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A NOVEL MICROSTRIP GRID ARRAY ANTENNA WITH BOTH HIGH-GAIN AND WIDEBAND PROPERTIES

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Abstract—A novel microstrip grid array antenna that is simultaneously high in gain and wide in bandwidth is proposed. To enhance its bandwidth, the antenna adopts elliptically shaped and variably dimensioned radiation elements as well as a linearly tapered ground plane, and is optimized by a parallel genetic algorithm (GA) on a cluster system. A prototype antenna was fabricated and tested. Results of simulation and measurement agree well and show the antenna exhibits encouraging properties, e.g., a maximum gain of approximately 15.1 dBi at 5.8 GHz; the $|S_{11}| < -10$ dB bandwidth and the 3 dB gain-drop bandwidth are 25.6% (from 5.03 GHz to 6.51 GHz) and 27.6% (from 5.0 GHz to 6.6 GHz), respectively, of the center frequency, both of which are much wider than that of conventional microstrip grid array antennas. Moreover, the overlap between the antenna's impedance bandwidth and the gain bandwidth results in a wide effective operating frequency bandwidth of 25.6%, which is the largest so far achieved for microstrip grid-array antennas.

1. INTRODUCTION

The grid array antenna is a low-profile flat and linear or circular polarization antenna composed of many grid cells formed by two kinds of lines: one acts as radiation elements, and the other as transmission lines that provide a phase delay of 360° at resonance to ensure the in-phase excitation of all the radiation elements.

The grid array antenna possesses many advantages such as high gain, narrow beam, simple feed, and easy construction. Since it was first proposed by Kraus in 1964 [1], there have been many successful

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designs. In 1981, Conti et al. [2] reported a microstrip version of the array, which allows the use of simple, low-cost, and accurate microstrip fabrication techniques. H. Nakano et al. [3–11] analyzed its radiation characteristics and has introduced some extensions since the mid-1990s. Sun et al. [12] have utilized the microstrip grid array antenna in a highly integrated 60 GHz radio. Chen et al. [13, 14] have developed a parallel genetic algorithm (GA) to optimize the design of microstrip grid-array antennas.

Though the grid array antenna has the advantages as noted earlier, it has not received enough attention or found wide applications. One major cause is that most grid array antennas are of narrow bandwidth. Their impedance bandwidth and gain bandwidth are typically within a few percentages of the center frequency [2–6, 8, 9, 12]. For example, the grid array antenna in [6] has $|S_{11}| < -10$ bandwidth of only 2.6% and a 3 dB gain-drop bandwidth of less than 7%; the microstrip grid array antenna designed in [7] has $|S_{11}| < -10$ bandwidth of approximately 13%; in [4, 8, 9], several grid array antennas are presented, but their 3 dB gain-drop bandwidth are only approximately 3.3%, 9%, and 5.6%, respectively.

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 antennas with both wideband and high gain to cover a wide frequency range. Indeed, there are countless researches proposed in the literature to design antennas with high gain or wide bandwidth, but few of them are for both properties together. Hence, antennas, especially low-profile planar antennas, which are simultaneously high in gain and wide in bandwidth, are very limited in their availability. Furthermore, in many applications, the effective operating bandwidth for an antenna should be the intersection of its impedance bandwidth and gain bandwidth. Thus, many antennas, though possessing both wide impedance bandwidth and wide gain bandwidth, are not true wideband antennas because their impedance bandwidth and gain bandwidth do not overlap each other.

In our previous work [13], a microstrip grid array antenna with a high gain of 18.3 dBi was designed, but this antenna is with narrow bandwidth, e.g., its $|S_{11}| < -10$ dB bandwidth is only 4.5% of the center frequency. In another our previous work [14], a wideband microstrip grid array antenna was proposed, by using elliptical radiation elements, the antenna's $|S_{11}| < -10$ dB bandwidth and 3-dB gain-drop bandwidth are 25% and 16.3% respectively of the center frequency, but its gain is medium (13.7 dBi) and its effective bandwidth is only 12.4% of the center frequency due to the relative low overlap between its impedance bandwidth and gain bandwidth. As an improvement of our previous works [13, 14], this work is dedicated to design a microstrip grid array antenna with both wide effective bandwidth and high gain properties. To achieve this design objective, the structure of the microstrip grid array antenna in this work is quite different from that in our two previous works. For example, the antenna will adopt elliptically shaped and variably dimensioned radiation elements as well as a linearly tapered ground plane to obtain the wideband property.

The remainder of the paper is organized as follows. Section 2 introduces the configuration of the proposed microstrip grid array antenna. The antenna optimization based on the parallel GA is presented in Section 3. Simulated and measured properties of the designed antenna are given in Section 4. Conclusions are stated in Section 5.

2. ANTENNA CONFIGURATION

Figure 1 illustrates a top view and a side view of the proposed microstrip grid array antenna. This antenna includes a grid array printed on a dielectric substrate of relative permittivity ε_r and thickness h_1, and is backed by a metal ground plane. An air space of thickness h_2 is between the substrate and the metal ground plane. The antenna is fed directly from a 50-Ω coaxial line, whose inner conductor penetrates both the metal board and the dielectric substrate, and then connects with the grid array at point A.

Just as other microstrip grid-array antennas, the proposed antenna's grid array is formed by two kinds of microstrip lines, which are short (X-directed) and long (Y-directed) sides of grid cells. As a resonant grid array antenna, the short and the long sides are usually chosen as about 0.5 and 1.0 wavelength of the working frequency, respectively. Hence, the currents are in-phase on the short sides while out of phase with each other on the long sides; thus, the short sides act as radiation elements while the long ones act as transmission lines.

Our previous research [14] has estimated that in comparison with the widely used rectangular radiation elements, elliptically shaped radiation elements are able to enhance the frequency bandwidth of the antenna due to their smooth and broad configuration. Therefore, in this work, the X-directed radiation elements are designed to be elliptically shaped as shown in Figure 1.

A widely used technique for designing wideband antennas is multiresonant radiating structures. The log periodic antennas are common examples of this category. The proposed microstrip grid array employs this technique for further enhancing the antenna's bandwidth.

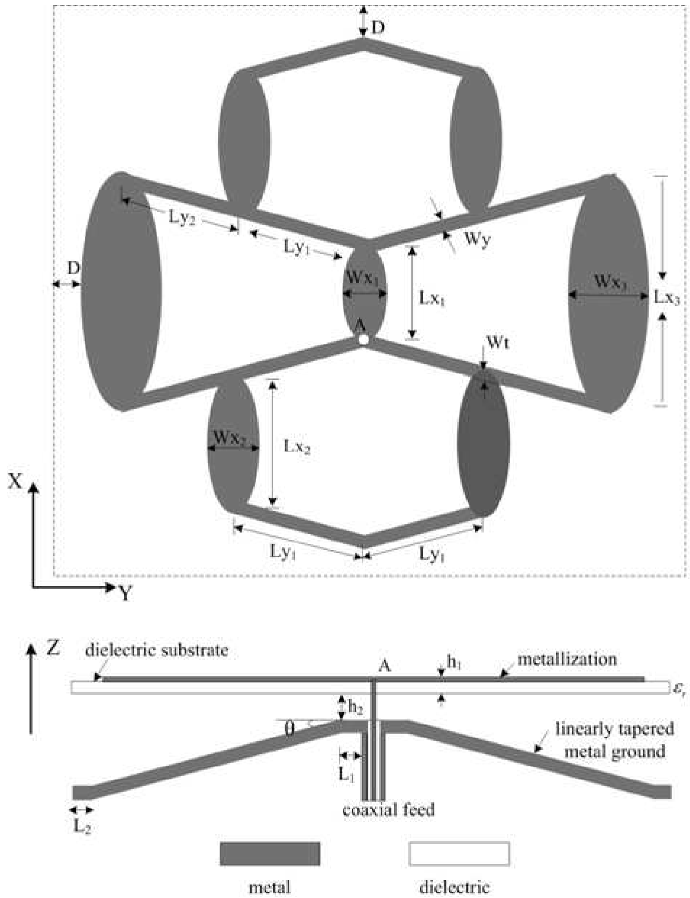

Figure 1. Geometry of the proposed microstrip grid array antenna.

Different from other microstrip grid arrays using identical radiation elements, the major axis length Lx_i and the minor axis length Wx_i for elliptical radiation elements in the proposed antenna are related to a scale factor τ_1 by

$$\tau_1 = \frac{Lx_i}{Lx_{i+1}} = \frac{Wx_i}{Wx_{i+1}}, \tag{1}$$

where i is the index number of radiation elements with different dimensions. The variable dimensions of the radiation elements mean that the antenna will be resonant at different frequencies and that may result in a wideband property.

To simplify the structure of the proposed antenna and reduce the number of the independent structural parameters, so as to alleviate the computation burden of the GA optimization, we order

$$\tau_2 = \frac{Lx_i}{Wx_i}. \tag{2}$$

In general, the ground plane constitutes a bandwidth-limiting factor for antennas [15], and this is why more effort must be invested in the design for a ground plane-backed antenna than one without a ground plane. The ground plane in this antenna is designed to be linearly tapered; hence, the distance between the radiation elements and the ground plane varies corresponding with the resonant wavelengths of the radiation elements. The tilt angle of the ground plane is assumed to be θ, and the ground including two horizontal segments with lengths L_1 and L_2, respectively, for the convenience of assembling grass sticks to separate the dielectric substrate and the ground plane.

3. ANTENNA OPTIMIZATION

As a powerful and efficient optimization technique, the genetic algorithm (GA) [13] makes use of a natural evolution process: the improvement of a population of parameters along successive generations by applying genetic operators, e.g., mutation, selection and crossover.

The GA starts with a set of trial solutions to evolve along different ways so as to search a global optimum. Those trial solutions are randomly constituted and may be far from the expected performances. The GA may carry out lots of computation in order to obtain an optimum solution, and thus save lots of human labor.

The GA has been successfully applied in the optimization of various antennas [13–17]. In this work, it is employed for optimizing the proposed microstrip grid-array antenna. The radiation properties of the antenna are obtained by full-wave simulations employing the popular commercial software CST MICROWAVE STUDIO (MWS) based on the finite integration technique (FIT).

A GA-based antenna design procedure usually invokes hundreds or even thousands of full-wave simulations, and hence is computationally intensive. As the GA exhibits an intrinsic parallelism and allows a very straightforward implementation on parallel computers, we implement the GA-based antenna design into parallel computation to make the computation more effective. The design procedure is parallelized in a master-slave model and implemented on a Beowulf cluster system [13] to reduce greatly the computation time. The Beowulf cluster system consists of 32 processors interconnected by a fast 1000 Mb/s Ethernet. One processor, named the "master processor," carries out the GA optimization while all the others, called "slave processors," execute the full-wave EM simulations using CST MWS.

The design goal is to achieve both the high-gain and the wideband properties for the proposed microstrip grid-array antenna. The antenna works in a desirable frequency band with the center of 5.8 GHz. Its gain at 5.8 GHz should be larger than 15 dBi while it possesses an effective frequency band as wide as possible. The effective frequency band is defined as the intersection of the antenna's $|S_{11}| < -10$ dB impedance bandwidth and 3 dB gain-drop bandwidth. To reach the desired gain, according to the results of several full-wave simulations, we use seven elliptical radiation elements for the proposed antenna.

For the antenna, a PCB (printed circuit board) with a relative dielectric constant $\varepsilon_r = 2.65$ and a thickness $h_1 = 1$ mm is used as its dielectric substrate, and the tapered metal ground is fabricated by an aluminum board with a thickness of 4.0 mm. Parameters D, L_1 and L_2 are fixed at 10 mm. There are a total of 9 unknown parameters to be optimized, i.e., Lx_2, Ly_1, Ly_2, Wy, Wt, θ, h_2, τ_1, and τ_2, where Ly_1 and Ly_2 are the lengths while Wy is the width of the Y-directed transmission lines, and Wt is the depth of a radiation element inserted into a transmission line.

For a GA optimization procedure, the determination of unknown parameters' possible value range is very important because it has a big impact on the optimization efficiency and results. The value range for unknown parameters should be a good tradeoff between ensuring the optimum to be included in the solution space and minimizing the solution space to alleviate the optimization difficulty. According to results in our previous works [13, 14], Lx_2 is around 0.5λ, Ly_1 and Ly_2 are slightly less than 0.5λ, Wy is about 0.03λ, Wt should be less than Wy, and h_2 is usually selected to be about $0.03\lambda \sim 0.08\lambda$, where λ is the free-space wavelength at the center frequency of 5.8 GHz. Furthermore, a set of full-wave simulations using CST MWS were conducted to accurately determine the possible value range of the aforementioned 9 unknown parameters. After giving a considerable margin for the GA-based optimization, the parameters Lx_2, Ly_1, Ly_2, Wy, Wt, and h_2 are confined within the ranges of 22–30 mm (0.43–0.58λ), 17–25 mm (0.33–0.48λ), 20–25 mm (0.39–0.48λ), 0.5–2.0 mm (0.01–0.039λ), 0.5–2.0 mm (0.01–0.039λ), and 1.0–5.0 mm (0.02–0.097λ), respectively; θ is restricted between 0–30°; τ_1, τ_2 is set between 0.5–1.0 and 1.0–3.0, respectively.

The fitness function plays a key role in GA optimization as it represents the desired performance requirements. Corresponding to

Table 1. Results of the GA-based optimization.

Lx_2	Ly_1	Ly_2	Wy	Wt
26.4 mm	20.5 mm	23.6 mm	0.7 mm	0.6 mm
0.51λ	0.4λ	0.46λ	0.014λ	0.012λ
h_2	θ	τ_1	τ_2	
3.2 mm 0.062λ	$10.5°$	0.885	1.64	

the optimization objective mentioned earlier, the fitness function is defined as

$$F = C_1 * Bandwidth + C_2 * Gain \tag{3}$$

where F is the fitness value; $Bandwidth$ is the effective bandwidth in percentage; $Gain$ is the gain in dBi at 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 study, they are determined from experience and are set to be 1.0 and 0.03 respectively, after careful adjustment.

A GA-based optimization is then executed. In the optimization, the GA employs tournament selection with elitism, single-point crossover with probability $P_c = 0.5$, and jump mutation with probability $P_m = 0.2$. It uses 100 generations, 110 chromosomes, and 80 individuals in a population.

4. RESULTS AND DISCUSSION

Results obtained by the GA-based optimization are listed in Table 1. The size of the designed antenna is 126 mm × 100 mm.

The GA-based antenna optimization procedure takes about 112 hours on our cluster system. Because one full-wave simulation in this case takes approximately 25 minutes 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 hours) without the parallel computation.

Using the parameters determined by GA optimization, a prototype antenna has been fabricated and is depicted in Figure 2. It will be used for the measurements presented later.

The reflection coefficient of the prototype antenna was measured by an Agilent E8362B Network Analyzer. The measured and the simulated $|S_{11}|$ are presented and compared in Figure 3. The

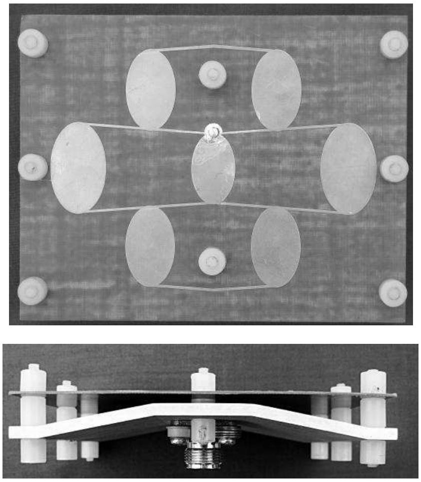

Figure 2. The top and the side views of the fabricated prototype antenna.

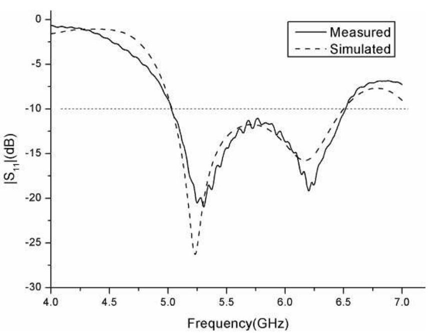

Figure 3. The measured and simulated reflection coefficients of the prototype antenna.

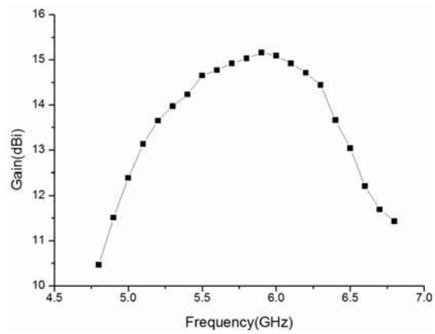

Figure 4. Gain of the proposed antenna against frequencies.

comparison shows that the two sets of data are in good agreement that validates the reliability of the GA-based antenna optimization One can observe that the impedance bandwidth for $|S_{11}| < -10\,\text{dB}$ is 25.6% (from 5.03 GHz to 6.51 GHz), which is much wider than that of grid array antennas introduced in previous literature [2, 3, 6, 7, 11–13] and slightly larger than that achieved in our previous research [14].

The measured gain of the designed antenna against frequencies is given in Figure 4, which shows that the maximum gain of the antenna is 15.1 dBi and it is obtained at 5.8 GHz. The 3-dB gain-drop bandwidth is 27.6% (from 5.0 GHz to 6.6 GHz), which is also much wider than that of grid array antennas in previous literatures [2–4, 6–8, 13], and even much wider than that in our previous work [14].

It is worth noting that for the proposed microstrip grid array

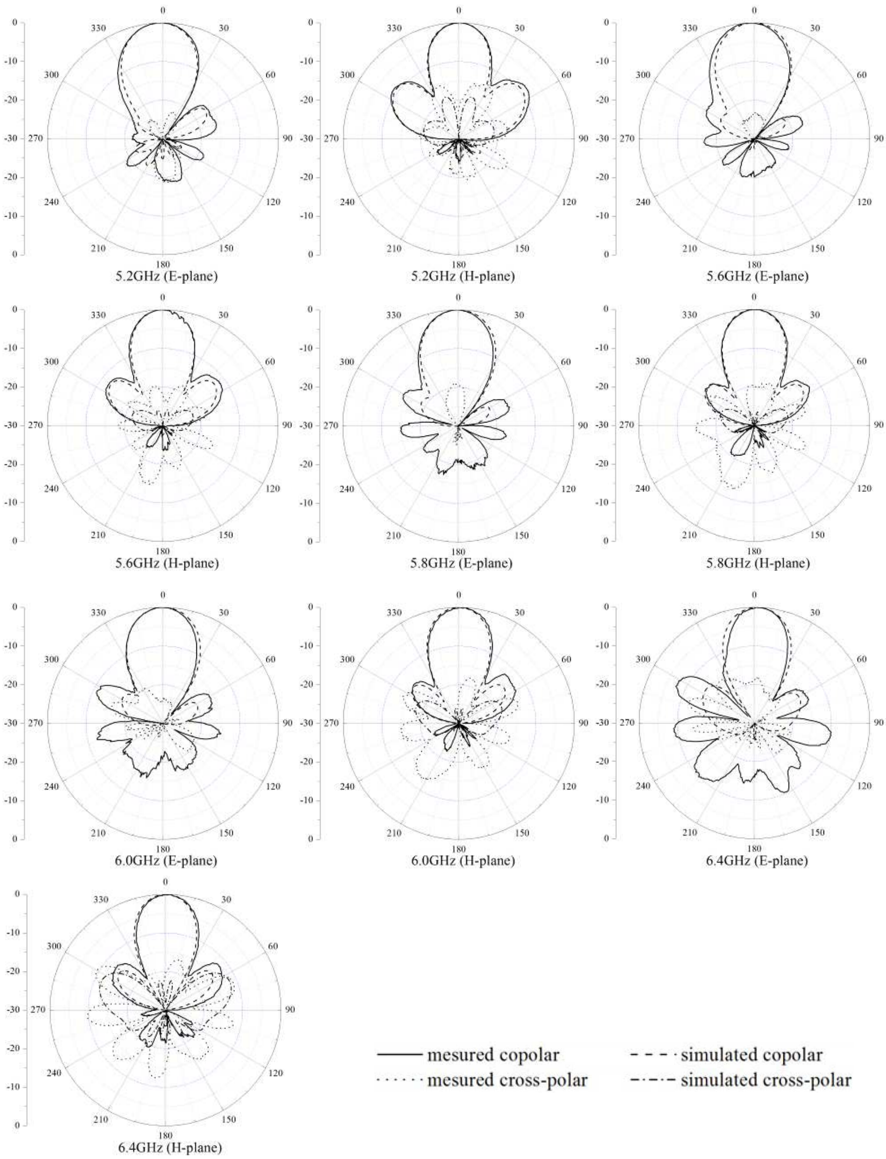

Figure 5. Measured and simulated radiation patterns on the E-plane and the H-plane at different frequencies.

antenna, the overlap between its impedance bandwidth and gain bandwidth results in an encouraging wide effective bandwidth of up to 25.6% of the center frequency (from 5.03 GHz to 6.51 GHz). To the knowledge of the authors, it is the largest effective bandwidth achieved so far, not only for the microstrip grid array but also for the grid array.

Figure 5 depicts the simulated and measured radiation patterns at different frequencies within the effective frequency band. One can observe that the simulated and the measured radiation patterns agree very well. At the center frequency of 5.8 GHz, the side lobes are approximately 12 dB below the main lobe, and the cross polarization level is less than −18 dB. Though its performances gradually degenerate with the frequency deviating from the center frequency, the antenna maintains good directional patterns over the entire operating band.

5. CONCLUSION

A novel microstrip grid array antenna is presented. To enhance the bandwidth, the antenna's radiation elements are designed to be elliptically shaped with variable dimensions, and the metal ground is fabricated to be tapered linearly. Structural parameters of the proposed antenna were optimized by a parallel GA on a cluster system to achieve both the high-gain and the wideband properties in a desirable frequency band with the center of 5.8 GHz. A prototype antenna was fabricated and measured. The measurement results and the simulation results agree well, and show that the optimized grid array antenna possesses some encouraging properties, i.e., its maximum gain is 15.1 dBi at 5.8 GHz, and it has the bandwidths for $|S_{11}| < -10\,\text{dB}$ and 3 dB gain-drop up to 25.6% and 27.6%, respectively. Moreover, its impedance bandwidth and gain bandwidth are in good overlap that results in a wide effective bandwidth of 25.6%, which is the largest effective bandwidth achieved for the grid antenna to the best knowledge of the authors. The merits of simultaneously high gain and wide bandwidth make this antenna a good candidate for various applications.

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