Outline and Progress of the Japanese Microwave Energy Transmission Program for SSPS

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***Abstract* — Institute for Unmanned Space Experiment Free Flyer, USEF, has been studying Space Solar Power System, SSPS, as future electricity alternative energy source since 1990s. From 2009, USEF started research and development project of Microwave Ground Wireless Power Transmission under a support of Ministry of Economy, Trade and Industry, METI. This project plans to test ground wireless power transmission as a previous stage to the next space proof of SSPS. Also this project includes the study for high efficient and thin structured phased array antenna, and the study for high efficient rectenna element. In this paper, outline and progress of this project are introduced.**

***Index Terms* — Demonstration Testing, Microwave Power Transmission, Receiving Rectenna (Rectifying Antenna), SSPS (Space Solar Power System), Transmission Phased Array**

I. INTRODUCTION

USEF has been studying SSPS under a support of METI and the other related agency since 1990s [1]-[3]. These studies have covered from basic laboratory testing level to the practical power plant level, See Fig.1.

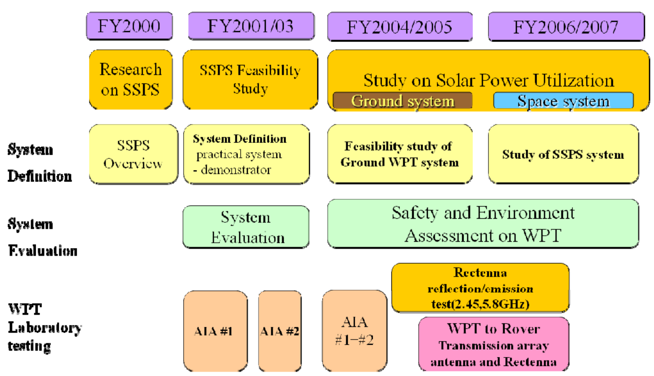

Fig. 1. SSPS activities by USEF

II. SUMMARY OF SSPS ACTIVITIES

The feasibility study of SSPS was carried out from FY2001 to FY2003. The Working Committee has investigated a simple, technically feasible, and practical configuration SSPS which consists of a large power generation /transmission panel or sandwich panel suspended by multi-tether wires from a bus system above the panel.

The beam control experiment was initiated from 2001. The active array panel with phase shifters, AIA#1[4], and the hardware retro-directive active integrated array panel, AIA#2[5], were developed and tested. The purpose of the development was to understand the issue derived by the microwave beam steering with integrated panels. And its evaluation was carried out in the anechoic chamber.

In 2007, high accurate beam control experiment was carried out using the phased array antenna (5.8GHz, one-dimensional, 12 elements, about 40 cm wide). Also, experiment of synchronized reference control system by closed loop technique for multiple phased array panels were carried out [6].

The WPT to remote object is a preferable application of SSPS technology. The rectenna array for rover, light weight phased array panel for transmitter on 5.8GHz had been developed. We also confirmed the low power command communication, 10mw, in 100W level microwave power transmitting condition [7][8]. See Fig.2.

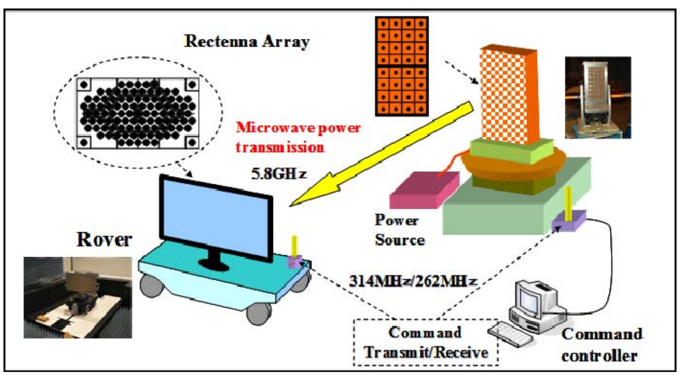

Fig. 2. WPT experiment to rover

Light weight transmitting panel is a key element for SSPS. As the output power level of each antenna element was about 4W therefore about 120 W output power was achieved with the 4kg weight. Therefore we have achieved weight to output power level of 33g/W. It included signal generation but did not include beam steering mechanism. The panel consists of 32 antenna element with array of three stages amplifiers. See Fig.3.

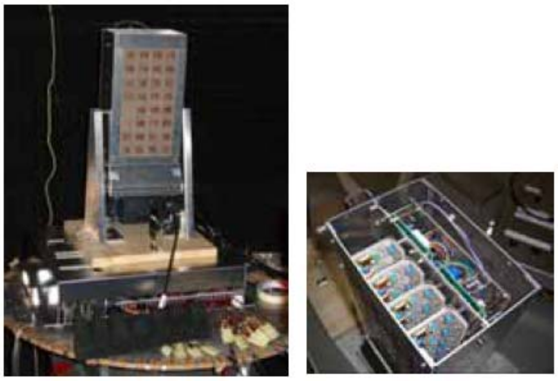

Fig. 3. Phased array panel for the transmission

Fig.4 shows developed rectenna array for the rover. The size is 340 x 600mm. The number of rectenna elements is 97. Weight is 2.5kg. Spacing between elements is 0.774 . Efficiency of the rectenna array is about 65%. Fig.5 indicates the condition of the buffer battery charge. Climbing line in this figure shows that the coming microwave power is sufficient. It can move the rover and charge the battery. Descending line indicates that the battery is discharged at this period. Starting and stopping rover indicates that the command communication worked between the rover and command equipment located outside of the system.

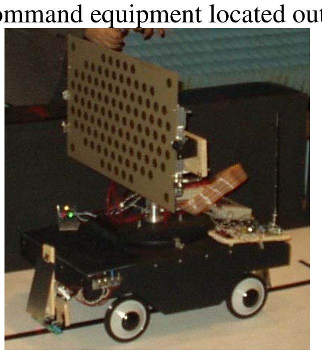

Fig. 4. Rover with rectenna

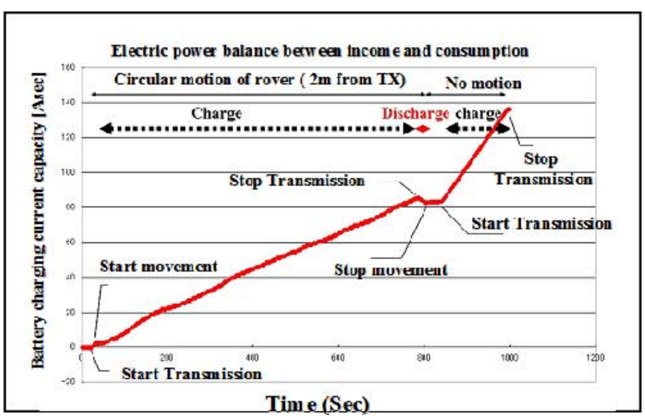

Fig. 5. Electric power balance during WPT test

III. JAPANESE NEW SPACE POLICY

The Japanese new space policy was enacted in 2008 and the basic plan for space policy was established in 2009. They have summarized 9 space systems and programs for the social demands to be realized through the use and R&D of space and a specific goal to correspond to each demand for the next 10 years. SSPS program was selected as one of the research development programs. After it was selected in the space policy, METI had initiated the research and development of microwave power transmission ground testing project. Though SSPS was selected as an important project, the large space system was not yet declared to be supplied. In this project, we lead the progress of the technology for the next space experiment phase, and conduct electric power transmission demonstration at the end of this period.

IV. THE OBJECTIVE OF THE PROJECT

In the previous study as described in paragraph II, we have already been clarifying the issues to be studied.

For the power transmission section, there are five key phrases to realize the SSPS. They are Large, High Efficient, High Accurate, Light Weight and Low Cost. Therefore, we are trying to realize Light Weight thin phased array antenna (thickness is some centimeter) by using High Efficient HPA(High Power Amplifier) that applied GaN HEMT and F class amplifier. As the SSPS has to be large system, multiple small power transmission sections shall be combined and synchronized operation has to be realized with High Accurate beam steering. Power transmission section is composed of four power transmission modules. To synchronize the phase of the transmitting microwave of these power transmission modules, this section has reference signal control function. The power transmission output power should be 1kW or more.

In the receiving section, there are two objectives. One is the stable operate system construction. The receiving panel assumes plural receiving modules connected in series parallel and taking out stable electricity. And the other is highly effective rectifying element development. The target efficiency of element is more than 80%.

A precise beam direction control of the microwave is an important issue for SSPS microwave transmission from 36,000km above. Japan Aerospace Exploration Agency (JAXA), that jointly executes this project, shares this part of research and development. The element electric field vector rotation method (REV method) will be applied to maximize the received electric power. Also software retro directive method will be applied to transmit the microwave beam to the designated direction where locates the receiving section. The angle accuracy to be achieved in beam control is less than 0.5 degree for the ground experiment.

These sections will be combined at the final phase of this project, and we can demonstrate the wireless power transmission.

V. Progress of the Project

Overall architecture of the system was determined, and functions and performance of the subsystem were defined. After this study, basic design and element examination work were pushed forward. These summaries are shown below.

A. Power Transmission Section

GaN HEMT with F-class power amplifier was applied to the power transmission section. GaN HEMT has attracted much attention as it is the state-of-the-arts microwave power transistor due to its high voltage and high power density capability. F-class operation was applied for high efficient power amplifier operation. In this work, an internally matched GaN HEMT high efficiency amplifier is developed, in which 2nd harmonic at input side and 2nd and 3rd harmonic at outside are tuned with internal matching circuit as shown in Fig.6. Very high Power Add Efficiency, PAE 70%, with 7W output power was successfully obtained. Fig.7 is the photograph of hermetic sealed metal packaged GaN HEMT high efficiency amplifier [9].

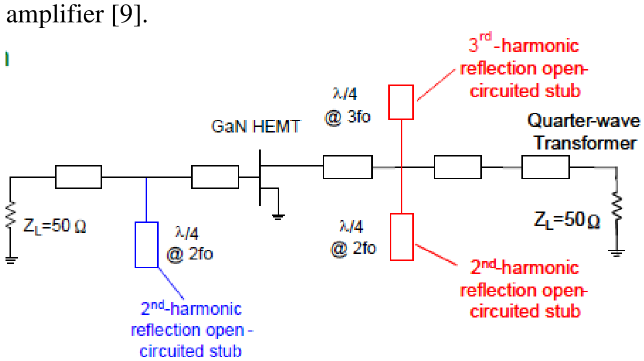

Fig.6. High Power Amplifier (HPA) Circuit

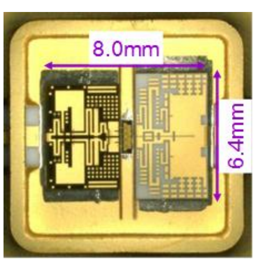

Fig. 7. Metal packaged GaN HEMT Amplifier

The output power from HPA is fed to antenna elements which have four elements sub-array structure via filter and the distributor, and the many sub-array antennas consist the power transmission module, which size is 60cm x 60cm. Furthermore, four transmission modules consist a power transmission phased array antenna, the total size is 120cm x 120cm.

For space application, antenna thickness is very important parameter. As the huge sized SSPS is required because of its performance requirement, light weight transportation size and the expansion in space are necessary. Fig.8 is the conceptual image of thin sub-array structure. Vertical power distribution is applied to reduce the thickness. The microwave is distributed from the circuit board to the vertically connected antenna array substrate. The achievement of the thickness is 44.4mm in our current design [10]. We are trying to reduce the thickness with small degradation.

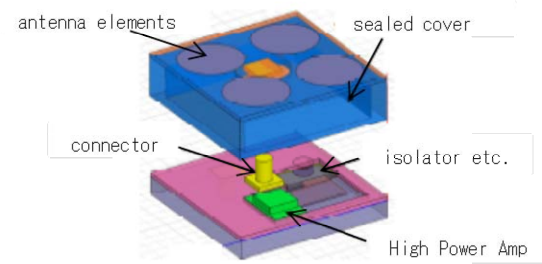

Fig. 8. Sub-array radiation part structure image

B. Power Receiving Section

The receiving section has function to rectify received microwave. It converts the received microwave energy to DC electricity. The total efficiency from transmitted power to the converted power mainly depends on the beam shape and the size of receiving antenna. The technological issue of receiving section is to predict the distribution of power flux density, and to take out the energy with appropriate antenna arrangement using series/parallel connection. To take stable electrical energy with high efficiency is very important.

Fig.9 is the typical block diagram of rectenna. Rectenna is composed of antenna and rectifying circuit. For SSPS System, transmitting microwave has narrow band and single frequency, for example 5.8GHz. Therefore, broadband characteristic is not required. Patch antenna is suitable than linear antenna because it has miniaturizing potential. Self-biased rectifying circuit is used in a rectenna. This circuit has input filter, rectifying diode and output filter. Most of the power loss might be caused by the loss in rectifying diode. We are considering improvement of efficiency with studying several diode parameters.

For the receiving antenna for the ground wireless power transmission demonstration, we are considering 2.5m sized receiving panel consisted of tens of square shaped receiving module.

In parallel to the receiving antenna development described above, we are trying to develop a high effective shottky barrier diode for rectifier using GaN material. The experimental manufacturing process and manufacturing condition are evaluated in this development [11].

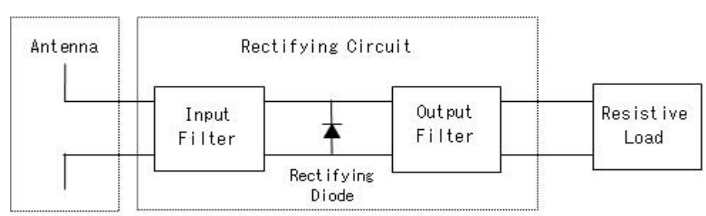

Fig. 9. Rectenna block diagram

C. Power Transmission Demonstration Test

As described before, phased array transmitting antenna size is 120cm x 120cm and the output power is 1.6kw. The power flux density at the receiving position center is calculated in Fig.10. We have selected the 50m distance according to the relationship between distance and energy.

An energy distribution at 50m point is analyzed as shown in Fig.11. The black flame in the figure is shape of the receiving panel being assumed now, and the electric power collection efficiency (energy that physically hits the receipt panel when the gross energy transmitted is assumed to be one) remains in about 58%. This microwave energy enters the receiving module, and then it is taken out as electricity. Around several hundred watts power can be taken out from the current demonstration.

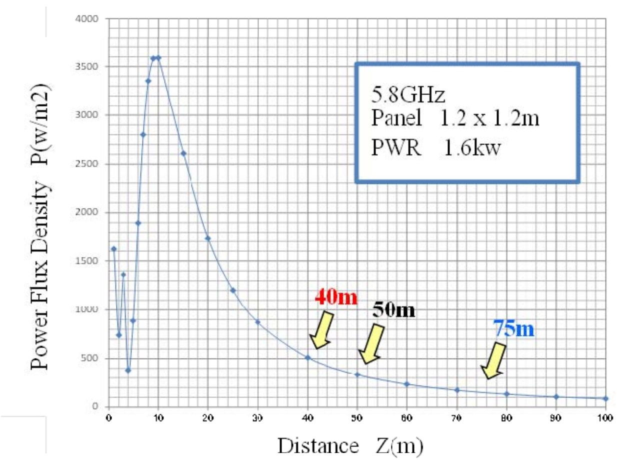

Fig.10. Power flux density

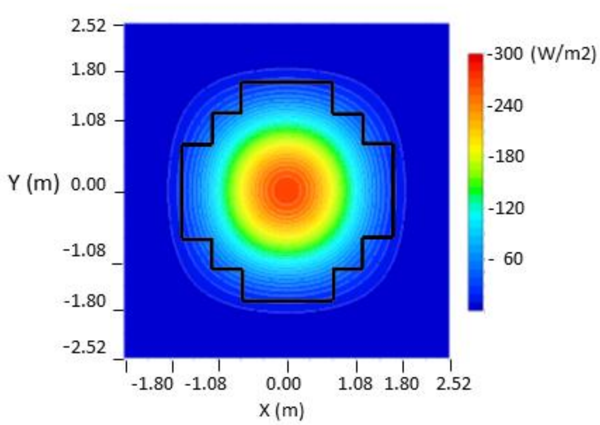

Fig.11. Energy distribution at 50m point

VI. Conclusion

Microwave power transmission project is now conducting. In this project, we lead the progress of the technology for the next space experiment phase, and conduct electric power transmission demonstration at the end of this period. We shall always consider the next coming space experiment step during this project.

Acknowledgement

The chairman of Microwave Power Wireless Power Transmission Technology Committee is Prof. Naoki Shinohara, Kyoto University. This committee consists of 11 members. Research and development related to the beam control section are shared with Japan Aerospace Exploration Agency, JAXA. USEF is working with Mitsubishi Electric Corporation, MELCO, at Power Transmitting section, and with IHI Aerospace Co., Ltd., IA, at Power Receiving section. This project is supported by the Ministry of Economy, Trade and Industry, METI. .

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