
h_z	3.2
L_t	14.64
Ls	62.14
R_1	3.02
R_2	2.68

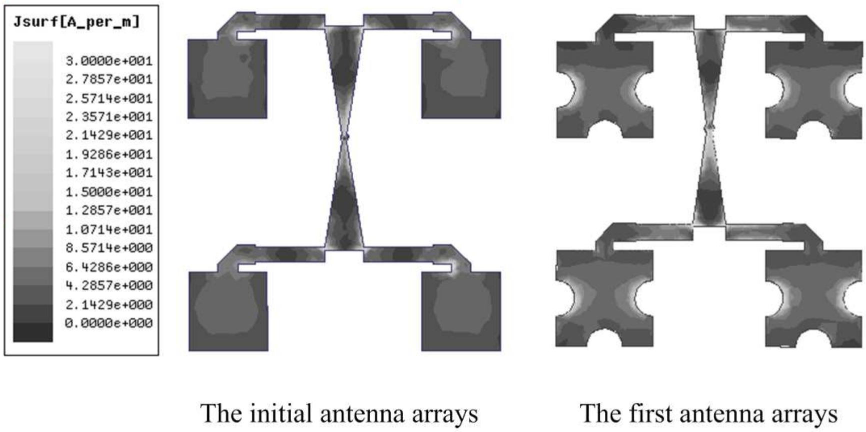

Figure 7. The current distributions on antenna patches.

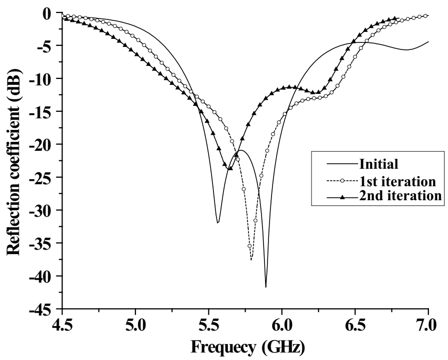

Figure 8. Comparison of the simulated reflection coefficient of the initial, 1st iteration and 2nd iteration.

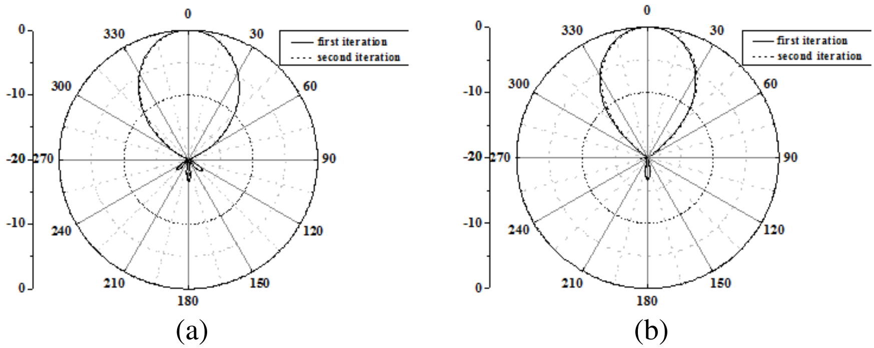

Figure 9. The comparison of simulated radiation patterns. (a) E-plane at 5.8 GHz. (b) H-plane at 5.8 GHz.

electrical size can be achieved.

All the parameters of the second iteration antenna array are set the same as the first one. The comparison of the reflection coefficient as S_{11} of the initial, first and second iterations of the Cross Snowflake fractal antenna is drawn in Fig. 8.

It can be observed that the simulated impedance bandwidth for the 2nd iteration Cross Snowflake fractal antenna array is 19.75% (from 5.20 GHz to 6.34 GHz), which is much wider than that of square antenna array and slightly larger than it can be achieved in 1st iteration. As the iteration of fractal geometry increases, its resonance frequency decreases, which may lead to an effective antenna miniaturization.

However, for iterations higher than the second iteration, the reduction of operating frequency cannot be implemented since the antenna design becomes quite complicated, and its fabrication becomes difficult. The configuration of Cross Snowflake fractal geometry becomes quite unwieldy for the iterations higher than the second iteration. The comparison of simulated radiation patterns between the 1st and 2nd iterations in the E- and H-planes of the antenna at 5.8 GHz is shown in Fig. 9.

The comparison of the radiation patterns for the 1st and 2nd iterations of the fractal antennas indicates that the influence of radiation patterns comes from the fractal iteration is almost negligible.

3. EXPERIMENTAL RESULTS

An antenna prototype with 2×2 radiation element has been fabricated and measured, which is shown in Fig. 10. Some glass sticks are used for propping them up.

Figure 11 is the comparison of the measured and reflection coefficient of the antenna prototype.

From the measurement, the measured impedance bandwidth of the antenna is 22.9% (from 5.18 GHz to 6.52 GHz) versus the simulated one which is 19.3% (from 5.28 GHz to 6.41 GHz) for 2×2 fractal antenna array. At its working frequency of 5.8 GHz, the antenna has an input reflection coefficient of -27.49 dB, which estimates that a good impedance match has been achieved. Fig. 12 depicts the simulated and measured radiation patterns at different frequencies within the effective frequency band.

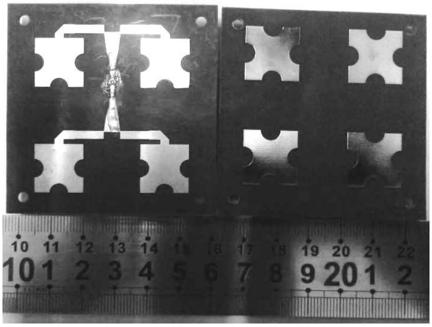

Figure 10. The both layers of the fabricated prototype antenna.

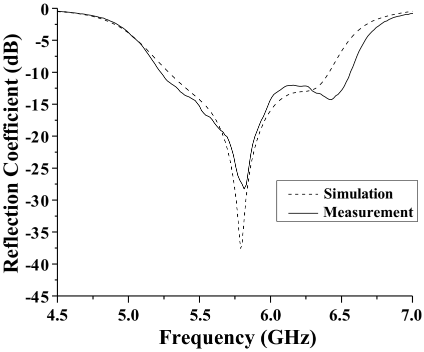

Figure 11. The measured and simulated reflection coefficients of the prototype antenna.

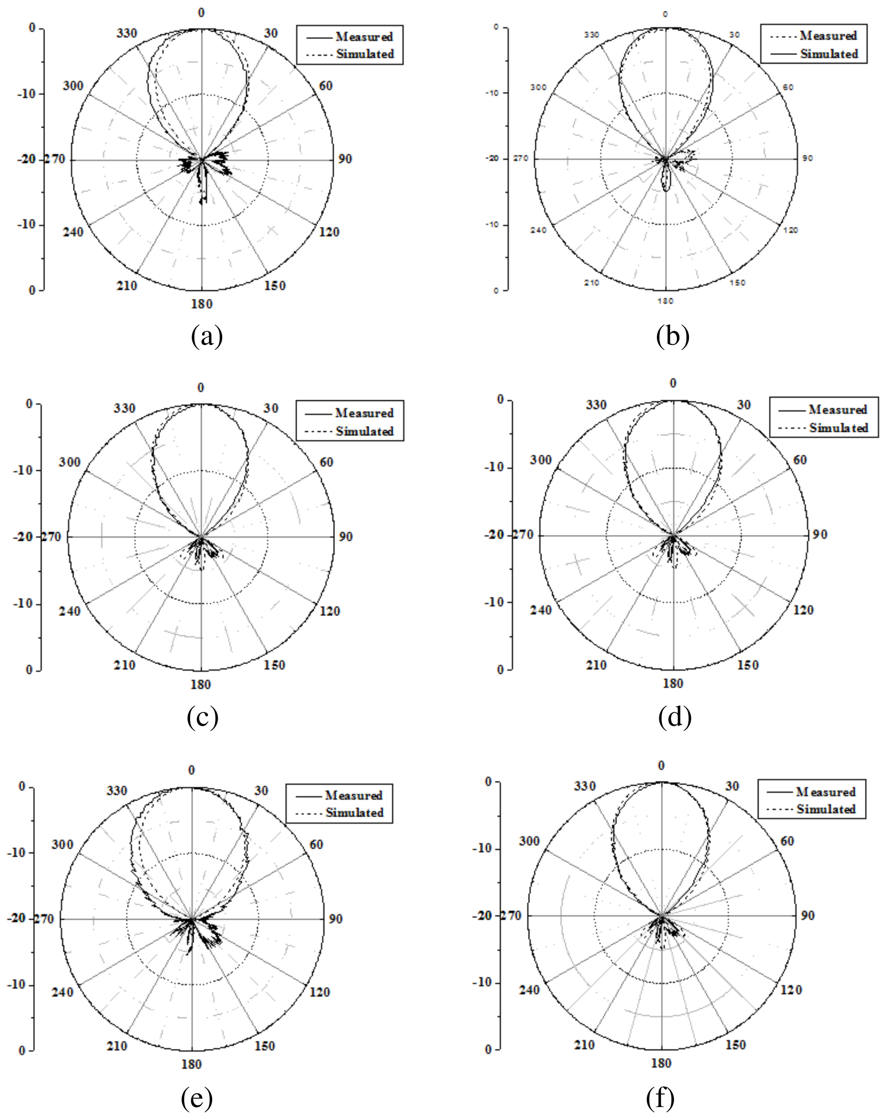

Figure 12. The measured and simulated radiation patterns on the E-plane and the H-plane at different frequencies. (a) E-plane at 5.3 GHz. (b) H-plane at 5.3 GHz. (c) E-plane at 5.8 GHz. (d) H-plane at 5.8 GHz. (e) E-plane at 6.3 GHz. (f) H-plane at 6.3 GHz.

4. CONCLUSION

A Cross Snowflake fractal antenna array is discussed. Structural parameters of the proposed antenna are optimized by GA to achieve both high aperture efficiency and wideband property over a desirable frequency band with a working frequency of 5.8 GHz. One antenna prototype was fabricated and measured. The measurement and simulation results agree well, which shows that the optimized antenna array possesses good properties. For example, the measured impedance bandwidth is 22.9% (from 5.18 GHz to 6.52 GHz) when $S_{11} < -10\,\mathrm{dB}$; the simulated gain is 12.0 dBi and its corresponding aperture efficiency up to 87.4% at the working frequency 5.8 GHz.

Under the same operating condition as the original array elements, the Cross Snowflake fractal antenna array is more effective in reducing the required aperture area (reduce 51%). Based on the conclusion above, the merits of wideband and high aperture efficiency make the proposed antenna a good candidate for various applications.

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