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DOUBLE-LAYER RADIAL LINE HELICAL ARRAY ANTENNA WITH RECTANGULAR APERTURE

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Abstract—A double-layer radial line helical array antenna with rectangular aperture is proposed. With rectangular aperture, the antenna can be assembled to form high gain antennas. The use of double-layer feed system ensures an equal-amplitude in-phase feed for all elements in an expected frequency band, which can improve antenna gain and aperture efficiency. This paper presents its design concept, derives pertinent design and performance, and a 16-element array antenna is simulated and measured. The experimental results show that in the range of 3.8 GHz to 4.2 GHz, the antenna gain is over 17.7 dB, aperture efficiency over 82%, antenna sidelobe level below −12.0 dB, antenna axial ratio below 3.2 dB, and antenna VSWR below 1.52.

1. INTRODUCTION

In recent years, antenna design for high power microwave (HPM) application becomes an issue. Many techniques have been invented to satisfy the special requirement of HPM, among which, the most representative ones involve mode conversion techniques [1–4], Vlasov antennas [5] and COBRA antenna [6]. These antennas are suitable for certain applications, but they have more or less some disadvantages. To further satisfy the requirement, a novel HPM antenna called high-power radial line helical array antenna is proposed and analyzed [7, 8]. This antenna arranges helical antennas to form a circular array, and it is proved to have a high efficiency, a compact structure, and a notable power-handling capacity. However, due to the limited coupling ability of the probes and the asymmetric energy distribution in the radial waveguide, it is difficult to obtain an expected coupling coefficient for

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each element of a big array. Consequently, the antenna with more radiation elements can not be designed correctly; it is therefore difficult to realize high gain radiation with a circular array.

An effective way to form high-gain arrays is the combination of multiple sub-arrays. The sub-array involved in the combination must be composable, which at least means no space exists among arrays after combination. It is evident that the circular array can not satisfy this requirement, and the simplest feasible structure is rectangular aperture array.

As seen from current research, there have already been many papers working on radial line helical array antenna [9–12], but the rectangular radial line array antenna is rarely reported. For this reason, the authors have investigated a single-layer rectangular radial line helical array antenna [13]. However, the disadvantage of the single-layer feed system is that it can not realize an equal-amplitude output in an expected frequency band, which reduces the antenna gain and aperture efficiency. To overcome this problem, this paper investigates a double-layer radial line helical array antenna with rectangular aperture. The use of double-layer feed system ensures an equal-amplitude in-phase feed for all elements in an expected frequency band, which can improve the antenna gain and aperture efficiency.

2. DESIGN CONCEPT AND BASIC STRUCTURE

The proposed antenna is a double-layer 16-element array antenna with rectangular aperture, as shown in Figure 1. It consists of 16 radiation elements and a double-layer feed system. The radiation elements are

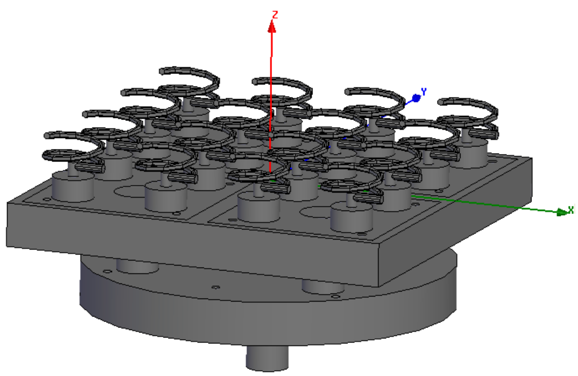

Figure 1. The structure of the proposed array antenna.

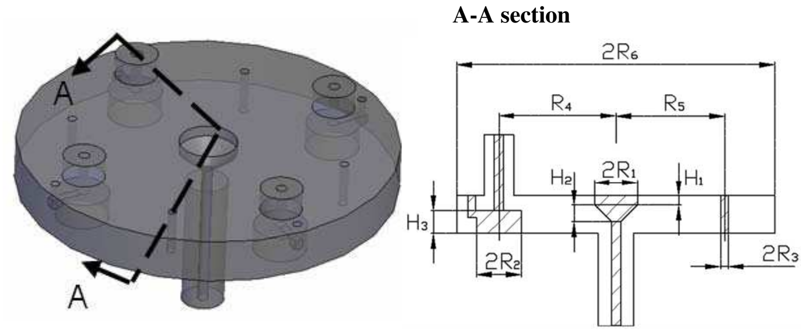

Figure 2. 1 : 4 circular power divider.

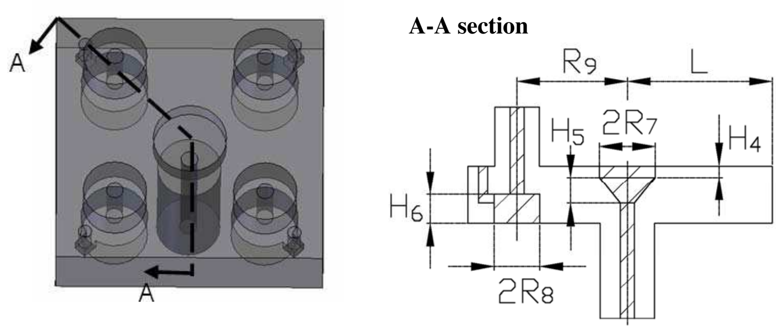

Figure 3. 1 : 4 rectangular power divider.

low-profile helical antennas which radiate circularly polarized (CP) microwave, and the double-layer feed system is composed of one 1 : 4 circular power divider and four 1 : 4 rectangular power dividers, as shown in Figures 2 and 3 respectively. The input waveguide is a coaxial waveguide, and it is excited by the coaxial TEM mode; the input microwave is divided to 16 identical parts by the double-layer feed system; each radiation element is connected with one output port of the feed system and excited by the divided microwave. Helices are arranged to form a 4×4 square array to realize directional CP radiation. The distance between two elements of the same row or same column as well as the distance from the center to the outer edge of the rectangular power divider is the same. Therefore, a number of proposed arrays can be placed together to form a high-gain equal-spacing rectangular grid array antenna, as shown in Figure 4.

Three remarks can be noted for this structure:

(1) The proposed array antenna satisfies the requirement of rectangular aperture, which makes it possible to form high-gain arrays.

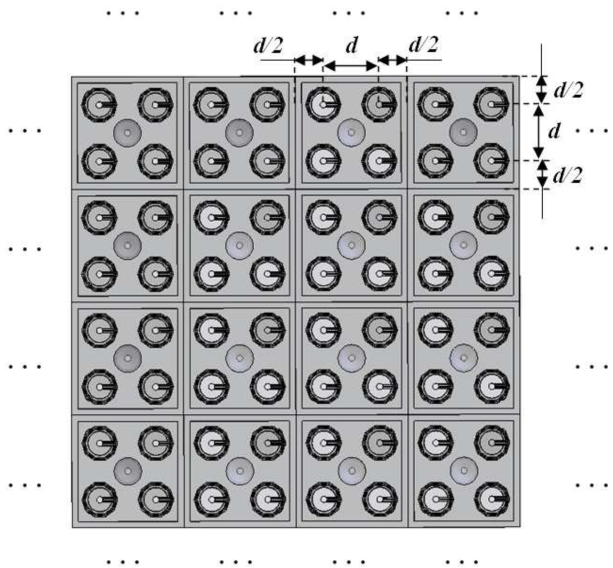

Figure 4. Combination of multiple arrays.

(2) The use of double-layer feed system makes all feeding passages exactly identical in structure. Therefore, the excitation amplitudes of the elements should be also identical in theory. This characteristic is useful to improving the antenna gain and aperture efficiency.

(3) The whole structure is constituted entirely by metal materials, which increases the power handling capacity of the antenna. The proposed structure also permits us to realize the vacuum condition in the antenna, which can greatly improve its power-handling capacity and make it suitable for high power applications.

3. DESIGN OF THE ANTENNA

The operating frequency is chosen to be 4.0 GHz (the free-space wavelength $\lambda = 75\,\mathrm{mm}$). The radiation element used in this antenna is the same as in [7]. Knowing the mutual coupling between the elements is important for constructing an array antenna. Figure 5 shows the location of two identical helices. The interaction is expressed by the S-parameter S_{21} when helix 1 is excited and helix 2 connected to conjugated matched-load impedance. Figure 5 shows the simulated result when $d = 0.6\lambda = 45\,\mathrm{mm}$. It can be seen that the level of the interaction is less than $-25\,\mathrm{dB}$ in the range of 3.7–4.3 GHz, which is relatively low for array construction. So the spacing between elements is chosen to be $d = 45\,\mathrm{mm}$.

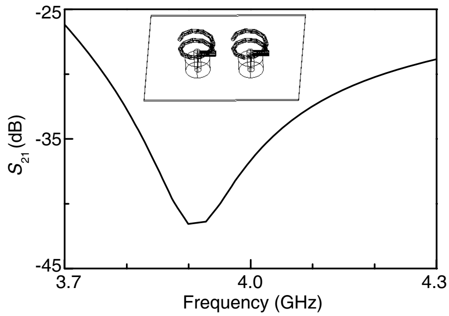

Figure 5. Mutual coupling between the elements.

Table 1. Optimization information of the input converter (Unit: mm).

Optimization parameters	R_1	$10 \sim 15$
	H_1	$0 \sim 10$
	H_2	$0 \sim 10$
Concerned performances	S-parameter S_{11} (4.0 GHz, 3.8 GHz, 4.2 GHz)	
Run-time	2 minutes for each set of parameters	

The 1 : 4 circular power divider and 1 : 4 rectangular power divider can be designed separately, and then connected to form the double-layer feed system. In order to facilitate the connection, the output ports of the circular power divider have a radius of $\sqrt{2} \times 0.6\lambda = 63.6$ mm. Consequently, the output port of the circular power divider can be connected with the input port of the rectangular power divider by a single straight waveguide.

The design of the power dividers is quite complicated, and a commercial FEM code is used for the design and optimization. The design procedure can be summarized as follows: first, the input converters are optimized to ensure the good conversion between the input coaxial waveguide to the radial waveguide; second, the coupling probes as well as matching posts are designed to obtain a favorable coupling performance and a small reflected performance; third, the inner edges of the power dividers are optimized to form the cavities and finalize the power divider design; also, the location of the inner edge may influence the coupling performance of the probes, and slight modifications of the probes may be needed.

Take the input converter of the circular power divider for example, its optimization information can be summarized in Table 1. Calculations are carried out for each set of parameters using the

Table 2. Dimensions of the structure (Unit: mm).

R_1	R_2	R_3	R_4	R_5	R_6	R_5	R_7	R_8	R_9
13.0	12.0	2.0	63.6	62.0	85.0	62.0	11.0	10.0	31.8
H_1	H_2	H_3	H_4	H_5	H_6	L			
5.0	9.0	12.0	6.0	8.1	12.5	40.0			

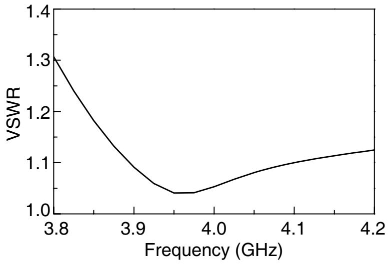

Figure 6. Simulated VSWR of the feed system.

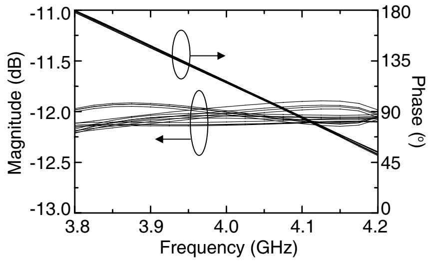

Figure 7. Simulated magnitude and phase for each output port.

parametric analysis function of the software and the results are compared to select a favorable combination. Table 2 specifies the principal dimensions of the structure. It should be noted that the distance $L = 40$ mm, so a distance of 5 mm can be left for the thickness of the metallic plates.

Figure 6 shows the simulated VSWR of the feed system. Figure 7 shows the simulated magnitude and phase for each output port of the feed system. The VSWR of the feed system is less than 1.3 in the range of 3.8–4.2 GHz, the simulated magnitude and phase for each output port of the feed system is almost the same, which coincide well with the theory.

The field distribution of the feed system is also calculated and shown in Figure 8. It can be seen that the maximum electric field is approximately 3000 V/m when the input power is 1 W. If we maintain the vacuum state in the power divider, and assume the breakdown threshold to be 50 MV/m under vacuum condition, the power-handling capacity for this feed system could reach 270 MW, which is suitable for high power application.

4. SIMULATED AND MEASURED RESULTS

An antenna model is accomplished by using the double-layer feed system to feed the radiation elements. The size of the antenna is

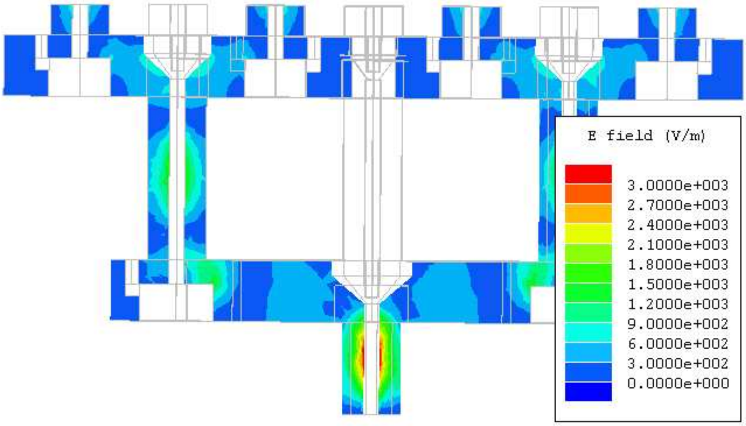

Figure 8. Field distribution of the feed system.

Figure 9. Photograph of the antenna.

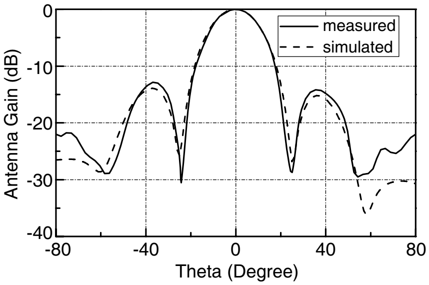

Figure 10. Simulated and measured antenna gain pattern at 4.0 GHz.

exactly $2.4\lambda \times 2.4\lambda$. The antenna is finalized and fabricated. Figure 9 shows a photograph of the antenna.

This antenna is simulated and measured to verify the above design concept. The simulation is carried out by the TEM code and the experiment is carried out in a microwave dark room of size $22 \times 15 \times 8\,\mathrm{m}^3$. As this antenna radiates a circularly polarized electric field, the measurement is carried out by the standard LP antenna comparison method [14]. The antenna gain can be obtained by the

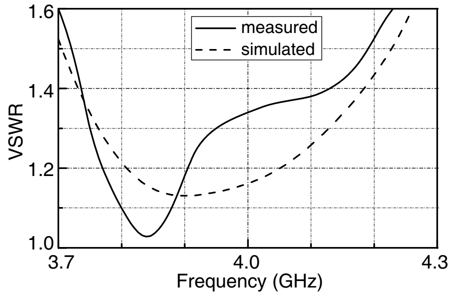

Figure 11. Simulated and measured VSWR of the antenna.

following formula:

$$G = 3 + 20 \log \left[\frac{1}{2} \left(1 + 10^{-\frac{r}{10}} \right) \right] + G_m \tag{1}$$

where G_m is the gain of the major axis and r the axial ratio.

Figure 10 shows the simulated and measured antenna gain patterns at 4.0 GHz in $\varphi = 0°$ plane. Figure 11 shows the simulated and measured VSWRs of the antenna. Table 3 summarizes the simulated and measured characteristics of the antenna at some important frequencies. The measured results show that in the range of 3.8–4.2 GHz, the antenna gain is over 17.7 dB, aperture efficiency over 82%, antenna sidelobe level below −12.0 dB, antenna axial ratio below 3.2 dB, and antenna VSWR below 1.52. It is clear that the antenna gain and aperture efficiency are improved compared to the single-layer array [13].

The measured results prove the feasibility of this antenna. However, the measured results are worse than the simulated ones, especially at high frequencies. These differences could be explained by the following two factors. First, machining and assembling could change the sizes of both the feed system and the radiation elements, these changes lead to the errors of magnitude and phase for each output port of the feed system as well as the performances of the radiation elements. Further experiment on single radiation element indicates that the VSWR and the radiation performance of the helix are actually worse than the simulated results, especially at high frequencies. Second, the junctures in the experiment increases the antenna's insertion loss, and the actual metallic material also has an ohmic loss, which does not exist in the simulation. Also, both the simulated and measured VSWRs of the antenna are worse than that of the feed system though comparing Figures 11 with 6. This fact is mainly caused by two reasons. First, because all of the 16

Table 3. Simulated and measured characteristics of the antenna (former: simulated results, latter: measured results).

Frequency/GHz	3.8	4.0	4.2
Gain/dB	18.1/17.7	18.6/18.2	19.0/18.2
Aperture efficiency	90.2%	91.3%	82.8%
Sidelobe/dB	−14.2/−12.5	−13.9/−12.8	−12.2/−12.0
Axial ratio/dB	2.4/2.7	2.7/2.9	2.9/3.2

radiation elements have identical feeding passages and structures, their reflectance must have the same phase at the input port. This leads to the in-phase superposition of the helical antenna's reflectance. Second, as indicated above, the VSWR of the single helix is not very low at high frequencies, which furthermore worsen antenna VSWR value.

5. CONCLUSION

In this paper, a double-layer radial line helical array antenna with rectangular aperture is proposed and designed. An antenna prototype is fabricated and measured. The measured results prove that its antenna gain and aperture efficiency are better than those of the single-layer array. This antenna can be simply assembled to form high gain antennas. However, some performances of the antenna such as the VSWR and axial ratio are poor, which should be improved in later research.

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