High-Gain Planar Array Designed by Using Fragmented Slots

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5 authors, including:

Yufeng Liu
Shanxi University

Changjun Liu
Sichuan University

Kama Huang
Sichuan University

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Yufeng Liu, Xing Chen, Xueyao Ren, Changjun Liu, Kama Huang

School of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China

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ABSTRACT: A novel planar array antenna is proposed. It utilizes fragmented slots as its radiation elements and explores employing this highly flexible structure for achieving high gain. Each fragmented slot is gridded into 8 × 8 rectangular pixels, whose dimensions as well as conducting or nonconducting properties are optimized by the Genetic Algorithm (GA) in parallel on a PC cluster. A prototype antenna with 4 × 4 slots was designed, fabricated and measured. Both the simulation and measurement results show that this antenna possesses a high gain of 20.5 dBi at its working frequency of 5.8 GHz, and thus the corresponding aperture efficiency is up to 95%, which is much higher than that of the planar arrays with rectangular slots or split-ring resonator (SRR) slots. Int J RF and Microwave CAE 24:382–388, 2014.

Keywords: fragmented slots; corporate feeding network; high-gain; genetic algorithm

I. INTRODUCTION

In recent years, the increasing demand of wireless communications for high-speed wireless LAN, satellite reception and various point-to-point links have led to the rapid development of directional antennas with high-gain performances. The planar printed antenna is an attractive choice for many modern wireless communications systems, due to its attractive features including low profile, light weight, and the ability of making use of cost-effective and accurate planar print techniques. Various antennas of this category have been proposed [1–4].

Some planar printed antennas use slots as their radiation elements. In our previous works [5,6], two planar printed slot array antennas have been devised. Both of them consist of 4 × 4 slots as their radiation elements, work at 5.8 GHz and are optimized by the Genetic Algorithm (GA). One [5] utilizes rectangular slots and achieves a gain of 18.7 dBi. Another [6] employs a metamaterial structure, the periodic split-ring resonator (SRR), to design its slots, and obtains a gain of 19.6 dBi. Those previous works estimate that the configuration of slots has a significant impact on antennas' performances such as the gain.

This work is an improvement of the two aforementioned works. It explores using a fragmented configuration to design radiation slots in a planar printed antenna for achieving high gain. The fragmented configuration is a highly stochastic structure, and has already been used in the antenna design [7–9]. Though the fragmented configuration is difficult to design due to its complicated configuration, its great flexibility allows it for accommodating many difficult requirements such as being wideband [7], electrically small [8] and etc. But this configuration rarely has been used to design radiation slots in a planar printed antenna for high gain. In this work, the proposed array antenna with fragmented slots will be designed by a GA software developed by us, and the GA will run in parallel on a PC cluster.

In the following, Section II introduces the configuration of the fragmented slots. The structure of the proposed antenna is given in Section III. Section IV presents the antenna design using the GA. The simulated and measured results are given in Section V. A conclusion is stated in Section VI.

II. THE FRAGMENTED SLOT

Figure 1 shows the configuration of the fragmented slot that will be utilized in the proposed planar printed array antenna. The slot is gridded into 8 × 8 pixels, where each pixel can be assigned either conducting or nonconducting properties, and periodically printed on a printed circuit

Correspondence to: X. Chen; xingc@live.cn
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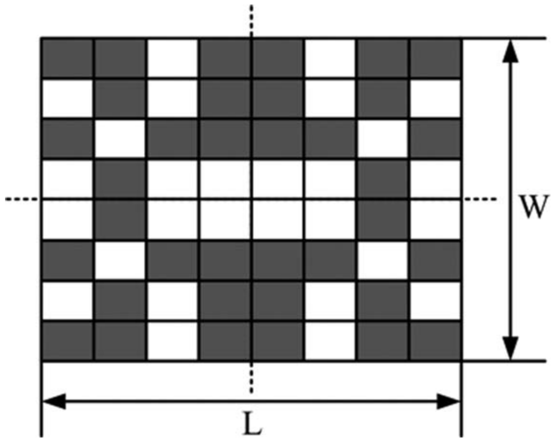

Figure 1 Geometry of a fragmented slot element.

board (PCB). The pixels in a fragmented slot can be divided into 4 equal quadrants symmetrically placed with respect to the aperture center. Hence, in a slot, there are 4 $\times$ 4 independent pixels, which are represented by pixels in the left-top quadrant and indexed (from left to right and from top to bottom) from 1 to 16, respectively. Variables $P_i(i=1, \ldots, 16)$ are employed for denoting the pixels' conducting ($P_i=1$) and nonconducting ($P_i=0$) properties.

III. ANTENNA CONFIGURATION

The configuration of the proposed antenna is illustrated in Figure 2. It comprises of two layers, e.g., the slot layer and the feeding layer. Both layers are printed on the PCB with permittivity $\varepsilon_r=2.65$ and thickness $h=1$ mm, The two layers are separated by air with distance of h_z. This array antenna will work at 5.8 GHz.

This antenna is directly fed from a 50 Ω coaxial line, whose inner conductor penetrates the PCB of the feeding layer and connects with a corporate-feed network on the feeding layer at the point *A*. The corporate-feed network provides equal amplitude and phase excitation to fragmented slots, which are etched on the slot layer and act as radiators. For the T-junctions of the divider, the widths of transmission lines W_1 and W_2 are set as 2.8 mm and 0.76 mm, which correspond to 50 and 100 Ω characteristic impedance, respectively.

Figure 3 illustrates the instantaneous electric current distribution shown by arrows on a fragmented slot at the working frequency. It is simulated by the popular commercial software CST (Computer Simulation Technology) MICROWAVE STUDIO (MWS) based on the finite integration technique (FIT). This figure reveals that the electromagnetic energy is coupled from the transmission lines of the corporate-feed network and radiated from the fragmented slots.

IV. ANTENNA OPTIMIZATION

As a powerful and efficient optimization technique, the Genetic Algorithm (GA) has been successfully applied in the optimization of various antennas [10–12]. Unlike most researches start from standard designs of antennas and employ the GA only for optimizing antennas' structural parameters, this work utilizes the GA not only to optimize the proposed antenna's structural parameters but also to determine the highly stochastic configuration of the antenna's slots. The optimization procedure is illustrated in Figure 4. The optimization goals are to achieve a high gain and a good impedance match at the working frequency of 5.8 GHz.

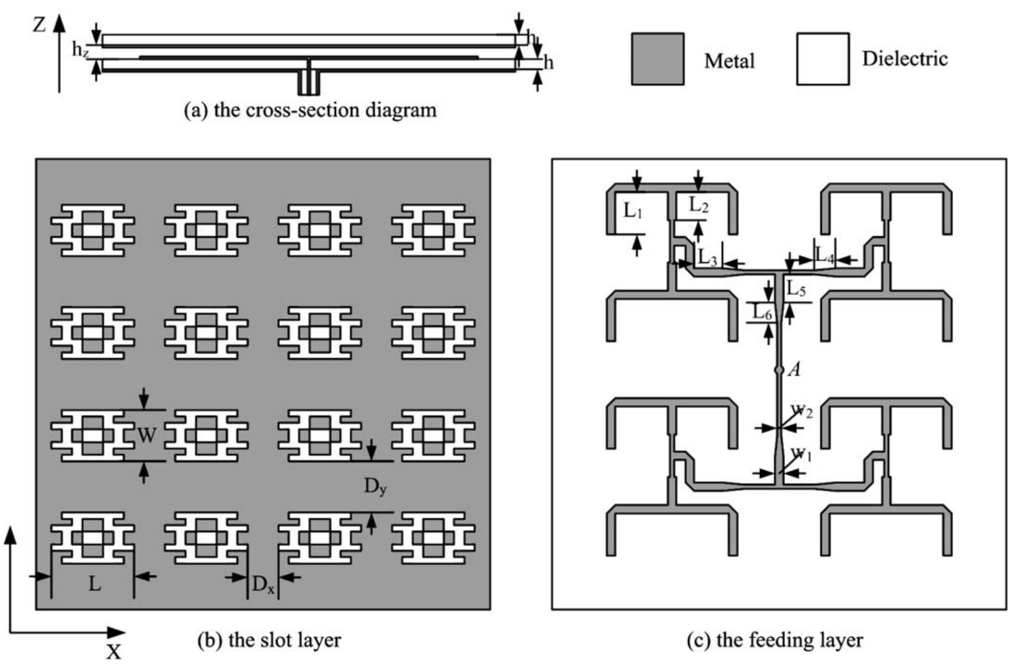

Figure 2 The configuration of the printed slot array antenna.

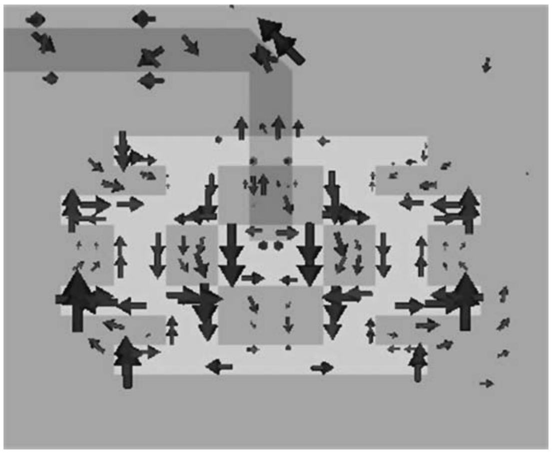

Figure 3 The current distribution on a fragmented slot.

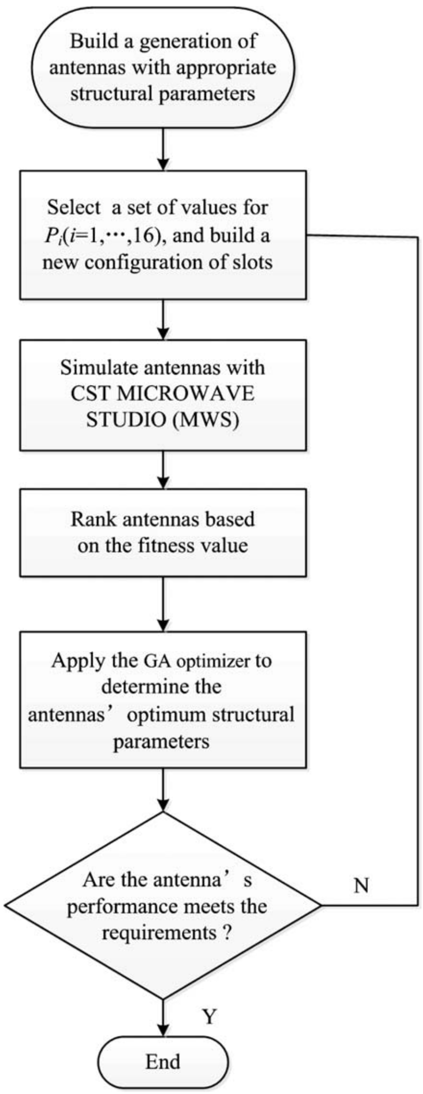

Figure 4 Flow diagram for the optimization

There are totally 29 parameters need to be optimized by the GA, e.g. $P_i(i=1, \ldots, 16)$, L, W, D_x, D_y, L_1, L_2, L_3, L_4, L_5, L_6, F_x, F_y and h_z. Owing to so many parameters need to be optimized, the GA will cost lots of time. To greatly reduce the computation time, in this work the GA-based antenna optimization is parallelized in a master-slave model and implemented on a Beowulf cluster system [13–16]. The Beowulf cluster system consists of 32 processors interconnected by a fast 1000 Mb s^{-1} Ethernet. One processor, named the master processor, carries out the GA optimization while all the others, called slave processors, execute full-wave EM simulations to obtain the performances of the proposed antenna by using CST MICROWAVE STUDIO.

The possible value ranges of the unknown parameters must be determined prior to the implementation of the GA optimization. By making reference to our previous researches [5,6], the slots' width and length W and L should $\sim 0.5\lambda$ at the resonance, where λ is the guided wavelength at the working frequency f_0=5.8 GHz and is calculated by $\lambda=\frac{\lambda_0}{\sqrt{\varepsilon_r}}=\frac{c}{f_0\sqrt{\varepsilon_r}}$, in which λ_0 is the free-space wavelength, c is the velocity of light in free space; to yield a good compromise among the side-lobe level, antenna gain and aperture efficiency, the edge-to-edge distances between two neighboring slots D_x and D_y should be about 0.5 λ; the parameters $L_1 \sim L_6$ usually range from 0.02 λ and 0.15λ; the horizontal and upper margins F_x and F_y should range from 0.1λ to 0.3λ to leave enough upper and horizontal margins for the feed lines.

After being given a considerable margin for the GA-based optimization, the parameters W, L, D_x, and D_y are restricted between 13 and 28 mm (about 0.4–0.88λ); L_1, L_2, L_3, L_4, L_5, L_6, F_x, F_y are set to be 3–13 mm (about 0.09–0.41 λ); h_z are restricted between 1 and 4 mm (about 0.03–0.126 λ).

The fitness function plays a key role in the GA optimization because it guides the optimization direction. In this work, the fitness function should take the high gain and good impedance match into account simultaneously, so it is defined as

$$Fitness = C_1 * Gain + C_2 * S_{11} \tag{1}$$

Where *Fitness* is the fitness value, *Gain* and S_{11} are the radiation gain in dBi and the return loss in dB at the working frequency of 5.8 GHz. C_1 and C_2 are weight factors representing the relative importance of items in the design requirements. No specific rules are found in the literature for determining their values. In this work, they are determined from experience and are set to be 0.025 and −0.03, respectively.

In the GA optimization, single-point crossover with probability $P=0.5$, jump mutation with probability $P_m=0.2$, and it uses 100 generations, 120 chromosomes, and 100 individuals in a population.

V. RESULTS AND ANALYSIS

The parameters determined by the GA-based optimization are as follows (unit: mm): L=26.6, W=15.3, D_x=16.6,

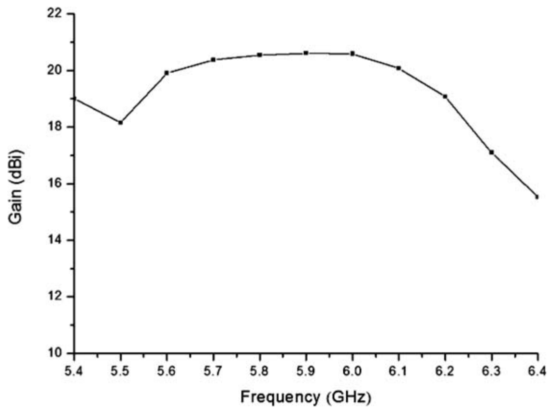

Figure 5 Simulated gain against frequency.

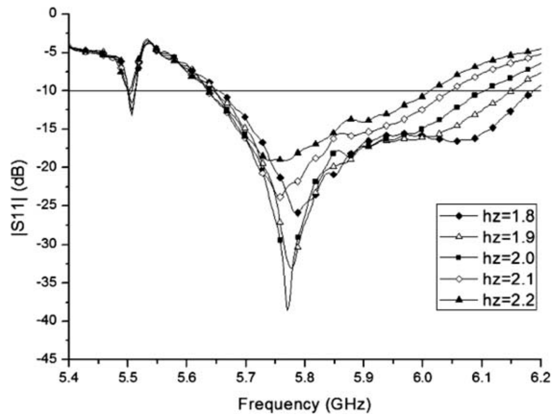

Figure 6 Simulated $|S_{11}|$ for different values of h_z.

D_y=18.9, L_1=10.8, L_2=7.0, L_3=11.7, L_4=10.1, L_5 = 5.3, L_6=6.3, F_x=4.5, F_y=10.5, h_z=2.0, and $P_i(i=1, \ldots, 16)$ equaling 1, 0, 0, 0, 1, 1, 0, 1, 0, 0, 0, 1, 1, 0, 1, 0.

The GA-based antenna optimization procedure takes about 112 h on our cluster system. Because one full-wave simulation in this case takes ~25 min on a single computer (with a Quad Core Q6600 at 2.66 GHz and 4 GB RAM) of the cluster, the optimization procedure would take much more time (nearly 3360 h) without the parallel computation.

Figure 5 gives the simulated gain against frequency for the proposed antenna. This figure shows the antenna exhibits a stable gain profile over a wide frequency band. For example, over the antenna's $|S_{11}| < -10 \quad dB$ impedance bandwidth (from 5.64 to 6.03 GHz), the gain varies from 19.9 to 20.6 dBi and the variation is <1 dBi.

As a planar printed antenna, the proposed antenna allows the use of the accurate microstrip fabrication techniques. Hence the parameter h_z, which denotes the distance between the slot layer and the feeding layer, is the only parameter that is relatively difficult to be precisely controlled in the fabrication procedure. To investigate the robustness of the proposed antenna, the $|S_{11}|$ and gain with respective to the variation of h_z are simulated and presented in Figures 6 and 7, respectively. One may

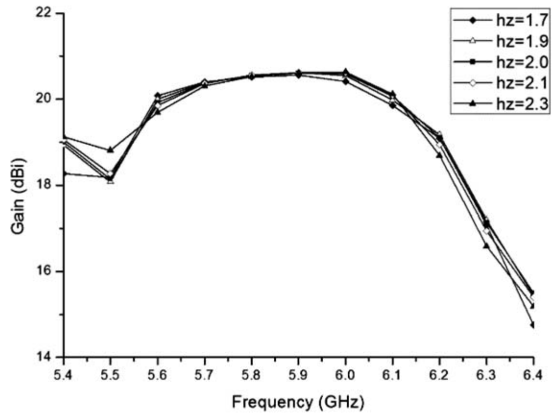

Figure 7 Simulated gain for different values of h_z.

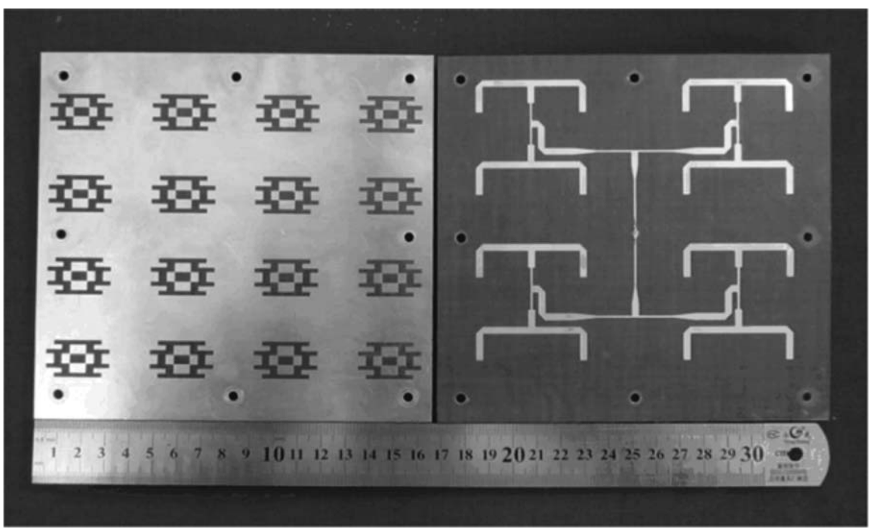

Figure 8 The two layers of the fabricated prototype antenna.

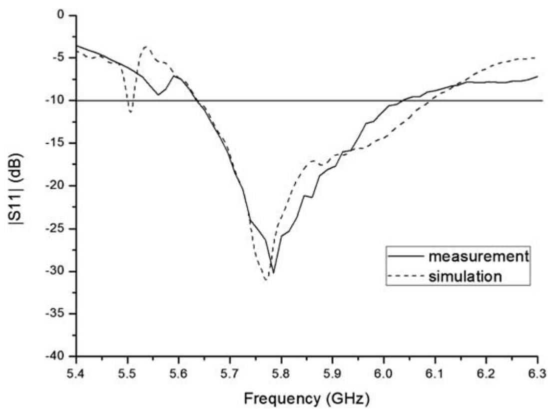

Figure 9 Measured and simulated $|S_{11}|$ of the prototype antenna.

observe that the $|S_{11}|$ and gain are insensitive to the variation of h_z, and thus this antenna has good robustness.

A prototype antenna (see Fig. 8) was fabricated and used for the following measurements. In the prototype antenna, the slot radiation layer and the feeding layer are separated by some glass sticks with a diameter of 5 mm. The total size of the antenna is 165 mm × 152 mm.

The reflection coefficient of the prototype antenna is measured by an Agilent E8362B Network Analyzer. As shown in Figure 9, the measured and the simulated $|S_{11}|$ agree well with each other. From the measurement, the $|S_{11}| < -10 \quad dB$ bandwidth is about 6.7% of the center frequency (from 5.64 to 6.03 GHz), At its working frequency of 5.8 GHz, the measured $|S_{11}|$ is about −25.9 dB, estimating a good impedance match has been achieved.

Measured and simulated radiation patterns on the XZ plane and YZ plane at the working frequency of 5.8 GHz are illustrated in Figure 10. They are in good agreement, and show at the working frequency of 5.8 GHz, the radiation gain is up to 20.5 dBi, the side-lobes are 9.5 dB below the main lobe, the antenna radiates in linear polarization with the main polarization in the direction of *Y* axis and the crosspolarization levels are <33 dB in both *XZ* and *YZ* planes.

It is worth noting that the gain of the proposed slot array antenna has been considerably improved by the utilization of the fragmented slots. Table 1 gives the comparison with the two slot array antennas in our previous works [5,6], the proposed antenna has improved the gain from 18.7 and 19.6 dBi, respectively to 20.5 dBi, and thus enhanced the corresponding aperture efficiency from 77% and 92%, respectively to 95%. The three antennas have the same number of slots and the same structure except

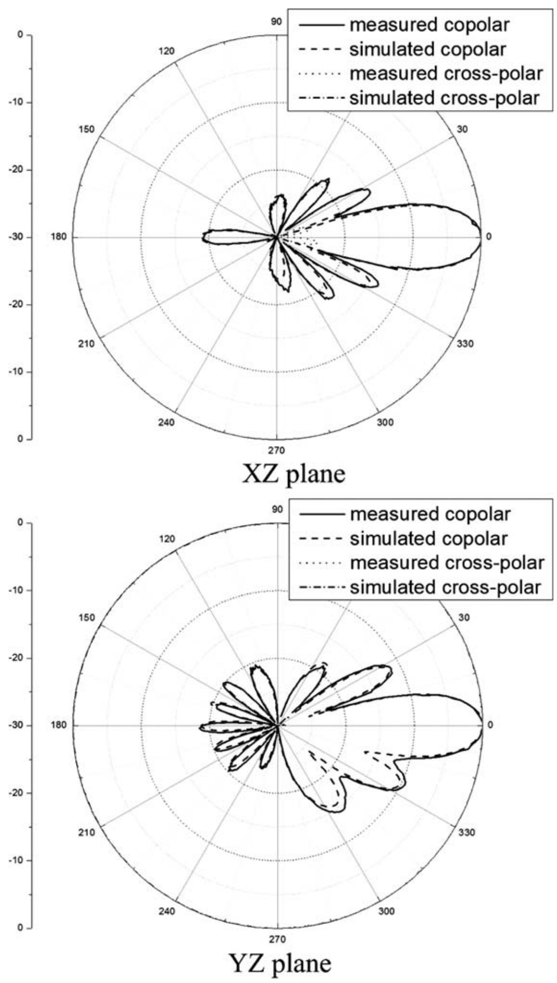

Figure 10 Measured and simulated radiation patterns on the *XZ* plane and *YZ* plane.

for the slots' configuration, so the improvement of the gain should owe to the employment of the fragmented slot.

VI. CONCLUSION

A novel slot array antenna with high gain property is presented. It adopts fragmented slots as its radiation elements. After optimized by the GA in parallel on a cluster system, a prototype antenna was fabricated and measured. Both the measured and simulated results show that, at its working frequency of 5.8 GHz the antenna achieves a high radiation gain up to 20.5 dBi, correspondingly the aperture efficiency is up to 95%. In comparison with other

TABLE 1 Comparison with the Two Slot Array Antennas in our Previous Works

	Rectangular Slot	SRR Slot	Fragmented Slot
$\lvert S_{11}\rvert < -10 \quad dB$ bandwidth	5.7% (5.67–6.0 GHz)	6.4% (5.72–6.1 GHz)	6.8% (5.64–6.04 GHz)
Gain	18.7 dBi	19.6 dBi	20.5 dBi
Aperture efficiency	77%	92%	95%

two slot array antennas that have same number of slots but utilize rectangular and SRR slots respectively, this antenna has considerably improved the gain and the aperture efficiency. The work demonstrates the great flexibility of the fragmented configuration provides an effective method to improve antennas' performances such as the gain and aperture efficiency.

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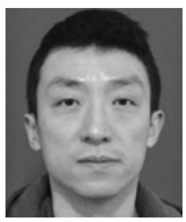
BIOGRAPHIES

Yufeng Liu received the B.S. degree in information and communication engineering from Sichuan University, Sichuan, China, in 2008, where he is currently working toward the Ph.D. degree in electromagnetics and microwave. His research is mainly focused on computational electromagnetics and antenna design.

Xing Chen received the M.S. degree in radio physics and the Ph.D. degree in biomedical engineering from Sichuan University, Sichuan, China, in 1999 and 2004, respectively. He joined the teaching staff in 1991 and is currently a Professor with the College of Electronics and Information Engineering, Sichuan University. His main research interests are in the fields of antenna, microwave imaging, global optimization, numerical methods applied in electromagnetics, and parallel computation. Dr. Chen is a Senior Member of the Chinese Institute of Electronics.



Xueyao Ren received the B.S. degree in information and communication engineering from Sichuan University, Sichuan, China, in 2005, where he is currently working toward the Ph.D. degree in electromagnetics and microwave. His research is mainly focused on computational electromagnetics and antenna design.

Changjun Liu received the M.S. and Ph.D. degrees from Sichuan University Chengdu, China, in 1997 and 2000, respectively. From 2001 to 2002, he was a Postdoc at Seoul National University, Seoul, Korea. He was a visiting scientist at Ulm University, Germany, in 2007. He is currently a professor in the School of Electronics and Information Engineering, Sichuan University. His research interests include microwave components, metamaterials, and microwave circuits.

Kama Huang received the M.S. and the Ph.D. degrees in microwave theory and technology from the University of Electronic Science and Technology, Chengdu, China, in 1988 and 1991, respectively. He has been a Professor of the College of Electronics and Information Engineering of Sichuan University, China since 1994, and the director of the College since 1997. In 1996, 1997, 1999, and 2001, he was a visiting scientist at the Scientific Research Center "Vidhuk," Kiev, Ukraine, the Institute of Biophysics CNR, Pisa, Italy, the Technical University Vienna, Vienna, Austria, and the Clemson University, Clemson, SC, respectively. At these institutions, he cooperated with the scientists to study the interaction between electromagnetic fields and complex media in biological structure and reaction systems.