A RECTENNA ARRAY MOUNTED ON A CYLINDRICAL CONDUCTOR FOR WIRELESS POWER RECEPTION

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1. Introduction

Wireless power transmission is a very useful technology in the area of high-altitude radio relay systems [1], space energy transmission such as solar power satellites [2,3] and robot applications [4]. The authors have developed a rectenna array mounted on a cylindrical conductor. It exhibits no degradation in efficiency with the variations of the incident angle in the cylinder radius plane, and it can easily hold cylindrical equipment, such as a cylindrical multi-joint robot to maintain or fabricate a space platform.

Two output power degradation factors for a cylindrical rectenna array are considered in comparison with a conventional planar rectenna array. The first is total input power reduction due to the difference in its shape. The other is caused by the parallel connection of output terminal rectenna elements with output power differences [5,6]. In this paper, we investigate both problems quantitatively and show an output power improvement method for the latter case. Also, we will offer a guide for constructing a cylindrical rectenna array.

2. Rectenna elements

To reduce the size of the wireless power transmission system, we used the higher frequency C band (5.8 GHz) rather than the conventional S band (2.45 GHz). Figure 1 shows the construction of the proposed rectenna array. At the side of the cylinder, rectenna elements that consist of a circular microstrip antenna (CMSA) [7] and rectifying circuit are attached [8]. The radius of the cylinder and the CMSA are a and b, and the polarization of the CMSA is fixed to ϕ direction linear polarization.

Next, figure 2 shows the configuration of a rectenna element [8]. The incident microwave is received by the CMSA and led to the rectifying circuit by a feed pin. An input filter, a diode and an output filter are mounted on the rectifying circuit. A low pass filter is used for the input filter and a GaAs Schottky diode (MA46135-32) is used for the rectifying diode.

The far field radiation pattern and gain of the CMSA on the cylinder can be calculated by reference [9]. The theoretical and experimental values of the front gain are 7.7 dBi and 8.0 dBi, respectively, when the radius of the cylinder is 71 mm. This difference is mainly because we approximated the cylinder into a regular nonagon pole to make it easier to fabricate the antenna for our experiment. Also, the calculated front gain remains almost constant as the cylinder radius increases.

Figure 3 shows the efficiency of the rectifying circuit as a function of incident power. The maximum efficiency and optimum load resistance are 73% and 200 Ω, respectively. The maximum efficiency is varied from 69% to 77% by changing the diode, and the diode that exhibits the median value of efficiency is indicated in figure 3. Also, the optimum load resistance is varied from 100 to 300 Ω. The result of figure 3 is used in the next section as a typical value for rectenna characteristics, in spite of the variations of the diodes.

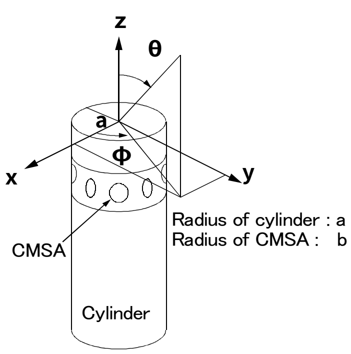

Figure 1 A rectenna array on a conducting cylinder

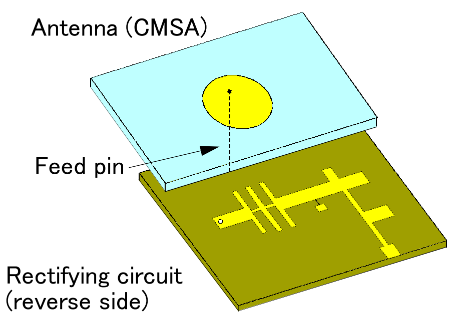

Figure 2 Configuration of the rectenna element

3. Cylindrical rectenna array

The output power pattern of a cylindrical rectenna array is estimated with the following procedure. (1) The incident rf power pattern of a rectenna element is calculated from the theoretical value of front gain and the assumed value of input power flux density (P_{fd}). (2) The output power pattern of each rectenna element is calculated from the result of (1) and the incident power versus efficiency characteristics (Fig. 3). (3) Repeat procedures (1) and (2) for the number of elements to get the output power sum of the rectenna array. Hereafter, we will call this value the "estimated value".

Also, when constructing a rectenna array, we assume that the inter-element spacing will be fixed at 0.91 λ (71 mm), which is the minimum possible value for fabrication. So, the number of elements and the cylinder radius will be changed simultaneously.

Next, we compared the input or output power of a cylindrical rectenna (P_c) with that of a planar rectenna (P_p) with the same projection area. We defined the power ratio (r) as follows;

$$r = \frac{P_c}{P_P} \quad (1)$$

Figure 4 denotes the estimated value of the power ratio (r) for the input or output power versus the number of elements for three different input P_{fd} values in the θ =90° plane. The power ratio of the input power becomes a constant value of 87% when there are more than nine elements. The power ratio of the output power varies depending on the P_{fd} value and becomes 72% when P_{fd} equals 2.1 kW/m^2 with nine elements. The minimum number of elements to get a constant power ratio (r) is nine. We thus conducted experiments on a cylindrical rectenna array with nine elements.

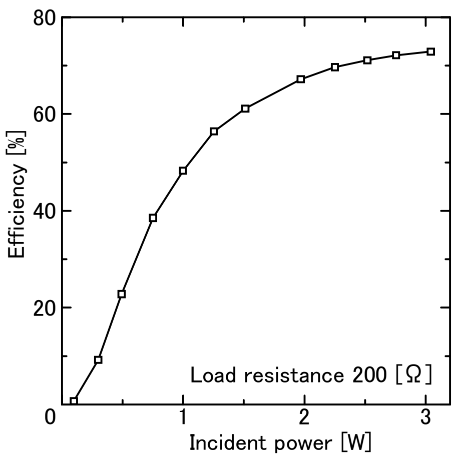

Figure 3 Incident power versus efficiency for the rectifying circuit

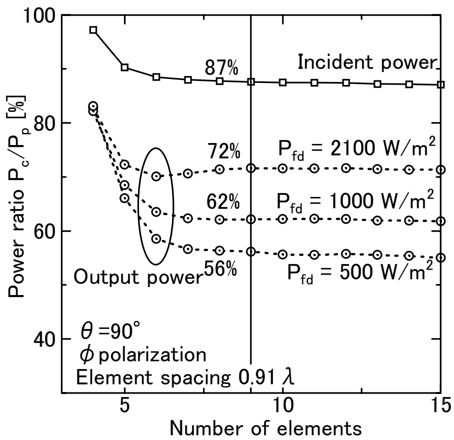

Figure 4 Estimated value of output power versus number of elements

4. Microwave power transmission experiment

The directivity of the nine-element cylindrical rectenna array was measured by using the microwave power transmission setup shown in figure 5. A 5.8-GHz microwave signal sent from a transmitting antenna was received by the rectenna at the distance of 0.6 m. An open-ended waveguide was used to measure the input P_{fd} value and it was positioned at the same place where the rectenna array will be mounted. The input P_{fd} is 2.1 kW/m^2 when the input power of the rectenna element is 3 W. The rectenna elements were terminated by their own optimum load resistance and this load connection case is called the "individual load" hereafter. The output power of the rectenna array is defined as the numerical sum of each rectenna's output power.

Figure 6 shows the experimental output power pattern of each rectenna element and the total rectenna array in the θ =90° plane. The total output power varies due to variations in the characteristics of the diodes. The estimated value and experimental result of the average output power of a cylindrical rectenna array in the θ =90° plane are 3.7 W and 3.2 W, respectively.

Three reasons can be considered for this

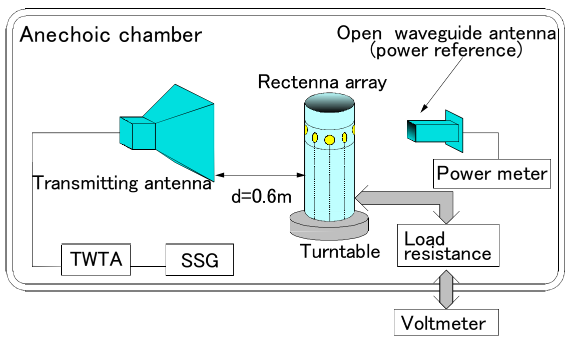

Figure 5 Experimental setup for microwave power transmission

difference. The first is the difference in the antenna gain between the theoretical and experimental value as mentioned before. The second is variations in the characteristics of the diodes. And the third reason is the amplitude distribution of the transmitting antenna projected on the cylindrical rectenna array.

Next, the dotted line in figure 6 illustrates the output power pattern when all of the cylindrical rectenna elements are connected in parallel. The optimum load resistance values of the rectenna elements are paralleled to obtain a parallel connection. This time its value was around 19 Ω. The angular average output power of the totally paralleled rectenna array is 1.9 W, which is 1.3W (41 %) lower than that for the individual load case. This is mainly because the totally parallel load case connected not only the front direction elements that provide high output power, but also connected the side and back direction elements that generate very low output power.

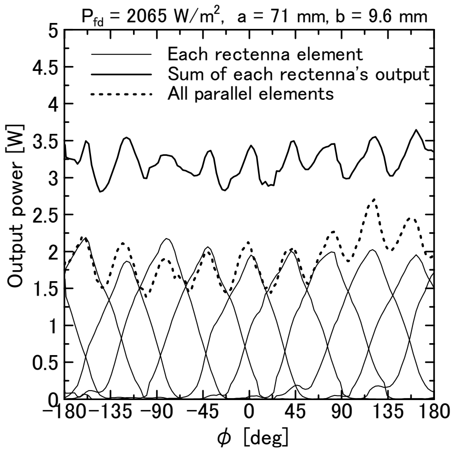

Figure 6 Output power pattern of rectenna array with 9 elements (θ =90°)

5. Output power improvement method

In this section, we tried to connect in parallel only the high output power rectenna elements to increase the output power from the totally paralleled case. The output characteristics that resulted from connecting two rectennas with different input power values was recently reported in reference [6], and we will introduce this method by expanding it for an arbitrary number of elements on a cylindrical rectenna array. The procedure is as follows. The input power pattern of the rectifying circuit is defined by a numerical approximation of the antenna pattern of one element. Next, the load characteristics (current as a function of voltage characteristics) of each element at this input power are measured and the currents are approximated by cubic function of the voltage using the least square method. A Kirchhoff's current equation can be applied at the connection point of the output terminals of paralleled rectenna elements and load resistance, and its equation becomes a cubic equation on common voltage [6]. The paralleled output power can be simulated to solve its voltage.

Figure 7 shows the experimental and simulated values of the output power pattern when two elements with higher output power are selectively connected in parallel. In the experiment, the average output power is 2.9 W, and the increment in output power is 1.0W (53 %) compared to the totally paralleled case. Also, the output power degradation remained at 0.3W (10.4 %) in comparison with the individual load case. Good agreement is observed between the simulation and experimental results, which confirms the validity of this method.

Figure 8 shows the experimental and simulated values of average output power versus the paralleled element number. These rectenna elements are also connected selectively with higher output power. The maximum difference between the simulation result and the experimental value is about 0.2W, and fairly good agreement between these two data is observed. The output power in the case of two or three paralleled elements is higher than that of more than four paralleled elements. So, for a cylindrical rectenna array with nine elements, the case of two or three parallel elements becomes

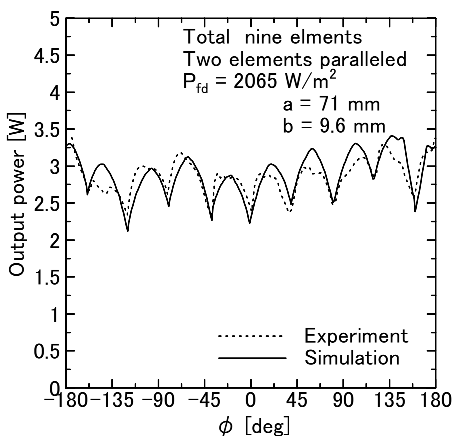

Figure 7 Output power pattern of two-element paralleled rectenna array (θ =90°)

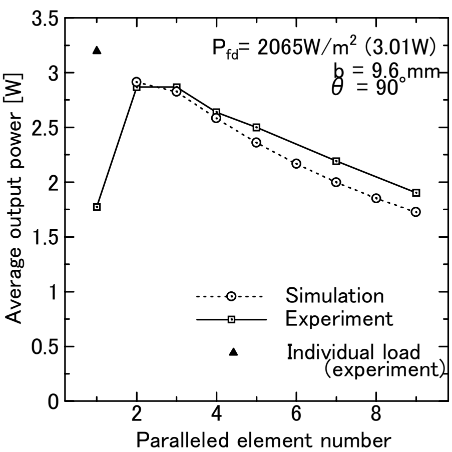

Figure 8 Experimental and simulated value of average output power versus paralleled element number

the optimum connection number.

In the optimum paralleled connection case, a 10.4% degradation of output power is observed and the power ratio between the cylindrical rectenna array and a planar array is 72% maximum, so a total output power ratio of 64% is possible compared to the planar rectenna array including the power degradation by parallel connection.

We investigated to determine whether a change in the optimum number of paralleled elements is simulated by an increase in the total number of cylindrical rectenna elements. The number of paralleled elements (*N*) versus output power as a parameter of the total element number (*M*) is indicated in figure 9. The total number of elements is changed from 5 to 30 in steps of one element, and captions are added at the point of each five elements in figure 8. In this case, to simplify the situation, the antenna pattern is fixed at the experimental value of nine elements without depending on the cylinder radius. Variations in the current versus voltage characteristics of the nine elements, which are observed in the experiment, are included. The maximum output power case is indicated by the black squares in figure 9 for each *M*. The paralleled element number (*N*) is limited from *0.2M* to *0.4M*, so when fabricating the cylindrical rectenna array, choosing a number of paralleled elements between *0.2M* and *0.4M* can maximize the output power.

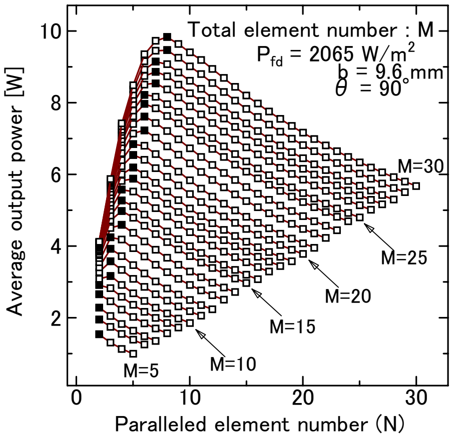

Figure 9 Average output power versus paralleled element number

6. Summary

Assuming wireless power transmission toward a multi-joint robot for a space platform, we developed a rectenna array mounted on a cylindrical conductor. The maximum output power ratio between a planar rectenna array and the proposed cylindrical rectenna array with an individual load was calculated to be 72% for a rectenna array with nine elements.

The output power degradation in a cylindrical rectenna array with nine elements due to the parallel connection of elements was also observed and an output power improvement method connecting only two or three elements in parallel was proposed. An output power improvement of 53 % was observed in comparison with the totally paralleled load case, while a 10.4 % degradation was detected in contrast to the individual load case. We thus found that the total available power ratio was 64 % compared to a planar rectenna array. This value is still effective for practical use.

Furthermore, the output power characteristics of a rectenna array with *M*-elements mounted on a cylindrical conductor were simulated and the maximum power could be observed when between *0.2M* and *0.4M* elements were connected in parallel. This result offers a guide for constructing a cylindrical rectenna array.

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