Experimental Study of Large Rectenna Array for Microwave Energy Transmission

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***Abstract*—For a field experiment on microwave power transmission (MPT) which was jointly conducted by the Radio Atmospheric Science Center of Kyoto University, Kobe University, and Kansai Electric Power Company from 1994 to 1995, we had developed and tested a new type of rectenna (rectifying antenna) based on a circular microstrip antenna (CMA). A square shape of array with an area of 3.2 m $\times$ 3.6 m was then constructed using the developed rectennas for experiment. The whole rectenna array is composed of 256 sub-arrays, each with nine rectenna elements. We place the rectenna sub-array with better RF–dc conversion efficiency in the central area of the whole rectenna array. Such spatial optimization is needed because the power density of the microwave beam used in the experiment has a spatial gradient with a peak at the center of the beam. We then examined dependence of the rectenna array characteristics on the electrical connection of the sub-arrays. The difference of the output dc power of the whole array for five different electrical connections is within 5%. The load characteristics, therefore, suffers little change even if the electrical connection of the rectenna sub-array is changed.**

***Index Terms*—Microwave power transmission, rectenna array, solar power station.**

I. INTRODUCTION

MICROWAVE power transmission (MPT) is a key technology necessary for the future solar power satellites (SPS's) [1]. The SPS is a giant power (5-GW) station to be placed on the geostationary orbit. The electrical power will be generated by solar cells in space and transmitted by microwaves of 2.45 GHz from the SPS to a rectenna site on the ground.

The word "rectenna" was first used by Brown [2], and means "rectifying antenna." In other words, the rectenna is a microwave receiver and a converter of microwaves into dc power in the MPT system. It consists of an antenna, an input filter, and a rectifying circuit with an output filter.

The first ground-to-ground MPT experiment was carried out by the Jet Propulsion Laboratory (JPL) and Raytheon in the United States in 1975 [3], [4]. In this experiment, electrical power was transferred by a microwave beam with a frequency of 2.45 GHz over a distance of 1.6 km. The dc output power from a 26.8-m^2 rectenna was 30 kW. Dipole-type antennas were used for the rectenna. The dc output from individual rectenna elements was connected electrically in parallel. The ratio of the dc output to the incident microwave power was 0.84. The overall dc-to-dc efficiency was 54%, which was certified by representatives from the JPL's Quality Assurance Organization.

From 1994 to 1995, a ground-to-ground MPT experiment was carried out in Yamasaki, Japan, by a joint team from the Radio Atmospheric Science Center (RASC) of Kyoto University, Kobe University, and Kansai Electric Power Company [5]. Kobe University developed a microwave power transmitter and Kyoto University developed a new rectenna array for the Yamasaki field experiment. In the Yamasaki MPT experiment, we used a microwave with a frequency of 2.45 GHz. The microwave on the transmitter side was generated by a magnetron of 5 kW and was radiated from a parabolic antenna with a diameter of 3 m.

II. RECTENNA USED IN THE YAMASAKI FIELD EXPERIMENT

We developed a new rectenna element for the field experiment. For the antenna part in the rectenna, we chose a circular microstrip antenna (CMA) which is electromagnetically coupled with the rectifying circuit through a slit. A bridged rectifier with 16 diodes was adopted for the rectifying circuit. The rectenna has a triple-layer structure consisting of 1) an "antenna" layer; 2) a "slit and ground" layer; and 3) a "filter and rectifying circuit" layer. Fig. 1 shows a see-through view of the rectenna element. Between each layer, we insert a glass–cross–Teflon dielectric base with a dielectric constant of 2.6 and thickness of 0.8 mm. The return loss of the CMA was −30.1 dB at the frequency of 2.45 GHz. The input filter is composed of a band-stop filter and two open stabs. The loss of the input filter is 0.2 dB at a frequency of 2.45 GHz. The losses at frequencies of second, third, and fourth harmonics are 30.8, 38.6, and 9.97 dB, respectively. The microwaves are rectified by 16 silicon Schottky-barrier chip diodes [NEC, 1SS281 (1)]. Between the input filter and the rectifying circuit, an open stab is inserted for impedance matching.

Fig. 2 shows the RF–dc conversion efficiency of the bridge rectifier including the input filter as a function of the input microwave power. The connected load is 500 Ω. A peak RF–dc efficiency of 64% is achieved at the input RF power of 2–4 W. The lower efficiency compared to the rectenna used in the JPL's experiment is mainly due to the usage of 16 diodes for the rectifying circuit. For the Yamasaki field experiment, we needed a rectenna which could receive and rectify 2.5 W of a microwave power that is determined by the transmitting

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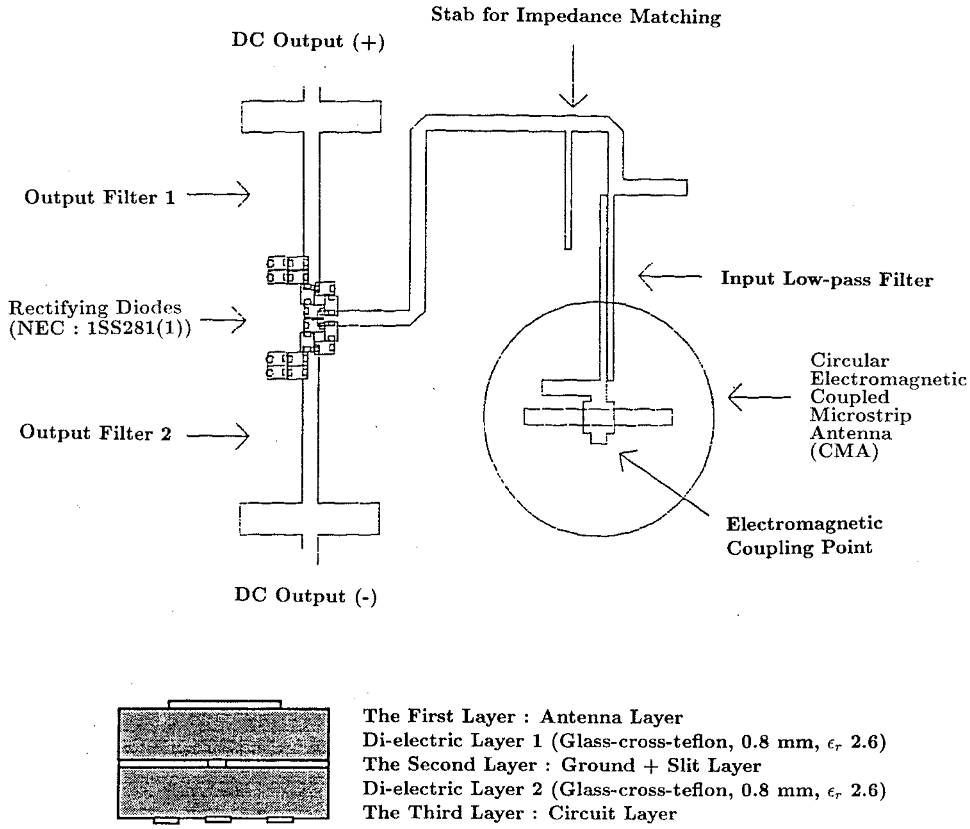

Fig. 1. Rectenna element used in this experiment (see-through illustration for triple-layer structure).

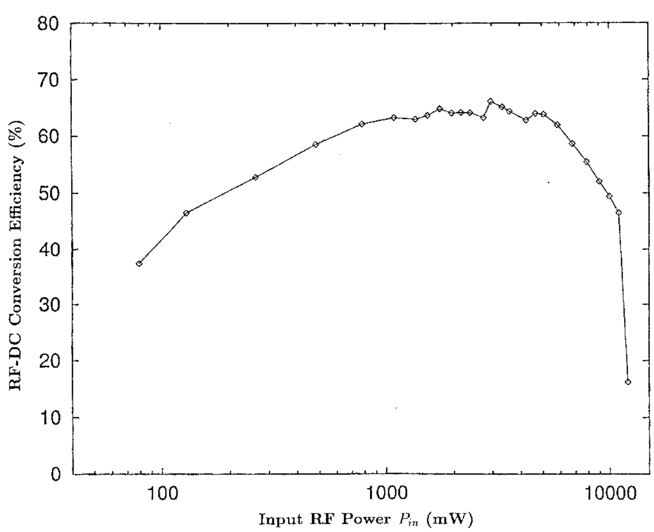

Fig. 2. RF–dc conversion efficiency of the rectifying circuit in a single rectenna element as a function of input microwave power.

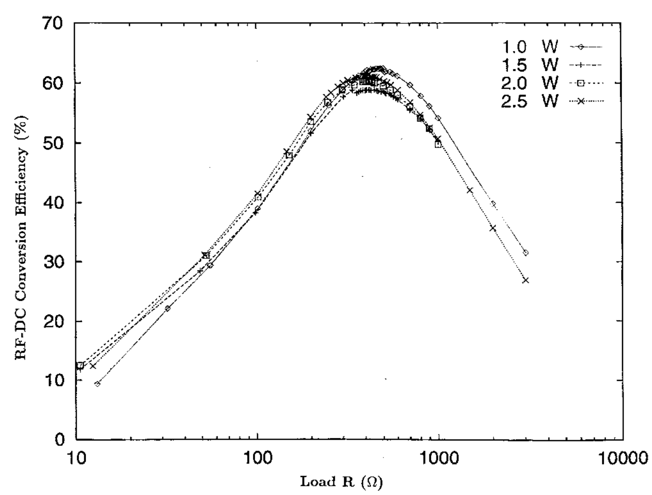

Fig. 3. RF–dc conversion efficiency of the rectifying circuit in a single rectenna element as a function of rectenna load.

power, the diameter of the transmitting antenna, and transmitter–receiver distance. However, a receiving system using only one diode such as used in the JPL experiment could not rectify such a high power of 2.5/diode. Therefore, we developed a new rectenna which can receive and rectify 2.5 W of microwave power, which inevitably decreased.

Fig. 3 illustrates the load dependence of the RF–dc conversion efficiency. Four lines are for different levels of the input RF power. The optimum load which gives the peak of the RF–dc conversion efficiency is between 300 and 500 Ω for all four input RF levels.

III. Experimental Studies of Rectenna Array

A. Rectenna Array Used in the Yamasaki Field Experiment

In the field experiment, we adopted a sub-array system for the rectenna array. Each sub-array consists of nine rectennas connected electrically in parallel. Spacing between the rectennas in the sub-array is 0.5λ. The rectenna array contains 16 ×

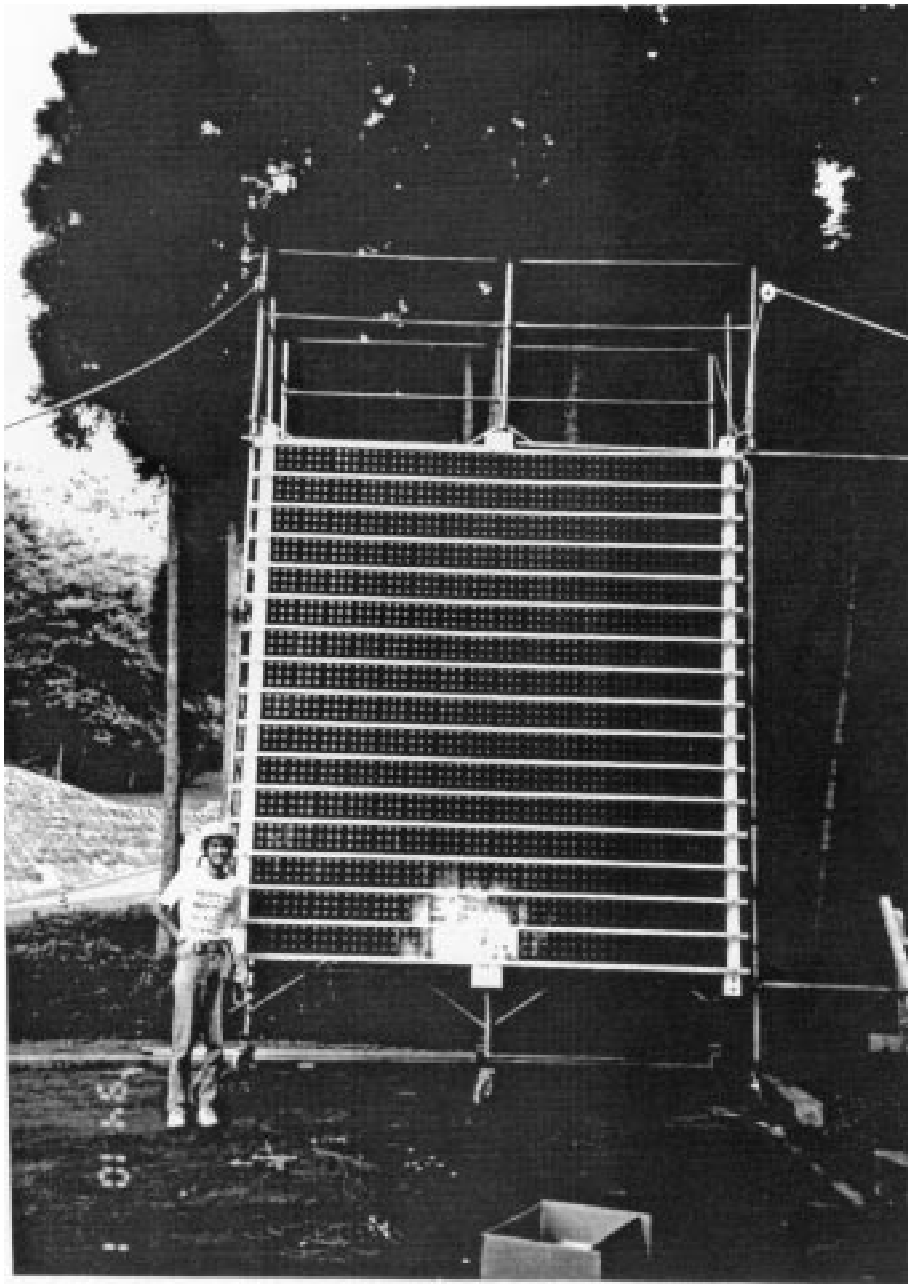

Fig. 4. The rectenna array used in the field experiment. The size is 3.2 m × 3.6 m.

16 = 256 sub-arrays, thus providing the total number of the rectenna elements of 256 × 9 = 2304. The size of the rectenna array is 3.2 m × 3.6 m (see Fig. 4). Such a sub-array system provides a flexibility of their mutual electrical connection. We tested five electrical connections of the sub-arrays (Table I).

It is also possible to change the location of the individual rectenna sub-array in the rectenna array. We set up the following two arrangements of the rectenna array in the field experiment. We call one setup an "arranged rectenna array." The arranged array was constructed by placing "good" rectennas in the central area of the array. We sorted the sub-arrays in an order of the higher RF–dc conversion efficiency based on the individual measurement conducted in the laboratory in advance of the field experiment, and selected the "good" sub-arrays. This is because the power density of the transmitted microwave beam is not a uniform, but is higher in the central area of the rectenna array. Fig. 5 indicates microwave power distribution on the surface of the rectenna array when a parabolic antenna transmits the microwave power of 5 kW.

TABLE I
ELECTRICAL CONNECTION OF 256 RECTENNA SUB-ARRAYS

	Connection of Sub-array
(1)	128 Series and 2 Parallel
(2)	64 Series and 4 Parallel
(3)	32 Series and 8 Parallel
(4)	16 Series and 16 Parallel
(5)	8 Series and 32 Parallel

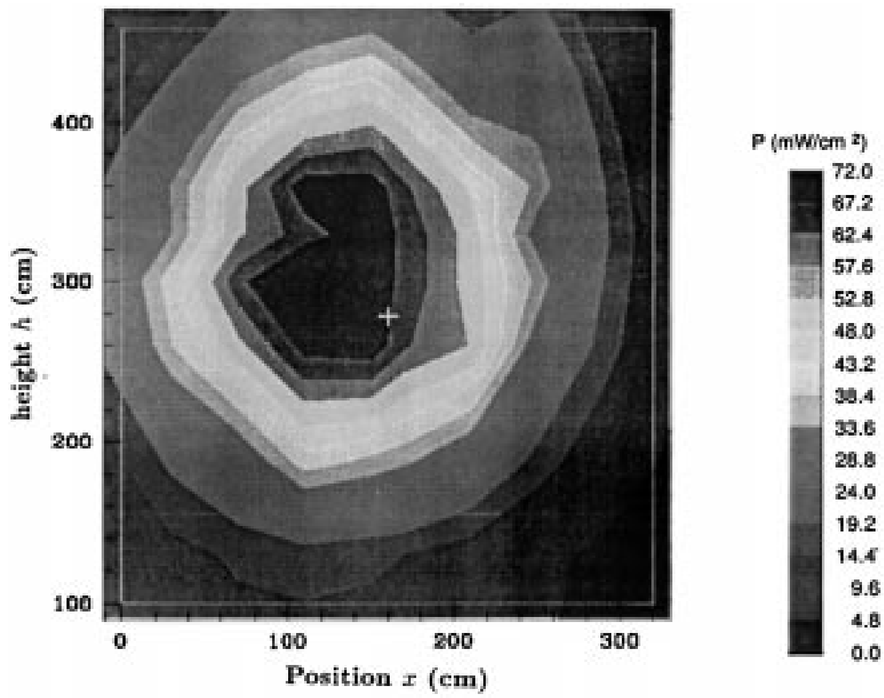

Fig. 5. Power distribution at the surface of rectenna array placed 42 m away from transmitting antenna.

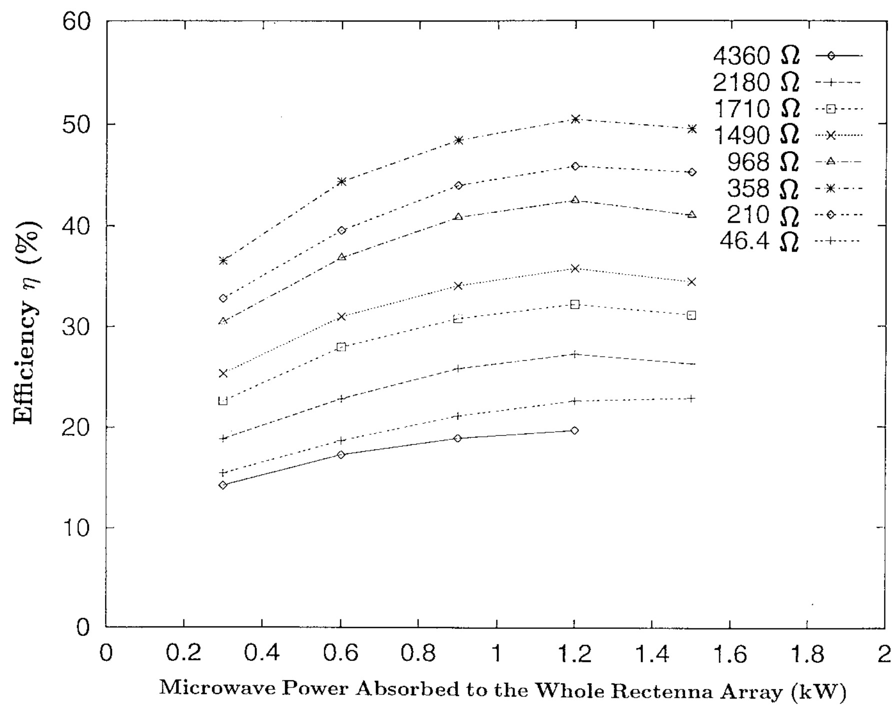

Fig. 6. RF–dc conversion efficiency of the rectenna array as a function of a microwave power absorbed to the whole rectenna array.

The other is a "randomly sampled rectenna array." We place the sub-array randomly in the rectenna array without paying any attention to their characteristics.

B. Results of the Experimental Studies

We define an RF–dc conversion efficiency η of the arranged rectenna array as follows:

$$\eta = \frac{\text{Output dc power}}{\text{Microwave power absorbed to the whole rectenna array}}. \quad (1)$$

We show the RF–dc conversion efficiency as a function of the absorbed microwave power in Fig. 6. Rectenna sub-arrays were electrically connected in a manner shown under #2 in Table I. A characteristic shown in Fig. 6 is similar to that of the rectenna element shown in Fig. 2. A difference of the RF–dc conversion efficiency between an element and the array is due to a power density gradient on a surface of the rectenna array shown in Fig. 5. Each rectenna element was not exposed in an optimum input power level.

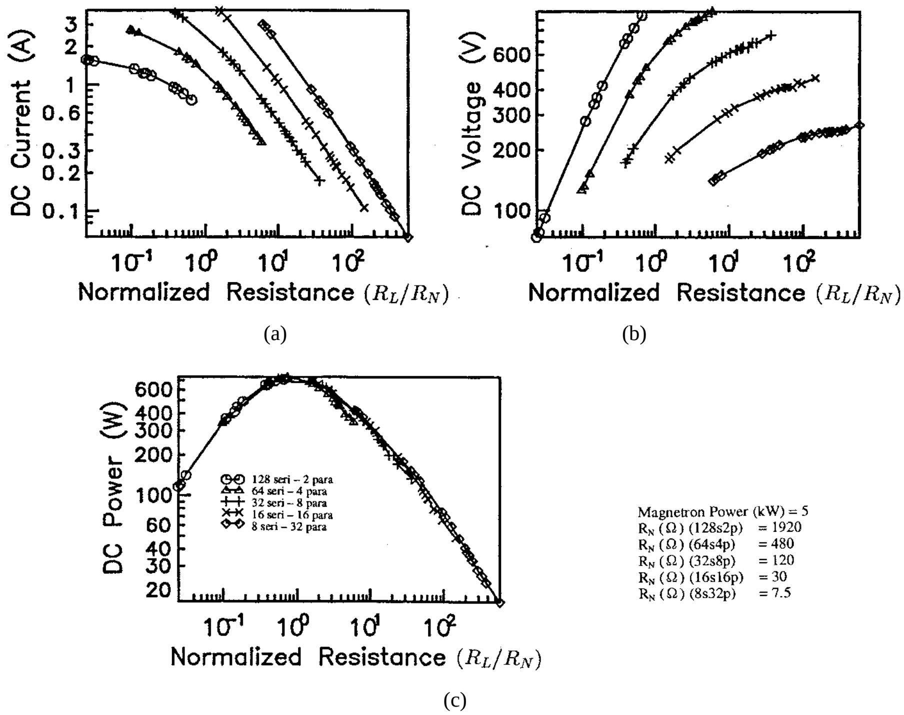

Fig. 7. Load dependence of the arranged rectenna array. (a) Output dc current. (b) Output dc voltage. (c) Output dc power.

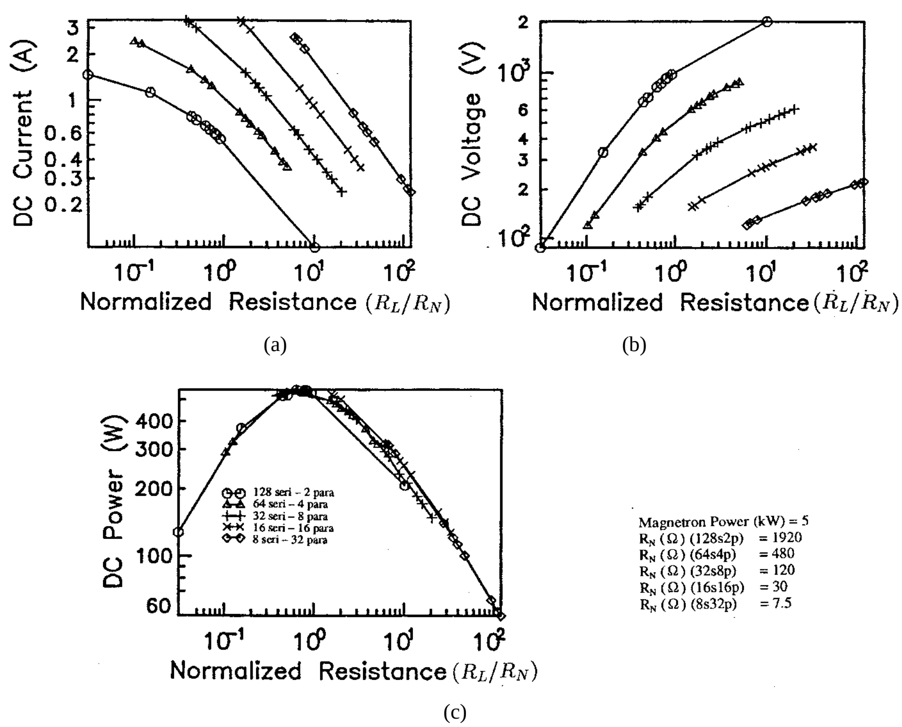

Fig. 8. Load dependence of the randomly sampled rectenna array. (a) Output dc current. (b) Output dc voltage. (c) Output dc power.

Fig. 7 shows a load dependence of the output dc power of the arranged rectenna array. Each figure corresponds to the output dc current, dc voltage, and output dc power of the rectenna array, respectively, as a function of the normalized resistance. Five symbols in each figure correspond to the results with five different electrical connections of the rectenna array shown in Table I. It is meaningless to compare the load dependence of the rectenna array with the absolute load impedance. It is because the optimum load resistance changes as the connection of sub-arrays is changed. Therefore, we introduce a relative load resistance called a normalized resistance.

Assuming a constant-voltage power supply and an internal impedance in a form of a simple equivalent circuit of the

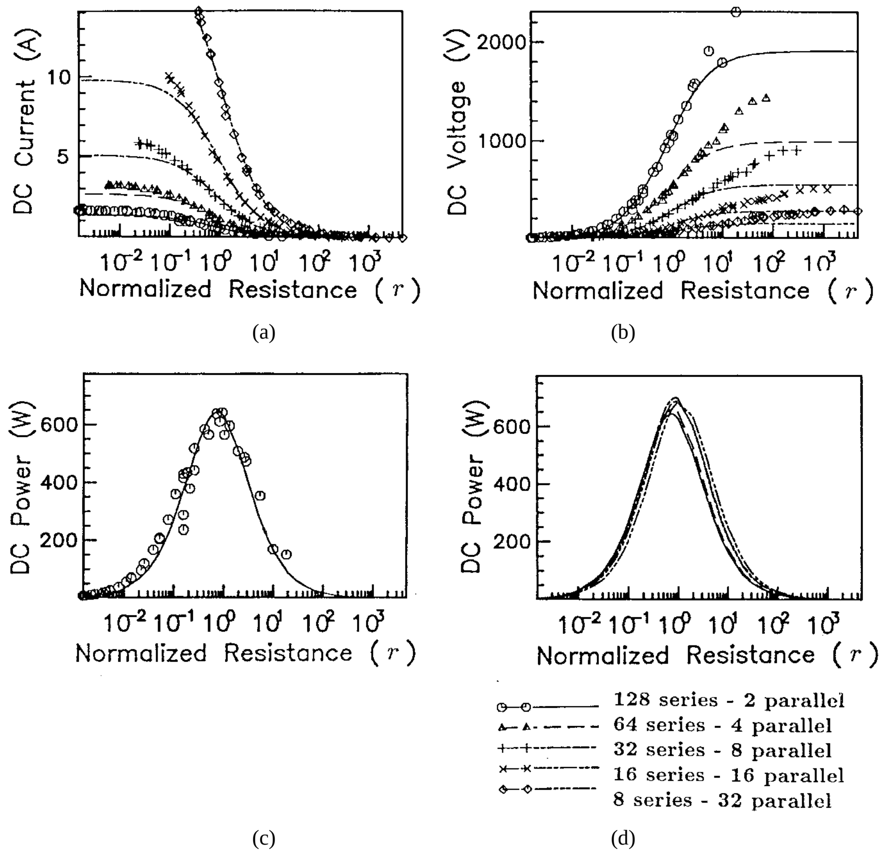

Fig. 9. Load dependence of the arranged rectenna array. (a) Output dc current. (b) Output dc voltage. (c) Output dc power. (d) Fitted curves of the output dc power.

rectenna, the optimum resistance can be calculated with the maximum power-transfer theorem. The optimum resistance gives a maximum RF–dc conversion efficiency. The optimum resistance is used as a reference for the normalized resistance of the rectenna array. For example, when we connect two rectennas in series, the added inner impedance of the rectenna array and the optimum resistance become twice as large as that of the rectenna element, respectively.

The data in Fig. 3 shows that the optimum load of a single rectenna is approximately 400 Ω. However, we chose the value of 270 Ω as a reference load for a single rectenna because of the availability of the resistors prepared in the field experiment. Therefore, the normalizing resistance of the rectenna sub-array is equal to 30 Ω because nine rectennas are connected in parallel on one sub-array. Similarly, we can calculate the following five normalizing resistances R_N corresponding to five connections shown in Table I.

1) $30 \times 8/2 \times 16 = 1920\ \Omega$.
2) $30 \times 8/2 \times 8/2 = 480\ \Omega$.
3) $30 \times 8/2 \times 4/4 = 120\ \Omega$.
4) $30 \times 8/2 \times 2/8 = 30\ \Omega$.
5) $30 \times 8/2/16 = 7.5\ \Omega$.

We used these five normalized resistances (R_L/R_N) to plot the load dependence of the dc current, dc voltage, and dc power in Fig. 7.

Fig. 8 shows the results for a randomly sampled (nonarranged) rectenna array. Comparing the results shown in Figs. 7 and 8, we can see the general trend of the load dependence are similar to each other for both arranged and nonarranged array cases. However, the maximum output dc power is 742 W for the arranged rectenna array, while that for the nonarranged rectenna array is only 541 W. The maximum output dc power is improved by 37% by arranging the rectenna sub-array configuration. The maximum output dc current is +21% improved, and the average dc current is also +13% improved. Likewise the output dc voltage is improved by 21% (maximum) and 14% (average). As a result, we could obtain the improvement by 46% in the maximum output dc power and 29% in the average dc power.

In order to examine the difference of the array characteristics for the five different connection, a similar experiment was conducted. Again, we used the five different connection of the 256 sub-arrays as in Table I and measured the array characteristics (V, I, and Power). The data are plotted in Fig. 9 as a function of the normalized resistance $r = R_L/R_S$ where R_L and R_S are the load and normalizing resistance, respectively. Note that the vertical scales are now in linear scale. The current and voltage data are given in Fig. 9(a) and (b) for all five connections, but the output dc power data are shown in Fig. 9(c) only for a case of 128 series—two parallel connections.

TABLE II
PARAMETER SET OF (V_S, R_S) FOR THE LEAST SQUARE FITTING

Connection of Sub-array	V_S	R_S
128 Series and 2 Parallel	1905.2	1410.1
64 Series and 4 Parallel	988.97	370.86
32 Series and 8 Parallel	548.80	107.59
16 Series and 16 Parallel	280.53	28.59
8 Series and 32 Parallel	152.52	8.475

We first attempt the data fitting for the dc power versus r plot using

$$P_L = \frac{R_L \cdot V_S^2}{(R_S + R_L)^2} = \frac{r \cdot V_S^2}{R_S(1+r)^2}. \tag{2}$$

The least square fitting curve is obtained for a parameter set of (V_S, R_S) = (1905.2, 1410.1). As seen in Fig. 9(d), the data fitting is quite good, including that the rectenna array dc output can be well approximated by (2). Similarly, we fitted the output dc power versus r data for the other four cases and found their fitting parameters (V_S, R_S) shown in Table II. Using these parameters (V_S, R_S), we plot the following curves for I and V in Fig. 9(a) and (b):

$$I_L = \frac{V_S}{R_S + R_L} = \frac{V_S}{R_S(1+r)} \tag{3}$$

$$V_L = \frac{R_L \cdot V_S}{R_S + R_L} = \frac{r \cdot V_S}{1+r}. \tag{4}$$

The data points for I (dc current) agree well with (3) except for low r value. Likewise, the data points for V (dc voltage) agree well with the theoretical curve (4), except for the higher r values. However, the rectenna characteristics for a normalized resistance r near $r \simeq 1$ (i.e., near optimum load) show a good agreement with the theoretical curve, which is based on an assumption that the rectenna can be expressed by a simple equivalent circuit composed of a series connection of a constant dc voltage source V_S and an internal resistance R_N.

Fig. 9(d) shows the fitting curves of the output dc power for the five connections. In order to examine the deviation of the maximum available power, we measure the difference of each maximum output from the average of the five maximum available output dc powers. It turns out that the deviation of the maximum power in relation to the average power caused by the different connection is within 5%.

IV. CONCLUSION

From 1994 to 1995, ground-to-ground MPT experiments were carried out in Yamasaki, Japan, by a joint team of the Radio Atmospheric Science Center of Kyoto University, Kobe University, and Kansai Electric Power Company. For the field experiments, we had developed a new microstrip rectennas at frequency of 2.45 GHz. A RF–dc conversion efficiency was 64% at 2.5 W.

We constructed a 3.2 m × 3.6 m rectenna array composed of 256 sub-arrays. Each of the sub-array has nine rectenna elements connected in parallel. Thus, the total number of rectenna element used in the rectenna array was 2304. Utilizing the dispensed RF–dc conversion efficiency of the 256 sub-arrays, we have tested two different arrays. One is an arranged array placing the high efficiency sub-arrays in the central area of the array, and the other is nonarranged (i.e., randomly placed) array. It turns out that the arranged array provides 46% higher dc maximum output.

In order to examine the influence of the electrical connection among the 256 sub-arrays on the dc current, dc voltage, and dc power output of the array, we tested five different electrical connections. The data are examined in terms of a simple equivalent circuit model of the rectenna. It turns out that the interconnection method would not yield a large difference (< 5%). In contrast, the choice of the optimum load gives a significant importance to the RF–dc conversion efficiency.

Necessary future works on the rectenna would be: 1) improvement of the RF–dc conversion efficiency of mass-productable type of rectenna and 2) to understand the mechanism of the deviation from the theoretical curve for the $I - r$, $V - r$ characteristics for the nonoptimum load resistance.

We will have to use thousands of rectennas for a wireless energy transmission. However, there were few studies for rectenna array. The results of this paper are useful for construction of a large rectenna array. In the near future it will be useful to transmit electrical power without wire by microwave from a power station or from space. We have to continue to study the rectenna array in the future.

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