Guidelines for Development of SPS 2000 Educational Model

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Abstract

SPS 2000 is a study model of 10 MW class Solar Power Satellite on a 1,100 km equatorial orbit. In order to study the engineering problems of SPS 2000 on a system level, an electrical functional model of SPS 2000 has been developed for ground testing. The model includes a solar cell array and a microwave power transmitter which are integrated on a scale model of SPS 2000. The SPS functional model has been tested in combination with a microwave receiver as the ground segment. It was used as an exhibit at the ISAS annual open house for educational purpose to demonstrate the SPS concept and associated technologies. This research note describes detailed specification of the electrical function model of SPS 2000 and provides basic information how to build the model for the beginners of SPS research.

1.Introduction

The idea of the Solar Power Satellite(SPS) was first proposed by Dr. Peter Glaser in 1968, as a sustainable energy source for mankind in the future[1]. The basic concept of SPS is illustrated in Fig.1. The solar energy is converted into electricity and fed to microwave generators on orbit. The microwave antenna transmits the microwave power beam to a receiving antenna on ground. The microwave energy is reconverted to electricity and then transmitted to the commercial power utility. The most significant benefit of this idea is the potential for a large-scale clean energy system substitutable for the existing non-renewable energy sources.

A feasibility study of the SPS concept was conducted extensively by NASA and the U.S.Department of Energy in the 1970's[2]. In the study, an SPS with an output power of 5 GW was designed and assessed as a reference model from the aspects of technology, economy, and environmental acceptability. The size and weight of the

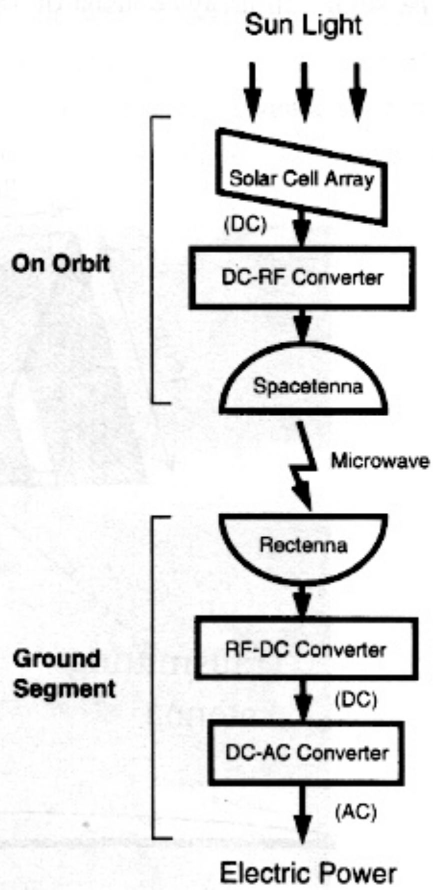

Fig.1 Basic concept of SPS.

model SPS on the geosynchronous orbit was 10 km x 5 km and 50,000 ton, respectively. Although the study demonstrated potential feasibility for the SPS concept, no further step toward its realization was taken because the society at that time did not recognize the reality of the awfully huge and costly space system.

As a different approach from the U.S. reference model, SPS 2000 has been proposed and studied in 1990's in Japan, aiming at creating a concept for a realistic and low-cost SPS model based on the near-term technologies. This study was conducted by the SPS 2000 task team voluntarily organized by the researchers from universities and research institutes. Figure 2 illustrates the concept of SPS 2000. The mission orbit is at an altitude of 1,100km above the equator, which is a compromise of transportation cost and environmental concerns such as space debris and high energy radiation. It has the shape of a triangular prism with a length of 300 m each side. The prism axis is in the north-south direction, perpendicular to the orbital velocity. The solar arrays are attached at the two upper planes of the prism, while the transmitting antenna is installed at the bottom plane, facing the ground all the time. The power generation and microwave power transmission are 16 MW and 10 MW, respectively. To simplify the system configuration, the model SPS has no energy storage, and the attitude is stabilized merely by gravity-gradient force. The total weight of SPS 2000 is estimated to be about 240 ton.

The main structure of SPS 2000 is made of double-bay single-raced beam, which is assembled of 3 meter-long aluminum pipes of 12-27 mm diameter with quick connection mechanisms. The task analysis for construction has shown that unmanned assembly is feasible under gravity-gradient force. The solar cell arrays consist of 180 rolls of 3 m x 300 m strips of solar cell panel. For

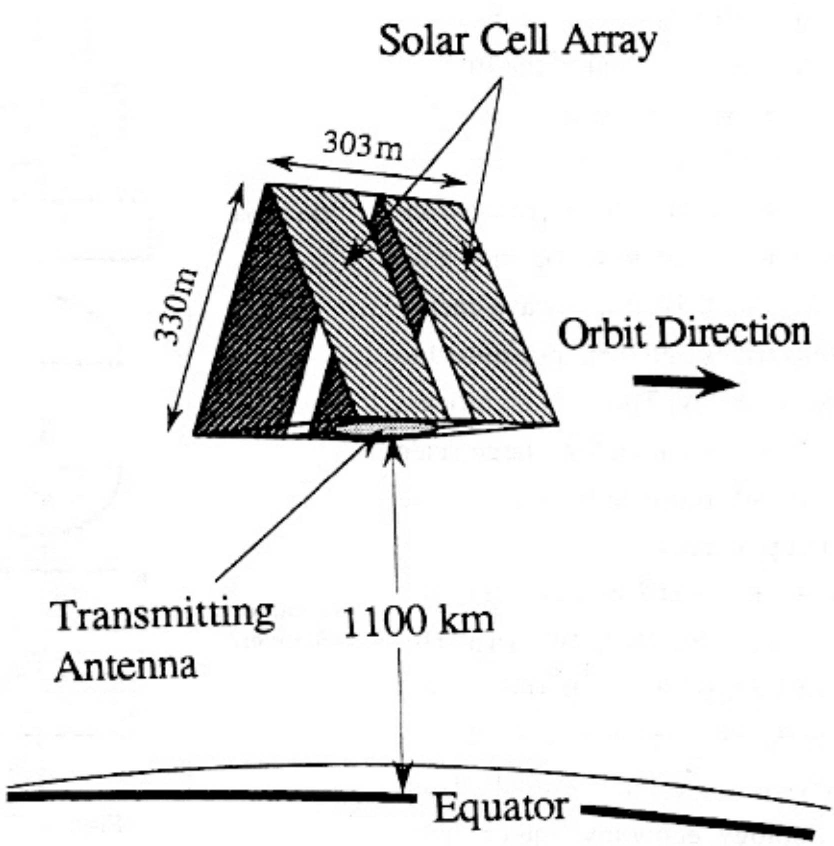

Fig.2 Concept of SPS 2000.

transportation from ground and deployment in space, amorphous silicon(a-Si) solar cell, a thin film type, will be used. The voltage of the power generation is 1,000 V to reduce the cable loss. Flat cables made of 1 mm thick copper plate are used for the electrical power collection. For the microwave power transmission, 2.45 GHz is selected as the most practical frequency for the near-future application because of technical maturity and a high transmission capability in the atmosphere. The transmitting antenna is usually called "spacetenna". The spacetenna 132 m by 132 m square consists of 2,000 subarrays, each including 1,300 antenna elements. The phased array system is capable of directing the microwave beam $\pm$ 30 degrees in east-west and $\pm$ 17 degrees in north-south to the normal. The receiving antenna of the microwave beam is called "rectenna". The size of rectenna is typically 2 km circular and a power of 300 kW is obtained on average at the rectenna site. Two types of rectenna have been designed; a simple mesh type called "magic carpet" and a hogline rectenna with circular micro-strip antennas. Both are almost transparent for the sunlight to minimize the environmental impact. More detailed description on the concept of SPS 2000 is given by Nagatomo et al[3].

After the preliminary conceptual design for SPS 2000 was completed, an electrical functional model has been developed to study the system-level problems as a practical approach. The study includes power generation depending on the sun angle, cabling for the electric power collection, electrical interface between the power generation and transmission subsystems, retrodirective function of the microwave beaming, and receiving antenna system. The model simulates the major electrical function of SPS 2000; power generation by the solar cell panels and microwave power transmission. Two sets of the functional model have been fabricated and tested so far since 1994, and the third model is now under development. The ground segment, the rectenna and dummy load, have been also built for the test and demonstration combined with the space segment. The model was exhibited at the ISAS annual open house in 1994 and 1995. Figure 3 shows a scene of

Fig.3 Scene of ISAS open house in 1994.

the 1994 exhibition. It was also on display at a museum in Reunion Island of France for half a year after the Wireless Power Transmission Workshop at Reunion in 1994.

Detailed description on the basic model is given in section 2, which can be used for those who want to build the SPS model for educational purpose. Knowledge of electronics on a college level is only required to build the educational model. Advanced type of the model is briefly described in section 3. For development of the advanced model, assistance of SPS 2000 team members may be required.

2. SPS2000 Basic Model

The basic model, a 1/300 scale model, is a 1-watt transmitting power system without phase control. The major functions of the model and the ground segment are shown in Fig.4. The frame structure of the space segment is made of angle aluminum. Solar cell modules are installed on one side of the triangular prism frame of 1 m scale. The solar cell array generates electric power by the light of Halogen lamps set at 1.8 m from the solar cells. The generated DC power is converted into microwave power and transmitted to the ground segment located at 1.3 m apart from the space segment. The ground segment consists of dipole antennas and dummy loads configured on a 3.6 m square diorama. The received power by the dipole antennas is fed to LEDs and miniature motors for demonstration of the power transmission.

2.1 System Configuration

Figure 5 illustrates the system configuration. The space segment and two sets of Halogen lamps are assembled in a frame and lifted with a crane above the ground segment. The electrical block diagram is shown in Fig.6. The solar cell array of polycrystalline silicon type generates an electric power of typically 20 watt by the two 1 kW Halogen lamps. The generated voltage around 17 V is regulated to 15 V and fed to a 2.45 GHz oscillator and microwave amplifier. The output power of the amplifier is supplied to four sets of cavity-backed slot antenna. As the rectenna, 96 sets of a dipole antenna together with a rectifier are used. The output power of the rectenna is totally 120 mW.

2.2 Major Components

(1) Halogen Lamps

Two Halogen lamps are used as a solar simulator for the solar cell. The type of Halogen lamp is DP LIGHT of Lowel-Light Manufacturing Inc. The specification is shown in Table 1.

Table 1 Specification of Halogen lamp

Input Power	1,000 W
Peak Wavelength	880 nm
Cost	$ 400(approx.)

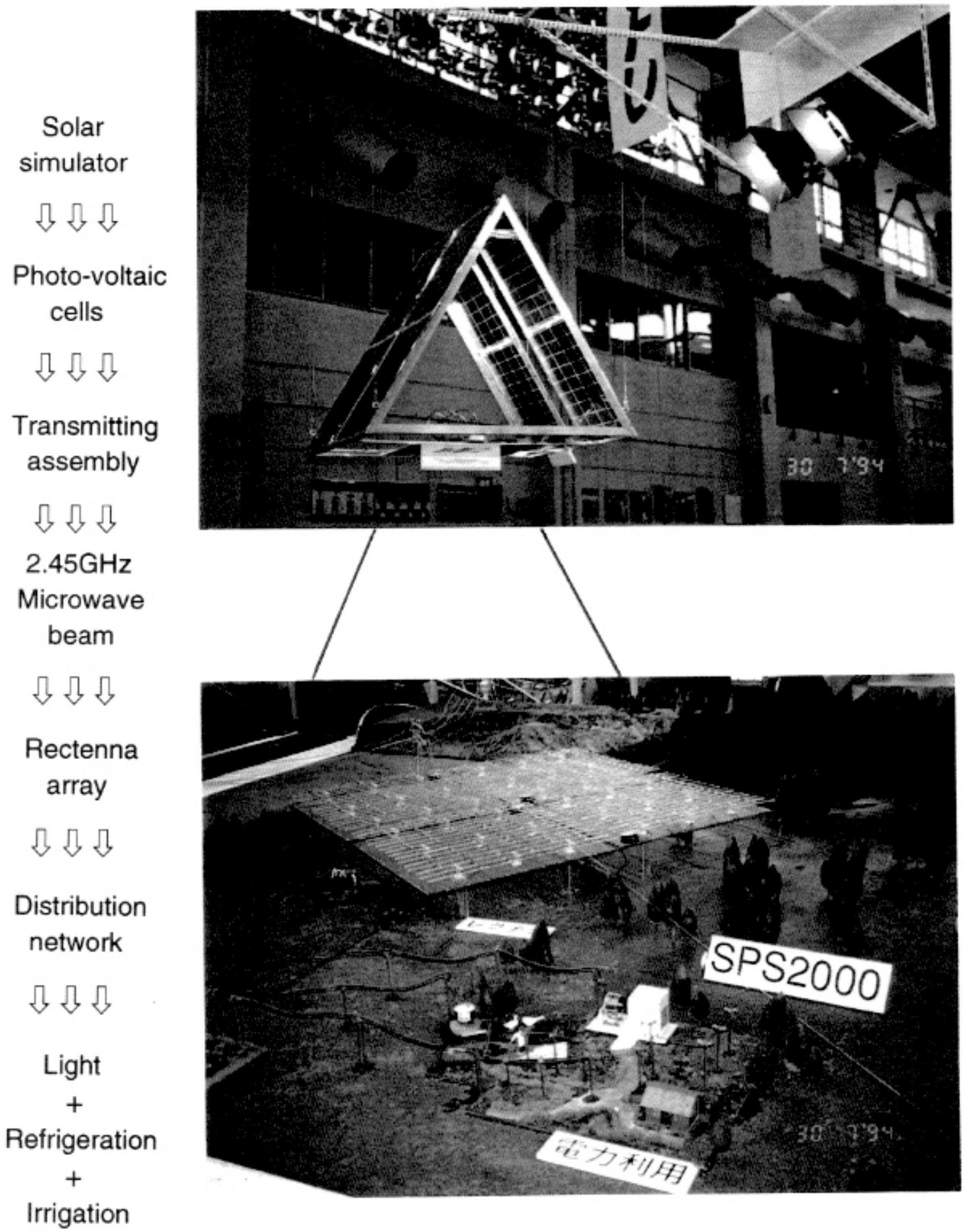

Fig.4 Major functions of SPS 2000 electrical functional model.

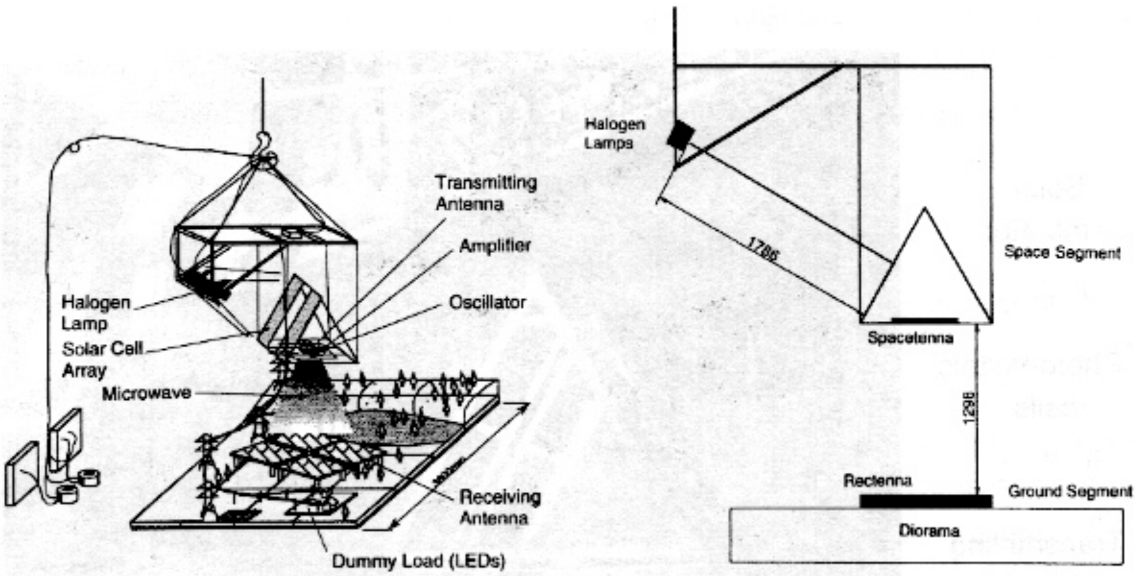

Fig.5 System configuration.

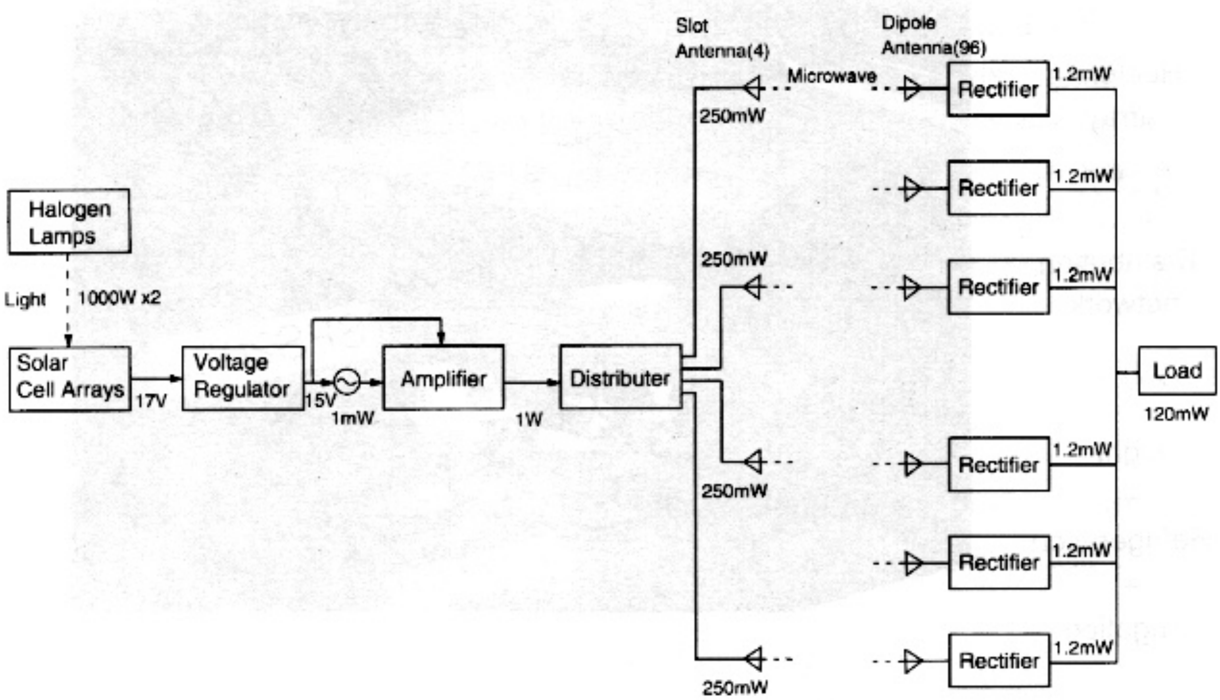

Fig.6 Electrical block diagram.

(2) Solar Cell Array

The solar cell array consists of 4 modules of polycrystalline solar cell connected in parallel. The solar cell module is a flexible type developed for the solar car and solar plane. The type of the solar cell module is PSF50H-361F of Kyocera Corporation. The specification is shown in Table 2. The distance of 1.8 m between the Halogen lamps and the solar cell modules is determined to keep the temperature of the solar cells less than 50℃. The efficiency of the solar cell degrades considerably when the temperature exceeds 60℃.

Table 2 Specification of solar cell module

Size	494.3 mm x 424 mm x 0.9 mm^t
Weight	215 g
Pmax	22.2 W(AM1.5, 1000W/m^2, 25 deg.C)
Voc	20.7 V
Isc	1.5 A
Cost	$ 320(approx.)

The manufacturer provides standard specification or test data of the solar cell module. However, for design of the electrical interface with the transmitter, it is necessary to measure the V/I characteristics of the solar cell array using the Halogen lamps under the actual model configuration. The V/I characteristics are obtained using the test circuit as shown in Fig.7. By changing the variable

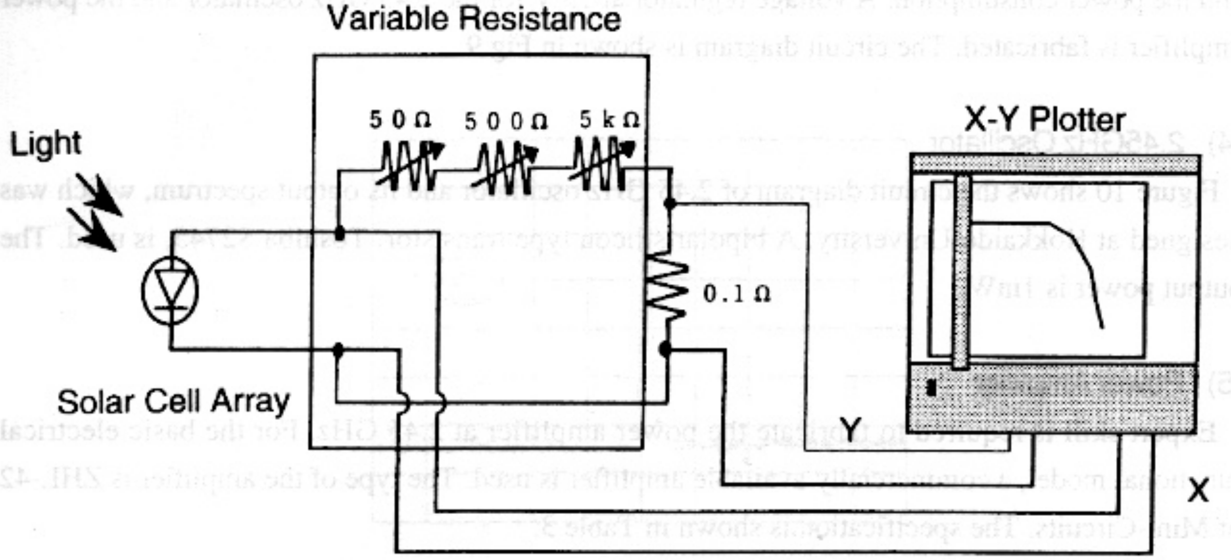

Fig.7 Test circuit to measure the voltage/current characteristics of the solar cell.

resistance, the V/I characteristics are obtained. The short current is measured when R=0. The open voltage is measured when R is large enough or the current is almost 0. It is necessary to operate the solar cell modules near the best operation point where the maximum power is obtained. Fig 8 shows the V/I characteristics of the solar cell array set at 1.8 m from the Halogen lamps. The maximum power 19 W is obtained at 17 V.

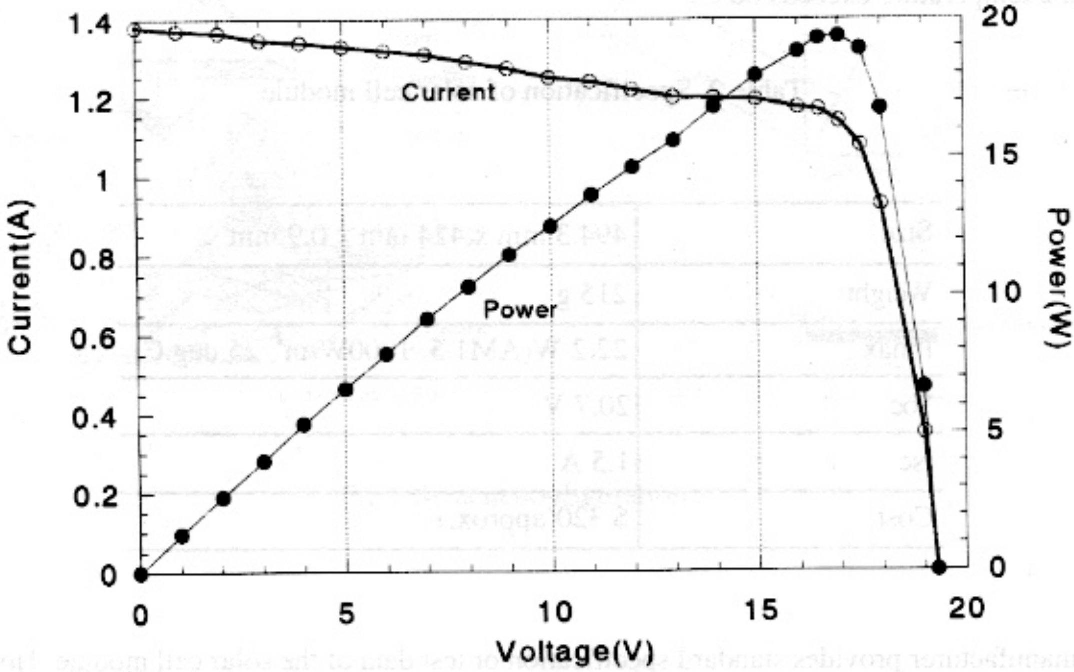

Fig.8 Voltage/current characteristics of the solar cell.

(3) Voltage Regulator

The output voltage of the solar cell array fluctuates near 17 V depending on the light condition and the power consumption. A voltage regulator at 15 V for the 2.45 GHz oscillator and the power amplifier is fabricated. The circuit diagram is shown in Fig.9.

(4) 2.45GHz Oscillator

Figure 10 shows the circuit diagram of 2.45 GHz oscillator and its output spectrum, which was designed at Hokkaido University. A bipolar silicon type transistor, Toshiba S2745, is used. The output power is 1mW.

(5) Power Amplifier

Expert skill is required to fabricate the power amplifier at 2.45 GHz. For the basic electrical functional model, a commercially available amplifier is used. The type of the amplifier is ZHL-42 of Mini-Circuits. The specification is shown in Table 3.

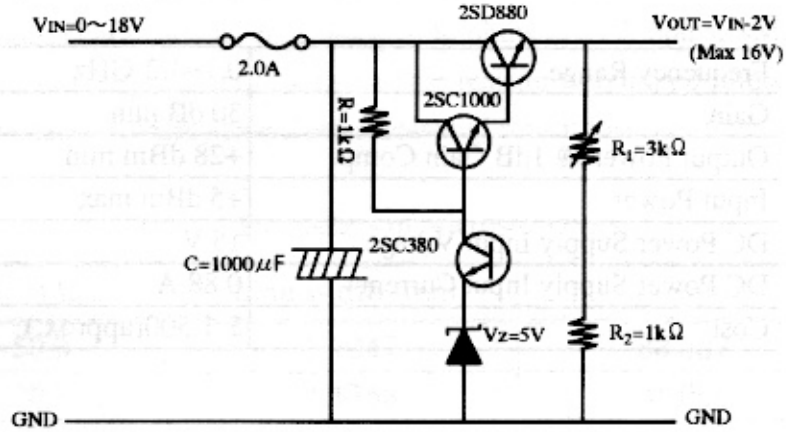

Fig.9 Circuit diagram of the voltage regulator.

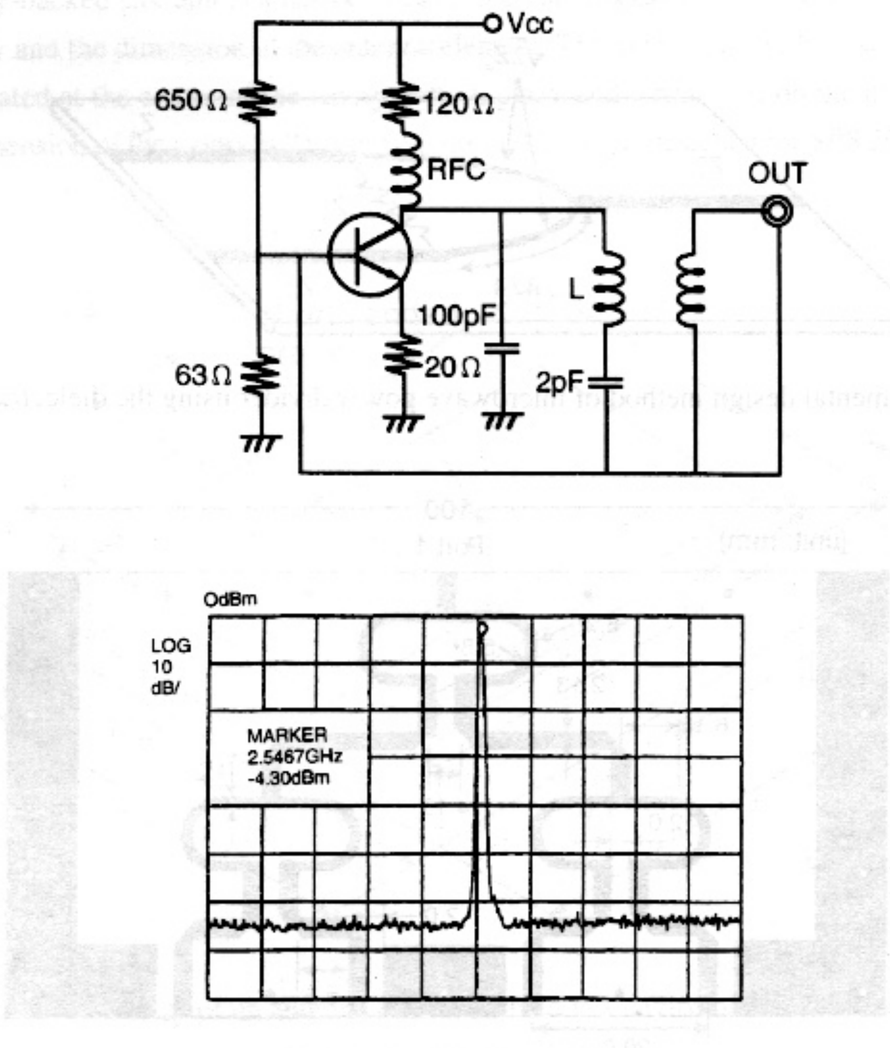

Fig.10 Circuit diagram of the 2.45 GHz oscillator and its output spectrum.

Table 3 Specification of microwave power amplifier

Frequency Range	0.7~4.2 GHz
Gain	30 dB min
Output Power @ 1dB Gain Comp.	+28 dBm min
Input Power	+5 dBm max
DC Power Supply Input Voltage	15 V
DC Power Supply Input Current	0.88 A
Cost	$ 1,500(approx.)

(6) Microwave Power Divider

The output power of 1 W from the power amplifier is divided and fed to the four slot antennas. The fundamental design method of Wilkinson power divider using the dielectric substrate is explained in the Fig. 11. The characteristic impedance of transmission line, Z_0, is assumed as 50

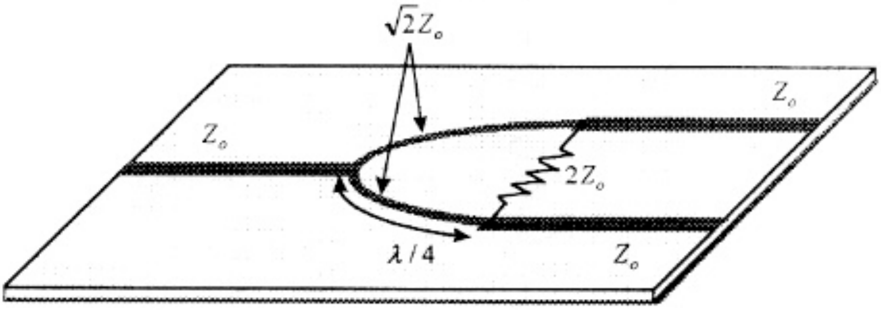

Fig.11 Fundamental design method of microwave power divider using the dielectric substrate.

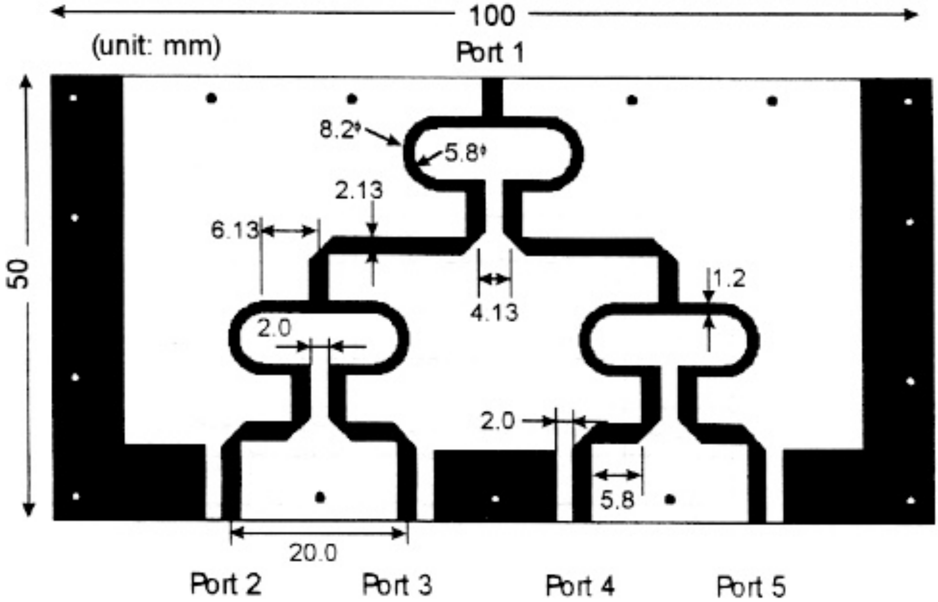

Fig.12 Layout pattern of Wilkinson power divider.

ohms. Two-stage Wilkinson type power divider shown in Fig. 12 was designed at Hokkaido University. A dielectric substrate of CHUKO FLO CGP500 (relative dielectric constant, ε_r=2.6 , and height of substrate, h=0.77mm) is used for the print circuit. Table 4 summarizes parameters of microstrip lines whose characteristic impedance is 50 ohms or 70.7 ohms. SMA connectors are installed at the input and output ports and also a chip resister of hundred-ohms is connected between the high impedance transmission lines. Measured return loss, coupling, and isolation are

Table 4 Parameters of microstrip lines.

Z_o (Ω)	Line width (mm)	λ (mm)
50.0	2.1047	83.382
70.7	1.1763	85.066

51.0 dB, 6.02dB, and 35.8 dB at the frequency of 2.45 GHz, respectively.

(7) Slot Antenna

The cavity-backed slot antenna has been developed at Hokkaido University[4]. Figure 13 shows the geometry and the dimension of the antenna element. The antenna is fed by a short-ended probe which is located at the center of the cavity bottom plane and terminated on the plane including a slot. The dimension of the cavity is 75 mm x 90 mm x 12 mm as designed for SPS 2000. The slot on

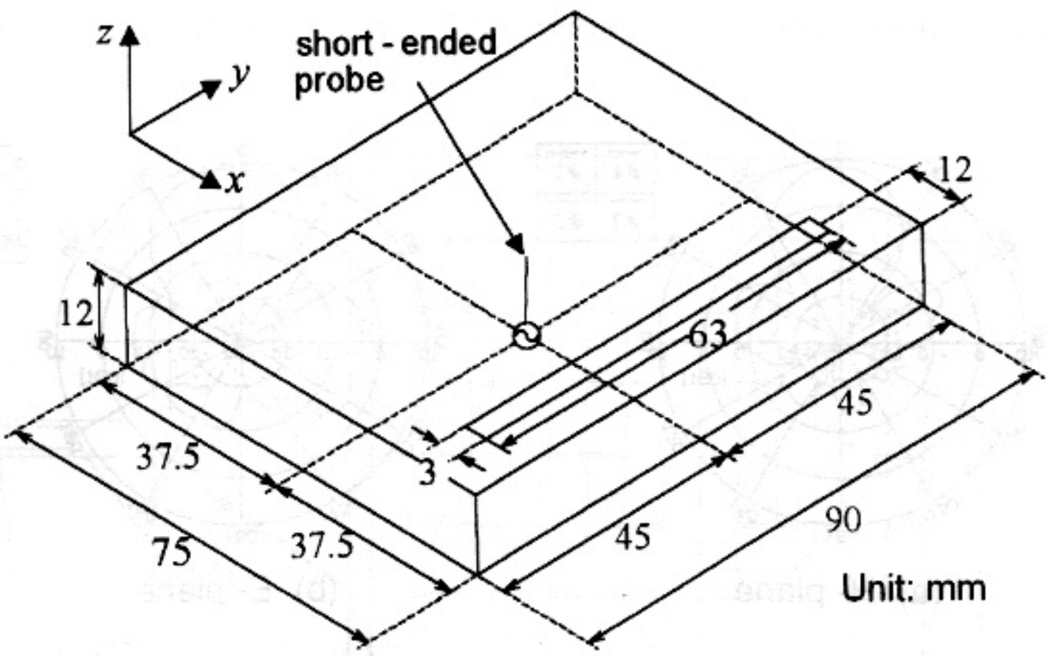

Fig.13 Geometry of an antenna element which is a cavity-backed slot antenna fed by a short-ended probe.

the top plane of the cavity is separated by 12 mm from the side of the cavity, whose length and width are 63 mm and 3 mm, respectively. We obtained a return loss of more than 20 dB at the frequency of 2.45 GHz experimentally. Figure 14 draws the sectional view of the connector and feeding probe.

Figure 15 shows the typical radiation patterns of the array antenna consisted of four elements. It

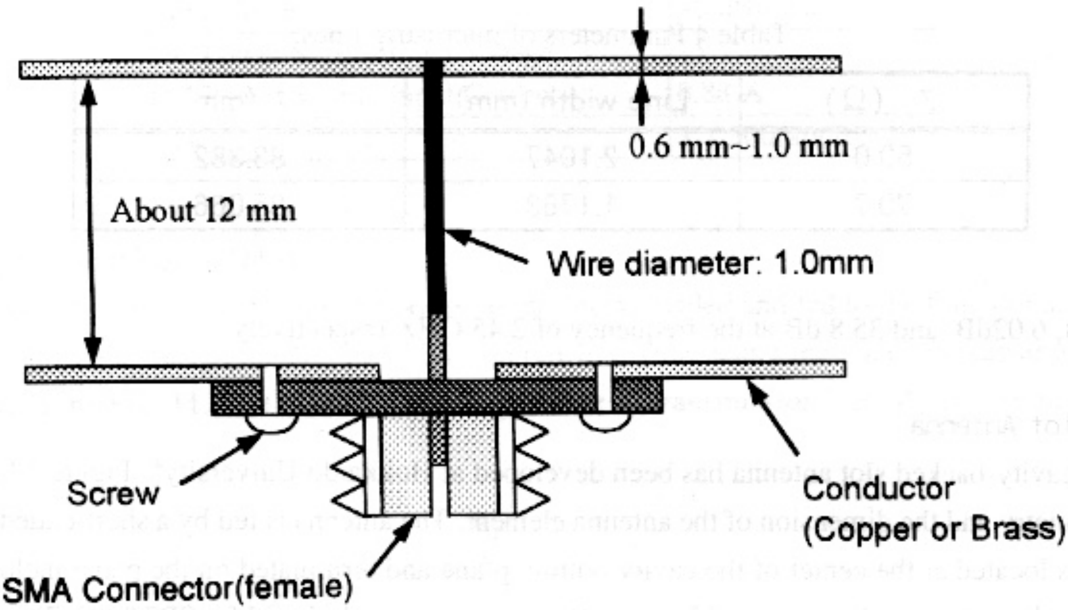

Fig.14 Cross-sectional view of cavity near the connector and feed probe.

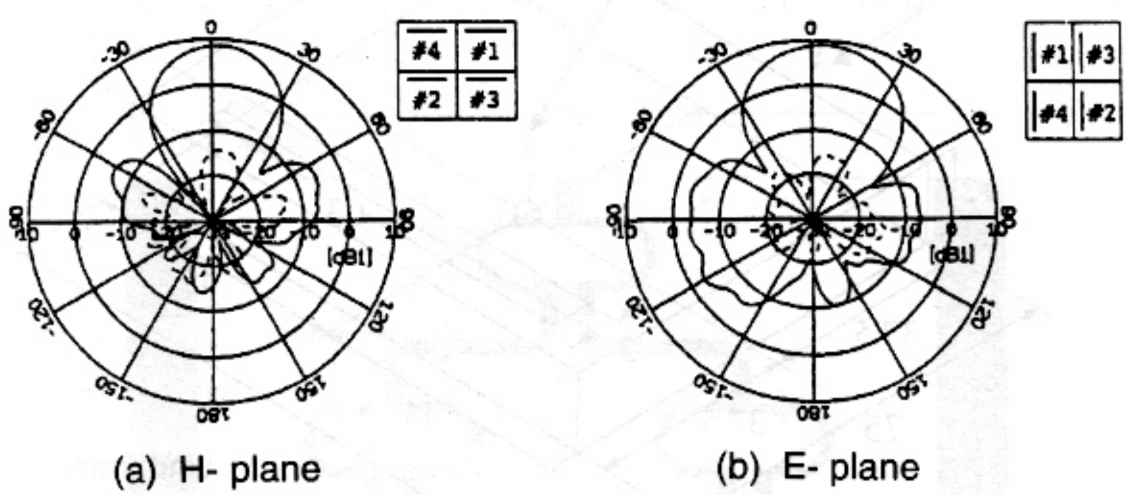

Fig.15 Typical radiation patterns of the array antenna.

has almost similar characteristic as the element used for the functional model.

The power density of the microwave beam from the transmitting antenna is generally expressed as;

$$P_d = A_t \cdot P_t / (\lambda \cdot d)^2 \qquad (1)$$

where, P_d : Power density
A_t : Transmitting antenna area
P_t : Transmitting power
λ : Wavelength
d : Transmitting distance.

This is an ideal case when the antennas are in phase to transmit the microwave beam to one direction. For SPS 2000 with the transmitting antenna of 132 x 132 m on the 1,100 km orbit, the power density on ground is calculated as 1 mW/cm^2. For the electrical functional model without the phase control, the power density is calculated by superimposing the beam characteristics of the four slot antennas. If we approximate the divergence of the microwave transmission to be ± 30 degrees, the power density at 1.3 m is calculated as 0.06 mW/cm^2.

(8) Dipole Antenna

4 units of rectenna array are used as the ground segment. One rectenna array consists of 24 dipole antennas with a 500 mm x 500 mm reflector. The reflector is a 1 mm wire net with 10 mm pitch installed at 31 mm behind the antennas. The configuration of rectenna array is shown in Fig.16. A Silicon Schottky Barrier Mixer Diode(NEC 1SS97) and a 10 pF ceramic capacitor are assembled with each antenna element. The specification of the Schottky diode is shown in Table 5. The characteristics of the dipole antenna of this type are described in detail in a research report by Pignolet[5].

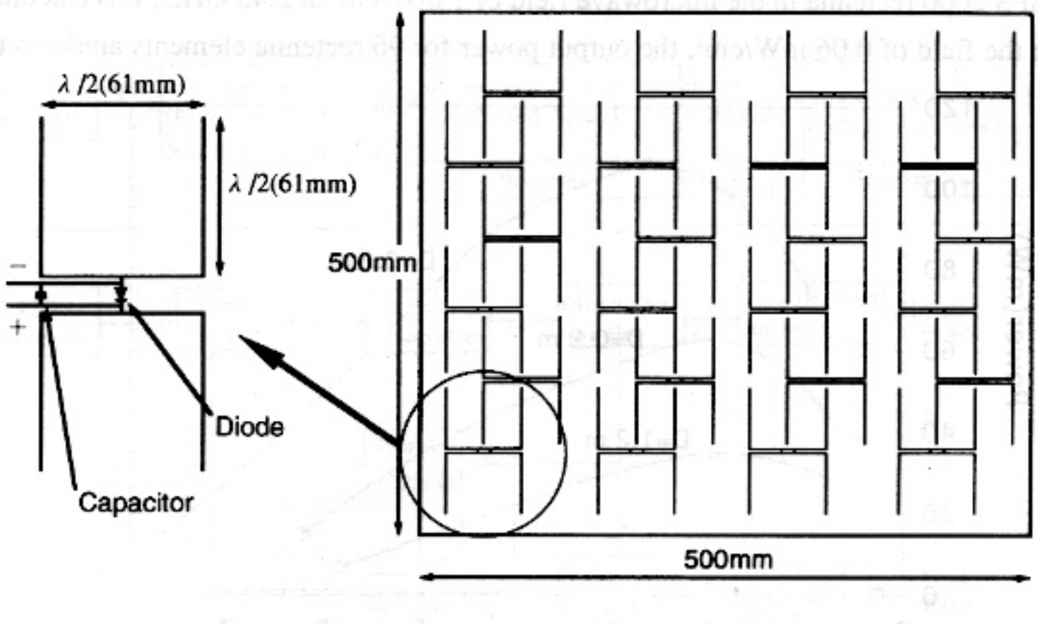

Fig.16 Configuration of rectenna array consisting of 24 dipole antennas.

Table 5 Specification of Silicon Schottky Barrier Mixer Diode (NEC 1SS97)

Absolute Maximum Ratings(T_a=25°C)	
Reverse Voltage V_R	30 V
Forward Current I_F	35 mA
DC Power Dissipation P_d	150 mW
Junction Temperature T_j	175 °C
Electrical Specifications(T_a=25°C)	
Min. Breakdown Voltage V_{BR}	30 V
Max. Forward Voltage V_F	410 mV
Forward Current at V_F=1V I_F	35 mA
Max. Reverse Leakage Current I_R	100 nA @ V_R=5.0 V
Typical Junction Capacitance C_j	1.0 pF @V_R=0 V, f=1.0 MHz

The conversion efficiency of the dipole antenna depends on the load resistance. The power obtained by one unit rectenna array configured at 0.6, 0.9 and 1.2 m from the transmitter is shown in Fig.17.

The power obtained by a dipole antenna is expressed as;

$$P=P_d \cdot A_{eff} \cdot G \qquad (2)$$

where, P: Obtained power by antenna

P_d:Microwave power density

A_{eff}:Effective receiving area($\lambda^2/4\pi$)

G: Antenna gain(1.5 for dipole antenna with a half wavelength).

For the SPS 2000 rectenna in the microwave field of 1 mW/cm^2 at 2.45 GHz , P is calculated as 18 mW. In the field of 0.06 mW/cm^2, the output power for 96 rectenna elements amounts to 100

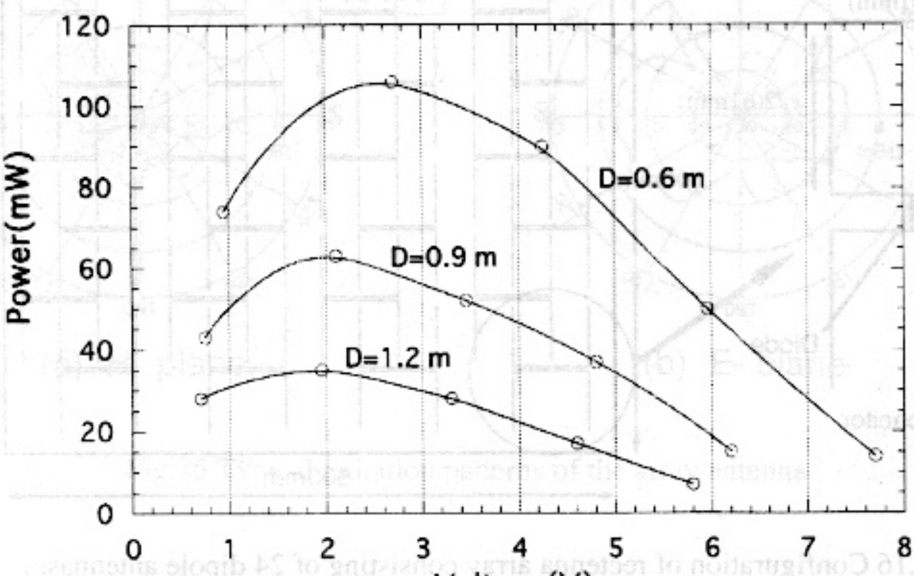

Fig.17 Output power of a rectenna array. D is the distance from the transmitter.

mW.

3. Advanced Model

The advanced model, a 1/200 scale model, is a 4-watt transmitting power system. The instrumentation is almost same as the basic model, but it has a capability of phase control for beam steering. The electrical block diagram of the model is shown in Fig.18. Four 1 kW Halogen lamps are used for the light source. Eight solar cell panels are attached to one side of the triangular prism. The microwave transmitter consists of 4 channels of phase-control loop. Each channel is connected to two slot antennas. The phase control loop has an analog phase shifter, an amplifier, a directional coupler and a phase detector. The controller compares the phase signal of the transmitter with that of the pilot signal, and then generates a control signal for the phase shifter to direct the microwave beam toward the pilot signal source. 800 MHz is used for the frequency of the pilot signal. In the test, three rectenna sites are configured so as to demonstrate the beam steering capability as shown in Fig.19.

A more powerful functional model, the third model, is now under development supported by an MOE(Ministry of Education, Science and Culture) Grant-in-Aid for Scientific Research. It is a 1/150 scale model with a capability of power generation more than 300 watt in the sunlight. Figure 20 shows a picture of the model in the field test. Figure 21 shows the configuration of the power generation system. Totally 32 solar cell modules are assembled on the two sides of a triangular prism structure. The side length is about 2 m. The 32 solar cell modules are grouped into 4 arrays. Array 1 and 2 are connected in series and installed on one side, and in the same way connected for Array 3 and 4 on the other side. Arrays 1/2 and 3/4 are connected in parallel. Diodes are used to prevent reverse current caused by uneven cell voltage. Figure 22 shows the V/I characteristics of the power generation system, which was obtained by the sunlight on a clear day. As a new type of active antenna for this model, a compact type of transmitting element which contains microwave

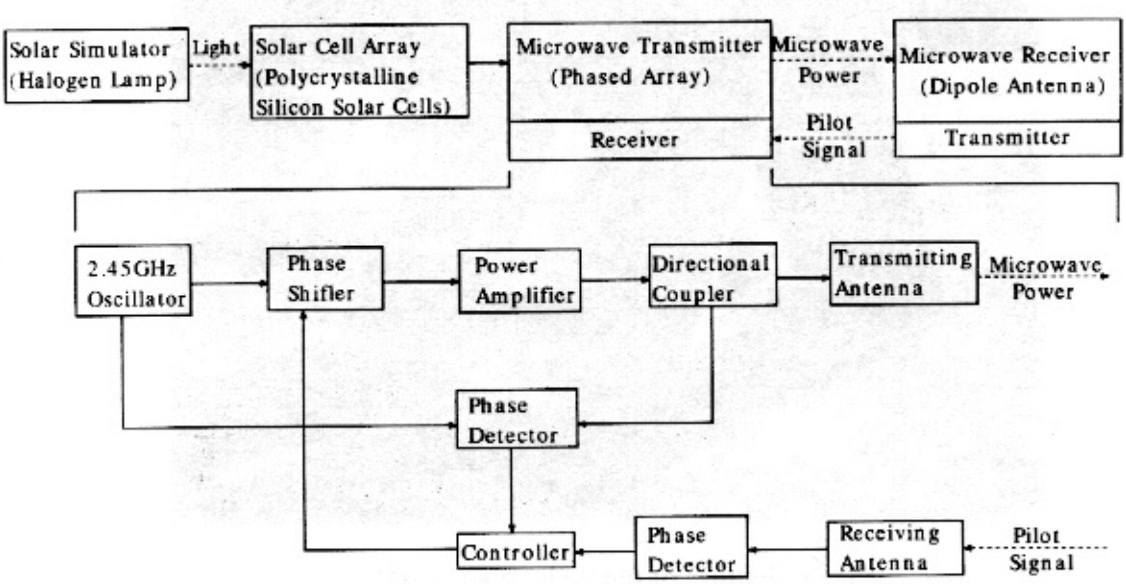

Fig.18 Electrical block diagram of the advanced model.

circuits and a transmitting antenna integrated into a multi-layer structure is now under development at Tokai University[6].

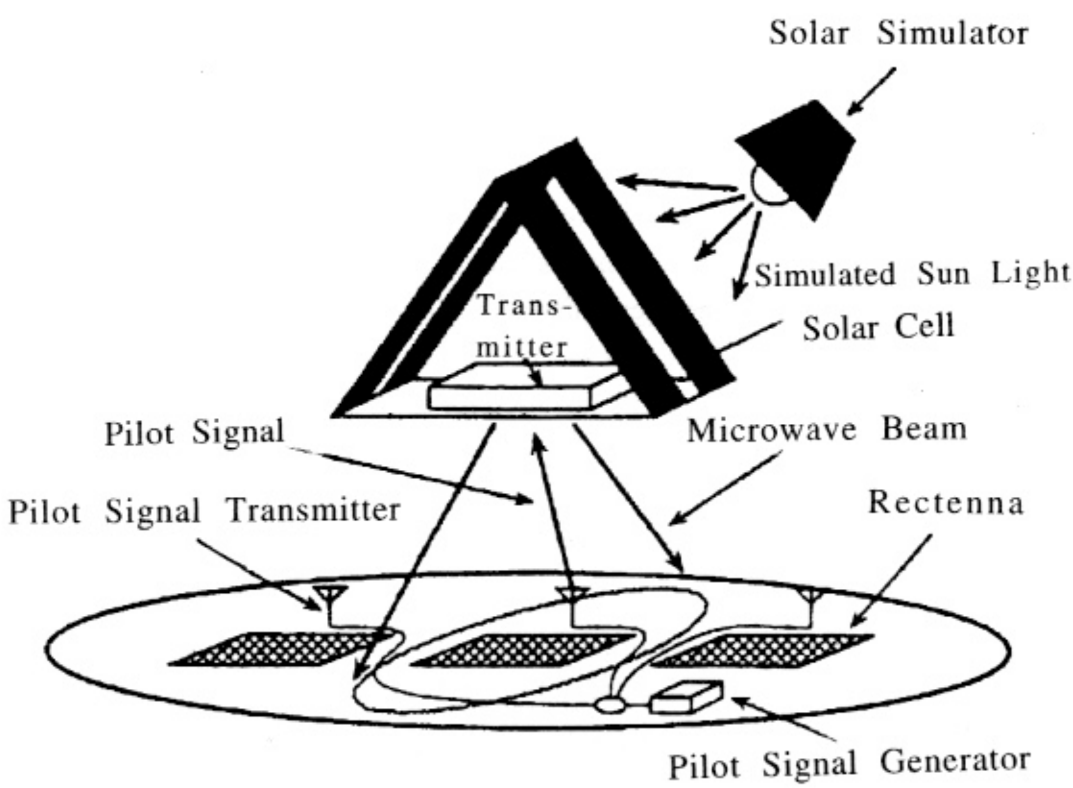

Fig.19 Demonstration for the beam steering capability of the advanced model.

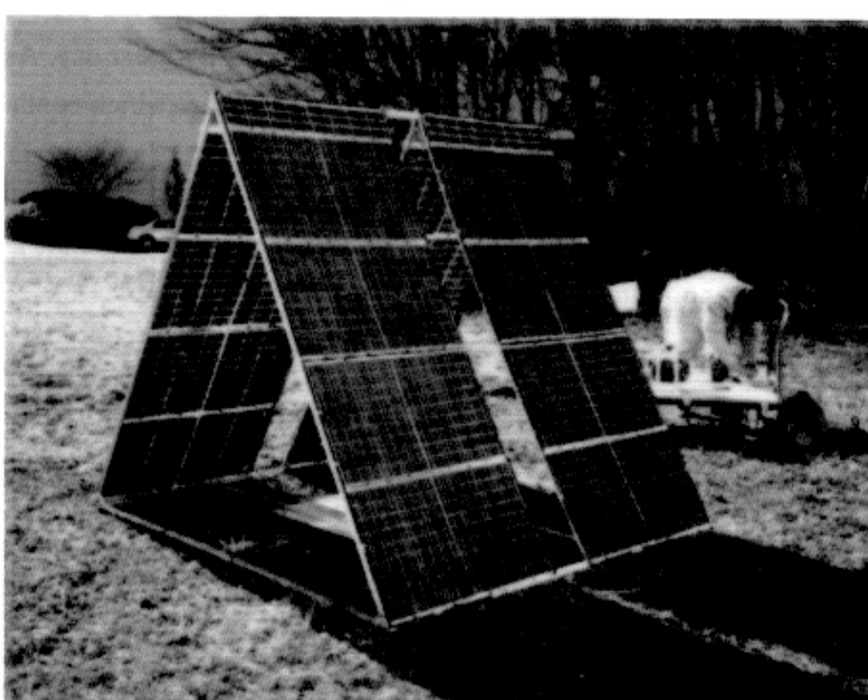

Fig.20 Picture of the high power model.

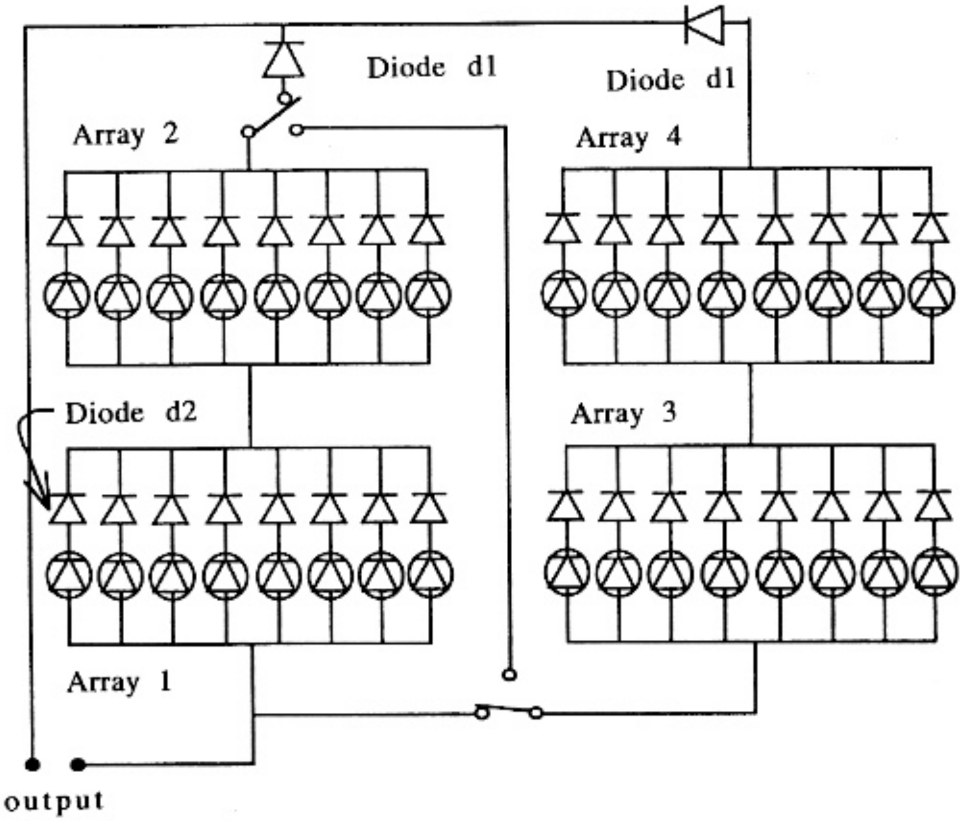

Fig.21 Configuration of the power system of the high power model.

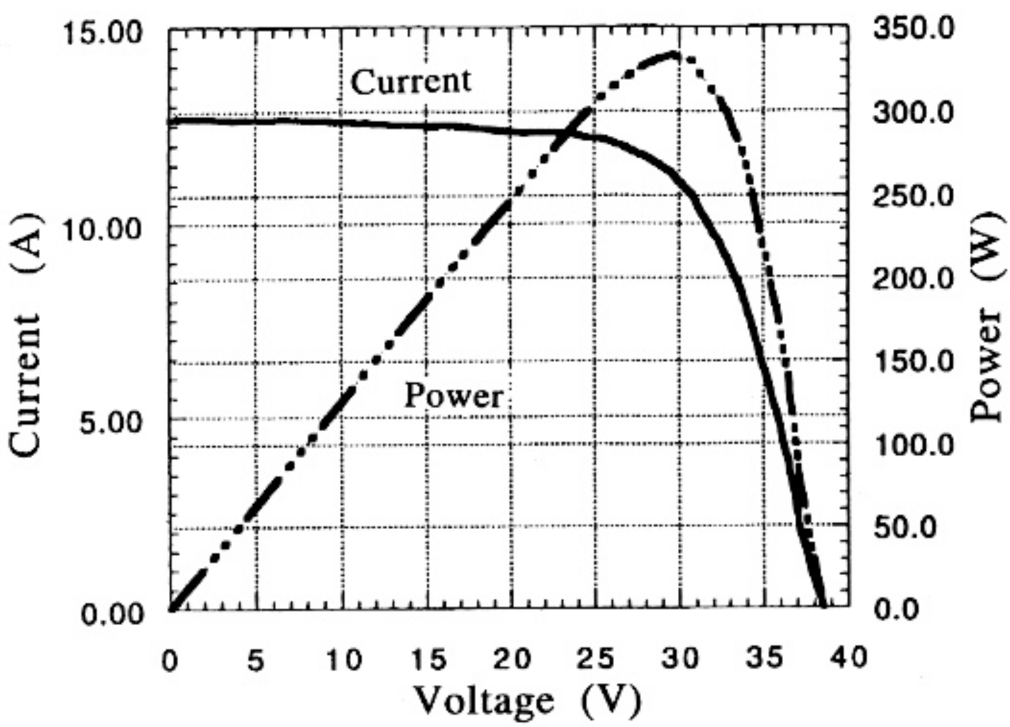

Fig.22 Voltage/current characteristics of the high power model.

4. Summary

The electrical function model of SPS 2000 has been introduced in detail. Besides for engineering research, it has been used for the purpose of education and publicity concerning the SPS concept and associated technologies. Undergraduate as well as graduate students at ISAS were involved in the design, fabrication and integration of the model. They also prepared for exhibition at the ISAS open house and participated in it as explainers. These activities have been quite educational for the young people to understand the SPS concept, technologies, and problem areas. More than 20,000 people visited ISAS at the open house in 1994 and 1995. Many of them came to the display of the SPS 2000 model and asked all kinds of questions to the students and SPS researchers. The model displayed in the museum of Reunion Island worked continuously for half a year without any trouble. The exhibition of the working model has significantly contributed to spreading scientific knowledge of SPS to public. If these activities take place in many countries, public acceptance and support for SPS will greatly be promoted.

Acknowledgement

The development of the SPS 2000 electrical functional model was conducted under the leadership of Prof.Nagatomo of ISAS. The authors greatly appreciate Profs.Ito and Omiya of Hokkaido University for their guidance and cooperation in development of the microwave transmission and receiving system. They also wish to express their sincere thanks to Dr.Pignolet for his effort in development of the receiving antenna for this model.

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