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A NOVEL PLANAR PRINTED ARRAY ANTENNA WITH SRR SLOTS

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Abstract—Metamaterials, which are composite materials constructed usually by periodic and artificial resonant structures, have been widely utilized in many fields including the antenna design. Quite different from popular methods of embedding an antenna inside a metamaterial or placing metamaterial plates in front of an antenna, this work explores using a metamaterial structure, the periodic split-ring resonator (SRR), to design radiation slots in a printed array antenna for high gain. A proposed array with 4×4 slots and working at 5.8 GHz has been automated designed by using the Genetic Algorithm (GA) in conjunction with the parallel computation on a cluster. Both results of numerical simulations and measurements demonstrate, in comparison with an array using conventional rectangular slots, that the proposed array with SRR slots possesses almost the same impedance bandwidth, side-lobe and cross polarization level, but the gain is improved from 18.7 dBi to 19.6 dBi.

1. INTRODUCTION

Nowadays, the rapid development of modern wireless communications systems, including high-speed wireless LAN, satellite reception and various point-to-point links, has brought about the demand for directional antennas with high-gain. Among existing high gain antennas, the planar printed antenna possesses very attractive properties including low profile, light weight, compactness, and cost-effectiveness. Hence various planar printed antennas with properties of directional radiation and high gain have been developed [1–3].

In our earlier work [4], a novel planar printed slot array antenna is proposed. Its basic structure is a suspended stripline comprising

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three layers. On the top layer, rectangular slots are etched and act as radiation elements. The middle layer consists of a suspended stripline power divider, and the bottom layer is a metal ground. This array antenna has achieved a high gain of 18.7 dBi at the working frequency of 5.8 GHz and with 4×4 radiation slots, as well as a $S_{11} < -10$ dB impedance bandwidth of 5.7% after it is optimized by a parallel Genetic Algorithm (GA) on a cluster system.

The array antenna in this work is an improvement of our earlier work mentioned above. The idea of this work comes from metamaterials, which are composite materials constructed by artificial resonant structures and exhibit special electromagnetic properties that have not been discovered in natural materials. For metamaterials, their abnormal properties make them widely utilized in many fields. For example, the negative refraction property of the left-handed material is able to focus electromagnetic wave and so provides a new method to enhance antennas' radiation gain. So far in the large numbers of previous researches, commonly adopted methods of applying metamaterials to enhance antennas' gain are to embed an antenna inside a metamaterial [5] or to place metamaterial plates in front of an antenna [6]. Quite different from those existing methods, this work utilizes a metamaterial structure, the split-ring resonator (SRR), to design the configuration of radiation slots in a planar printed array antenna to improve its gain.

In the following, Section 2 briefly introduces metamaterials and the SRR. The structure of the proposed antenna and its optimization using the parallel GA are described in Section 3 and Section 4 respectively. The simulated and measured properties of the proposed antenna are given in Section 5, and a conclusion is stated in Section 6.

2. METAMATERIALS AND SRR

As a special class of artificial materials, metamaterials usually gain their properties from structure rather than composition, and their properties may be unavailable in nature. Metamaterials were theoretically proposed first by Veselago [7] in 1968. In 1999, almost 30 years later, Pendry et al. suggested the model of negative permittivity ε and negative permeability μ materials with periodic arrangement of SRR and copper wire [8]. After that, on the basis of Pendry's research, Smith et al. fabricated the first left-handed material (LHM) consisting of an array of SRRs and wires in alternating layers [9]. Recently, various metamaterials are widely studied, e.g., the left-handed material, composite right left-handed transmission line, photonic crystal, artificial magnetic conductors (AMC), etc.

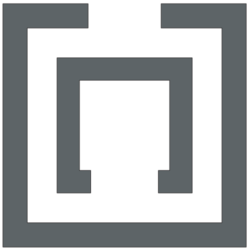

Figure 1. Geometry of a SRR.

As a kind of single negative (SNG) metamaterials and a component part of the left-handed material, the SRR is a well-known metamaterial structure. The SRR is a pair of concentric annular rings with splits in them at opposite ends, and its rings are made of nonmagnetic metal as copper and have small gap between them (see Figure 1). At frequencies higher than resonance, the real part of the magnetic permeability of the SRR may be negative.

Applying metamaterials to increase the performance of antennas has garnered much interest. Metamaterials could be applied to enhance antennas' radiation gain as well as design antennas with electrically small size or tunable operation frequency. This work explores using the configuration of the SRR to design radiation slots in a printed array antenna for a high gain.

3. ANTENNA CONFIGURATION

As illustrated in Figure 2, the proposed planar printed array comprises three layers, e.g., the slot radiation layer, suspending stripline feeding layer, and metal reflecting layer. The three layers together form a suspended stripline. Both the top and middle layers are printed on the PCB (printed circuit board) with permittivity 2.65 and thickness 1.0 mm, and an aluminum board with thickness 4.0 mm is chosen as its metal reflecting layer. The three layers are separated by air with distance $h = 2$ mm, and some glass sticks with a diameter of 5 mm are used for propping them up.

The suspended stripline is an unbalanced transmission line, so this antenna is directly fed from a 50 Ω coaxial line, whose inner conductor penetrates the metal reflecting layer and connects with the suspending stripline feeding layer at feed point A. A parallel and series hybrid power divider is printed on the suspending stripline feeding layer. The power divider is to effectively deliver electromagnetic energy and then feed the slots on the slot radiation layer with in-phase excitation. To realize low return loss, corners of striplines in

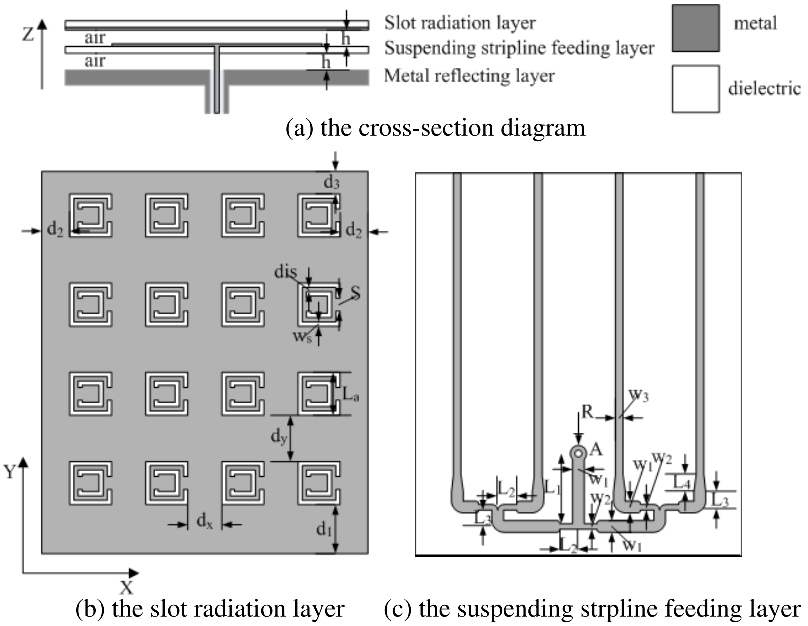

Figure 2. The geometry of the planar printed array antenna with SRR slots.

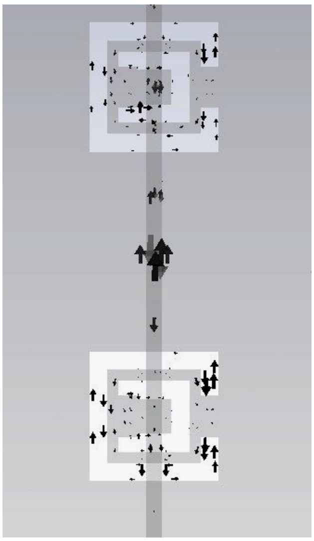

Figure 3. Simulated surface current distribution on the antenna.

this power divider are blended, and a segment, whose width is tapered from w_1 to w_3, is utilized to gradually transform the characteristic impedance of striplines. The slots on the slot radiation layer act as radiators, which couple electromagnetic energy from the power divider and radiate energy out to form a directional radiation pattern with high gain.

Figure 3 shows the surface current distribution on the antenna at its resonant frequency, which is obtained by a popular commercial software CST MICROWAVE STUDIO (MWS) based on the finite integration technique (FIT). From this figure, it is obvious that the current mainly flows along striplines and then is coupled from striplines to SRR slots. Due to the complex configuration of the SRR, the current distribution inside the slots is very complicated.

4. ANTENNA OPTIMIZATION

In this work, a proposed array antenna with 4×4 SRR slots and working at 5.8 GHz is optimized by the GA on a cluster system. The optimization method, basic structure of the antenna, number of slots and working frequency in this work are the same as that in our earlier work [4]. The only difference is the configuration of slots, i.e., SRR slots in this work versus rectangular slots in our earlier work.

The GA [10] is a powerful and efficient optimization technique and has been widely applied to the optimization of various antennas [11–13]. In this work, we employ the GA to optimize structural parameters of the proposed planar slot array antenna for achieving high gain and good impedance match at the working frequency. The radiation properties of the antenna are obtained by the full-wave EM simulation using the finite-difference time-domain (FDTD) method. To greatly reduce the optimization time, the computation of the GA-based antenna optimization is parallelized in a master-slave model and implemented on a Beowulf cluster system [14–17]. The Beowulf cluster system is composed of 32 processors interconnected by a fast 1000 Mb/s Ethernet and uses the message passing interface (MPI) library. One processor, named the master processor, carries out the GA optimization while other processors, called slave processors, execute full-wave EM simulations using FDTD.

To leave enough room for the T junction of the power divider, the bottom margin d_1 is set to be 25 mm, and d_2 that denotes the margin on left and right sides is fixed to be 8.0 mm. For the T-junctions of the divider, the widths of striplines w_1 and w_2 are set as 4.2 mm and 2.1 mm, which correspond to 50 Ω and 70 Ω characteristic impedance respectively. The other 11 structural parameters, i.e., L_a, d_x, d_y, d_3,

L_2, L_3, L_4, w_s, w_3, S and dis, are needed to be optimized. Compared to that in our earlier work [4], most parameters are the same, except for two parameters involving the SRR, i.e., the gap width S as well as the distance between the inner and outer rings dis.

The possible ranges for these structural parameters are determined first for the GA optimization. After learning from the optimization results in our earlier work [4] and giving a considerable margin for the GA-based optimization, the parameters d_x and d_y are to be confined within the range of 16 mm $\sim$ 26 mm (about $0.5\lambda \sim 0.8\lambda$), and L_a is set to be 13 mm $\sim$ 20 mm (about $0.4\lambda \sim 0.6\lambda$), d_3, L_2, L_3, L_4, w_s and w_3 are restricted to be 1 mm $\sim$ 10 mm (about $0.03\lambda \sim 0.3\lambda$), where λ is the guided wavelength at the working frequency f_0 and 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; and ε_r is the relative dielectric constant of the substrate.

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

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

where F is the fitness value. $Gain$ and S_{11} are the radiation gain and the return loss at the working frequency of 5.8 GHz. C_1 and C_2 are weight factors, which are determined by experience and are set to be 0.025 and -0.03, respectively.

In the optimization, the GA employs tournament selection with elitism, 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.

5. RESULTS AND DISCUSSION

The structural parameters generated by the GA-based optimization are as follow (unit: mm): $L_a = 16.0(0.5\lambda)$, $d_x = 22.1(0.7\lambda)$, $d_y = 24.6(0.77\lambda)$, $d_3 = 2.1(0.07\lambda)$, $L_2 = 9.0(0.28\lambda)$, $L_3 = 6.3(0.2\lambda)$, $L_4 = 4.0(0.13\lambda)$, $dis = 1.4(0.04\lambda)$, $S = 5.1(0.16\lambda)$, $w_s = 3.6(0.11\lambda)$, $w_3 = 2.0(0.06\lambda)$.

A prototype antenna as shown in Figure 4 has been fabricated and measured. Figure 5 compares the measured and simulated return losses of the prototype antenna. One can observe that the measured and simulated results are in good agreement. The measured $S_{11} \leq -10$ dB bandwidth is about 6.4% (from 5.72 GHz to 6.1 GHz). At its working frequency of 5.8 GHz, the antenna has a reflection coefficient of −23.1 dB, which estimates that 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 6. It is obvious that the measured and simulated radiation patterns agree very well. The gain at 5.8 GHz is up to 19.6 dBi. The measured side-lobes are approximately 13 dB below the main lobe. The simulation and measurement show that the antenna radiates in linear polarization with the main polarization in the direction of Y axis and the cross-polarization level less than −20 dB.

In comparison with the planar printed array with conventional rectangular slots in our earlier work [4], the proposed array with SRR slots possesses almost the same impedance bandwidth, side-lobe and cross polarization level, but the gain is improved from 18.7 dBi to 19.6 dBi, and correspondingly the aperture efficiency is increased from 77% to 92%. Considering that the two array antennas differ only in the configuration of their slots and that all have been optimized by the GA, we think that the improvement of the gain is really great, which owes to the utilization of SRR slots.

It is worth noting that this work uses the configuration of the SRR to design the slots, rather than views the SRR slot as a single negative (SNG) metamaterial or a component part of the left-handed material. If a metamaterial is to behave as a homogeneous material accurately described by the constitutive effective parameters, e.g., permittivity ε, permeability μ and refractive index n, its dimensions must be much smaller than the wavelength. However, for the SRR slots in this works, their dimensions are on the order of a wavelength, so it is invalid to characterize them by retrieving the constitutive effective parameters.

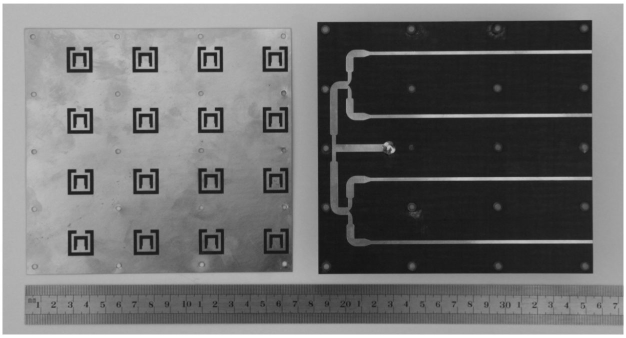

Figure 4. The top and middle layers of the fabricated prototype antenna.

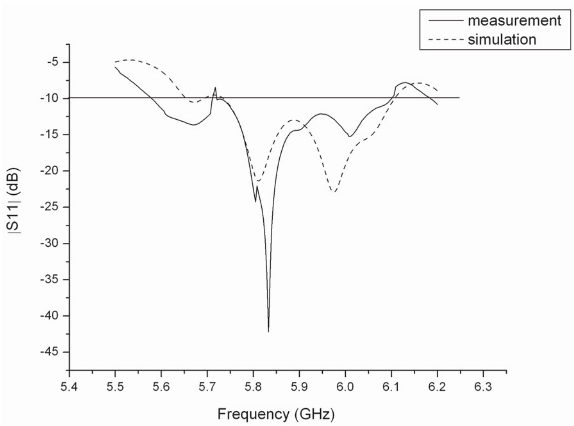

Figure 5. The measured and simulated return loss of the prototype antenna.

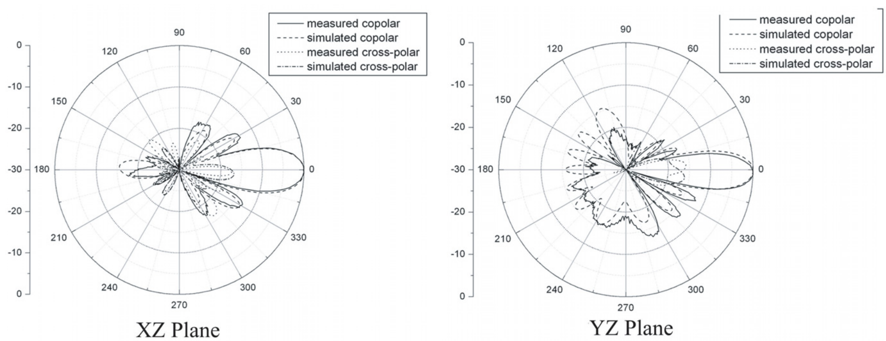

Figure 6. Measured and simulated radiation patterns on the XZ Plane and YZ plane.

6. CONCLUSION

A novel planar printed array antenna with high gain is presented. As an improvement of our earlier work, it, for the first time, utilizes the configuration of the SRR, a widely used metamaterial structure, to design its radiation slots. After optimized by the GA in parallel on a cluster system, a prototype antenna was fabricated and measured. Both the measured and simulated results demonstrate that the utilization of the SRR slots has increased the gain of the planar printed array by 0.9 dB (from 18.7 dBi to 19.6 dBi, and correspondingly the aperture efficiency is improved from 77% to 92%) at its working frequency, in comparison with the array with conventional rectangular slots in our earlier work. The research of this work provides a new method to enhance the gain of antennas.

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