MICROWAVE WPT TECHNOLOGY DEVELOPMENTS FOR SSPS APPLICATION

Takashi Saito , Yoshiharu Fuse, Shoichiro Mihara, Shuji Nakamura, Koichi Ijichi
Japan Space Systems(J-spacesystems) 3-5-8 Shibakoen, Minato-ku, Tokyo 105-0011 JAPAN
{Saito-Takashi, Fuse-Yoshiharu, Mihara-Shoichiro, Nakamura-Shuji, Ijichi-Koichi}@jspacesystems.or.jp

Yukihiro Homma, Takuro Sasaki
Mitsubishi Electric Corporation (MELCO) 8-1-1 Tsukaguchi-Honmachi,Amagasakicity,Hyogo,661-8661 JAPAN
Homma.Yukihiro@df.MitsubishiElectric.co.jp, Takuro.Sasaki@dn.MitsubishiElectric.co.jp

Eiichiro Fujiwara, Yuichiro Ozawa, Teruo Fujiwara
IHI Aerospace Co., Ltd. (IA) 900 Fujiki, Tomiokacity,Gunma,370-2398 JAPAN
{yuichiro-ozawa, e-fujiwara}@iac.co.jp, qfuji@js5.so-net.ne.jp

Keywords: Space solar power system (SSPS), Wireless Power Transmission(WPT), Japanese new space policy & new space plan, Ground microwave WPT

Abstract: Japan Space Systems(J-spacesystems), formerly known as Institute for Unmanned Space Experiment Free Flyer (USEF), has been studying Space Solar Power System as future electricity alternative energy source. Since 2009, J-spacesystems started new research and development project of the Microwave Ground Wireless Power Transmission under a support of Ministry of Economy, Trade and Industry. This project includes the study for highly-efficient and thin structured phased array antenna, and the study for highly-efficient rectenna element. Also this project plans to demonstrate ground wireless power transmission as a previous stage to the next space proof of SSPS. In this paper, outline and progress of this project are introduced.

1 INTRODUCTION

Japan Space Systems(J-spacesystems, formerly USEF) has been studying Space Solar Power System (SSPS) under a support of Ministry of Economy, Trade and Industry(METI) and the other related agency since 1990s. These studies were ranging from laboratory tests to concept study of SSPS. (Mihara et al., 2009).

In 2008, the Japanese new space policy(the Basic Space Law) was enacted and the Basic Plan for Space Policy was established in 2009. They have selected "5 systems for utilization" and "4 programs od R&D" . SSPS is one of the R&D programs. This Plan is a five-year-program, from FY2009 to FY2013, foreseeing the next ten years, describing the basic policy and the measures which the Government should take during this period. (Strategic Headquarters for Space Policy, 2009)

In 2009, METI requested for propals for the Microwave Power Transmission(MPT) ground test(demonstration) according to the Basic Plan, and the proposal of the team of J-spacesystems and companies(Mitsubishi Electric Co. and IHI Aerospace Co.) was adopted. (Fuse et al., 2011)

This is also a joint program between J-spacesystems and the Japan Aerospace Exploration Agency (JAXA). We are planning to conduct a joint MPT ground experiment in fiscal 2014. We will demonstrate the technologies needed to transmit a kW class microwave precisely to the receiving site

Saito T., Fuse Y., Mihara S., Nakamura S., Ijichi K., Homma Y., Sasaki T., Fujiwara E., Ozawa Y. and Fujiwara T.
MICROWAVE WPT TECHNOLOGY DEVELOPMENTS FOR SSPS APPLICATION.
DOI: 10.5220/0005413600350043
In *Proceedings of the First International Conference on Telecommunications and Remote Sensing (ICTRS 2012)*, pages 35-43
ISBN: 978-989-8565-28-0

located 50 m from the power transmitting section. In this joint effort, J-spacesystems is in charge of the power transmitting section and the power receiving section, and JAXA is in charge of the Beam Steering Control (BSC) section. (Miyakawa et al., 2011)

2 SSPS REFERENCE MODELS

2.1 Single-bus type Model (FY2002)

Figure 1 illustrates the concept of the tethered-SSPS which is capable of 1.2GW power supply maximum and 0.75GW average on the ground. It is composed of a power generation/transmission panel of 2.0km×1.9km suspended by multi-wires(tethers) deployed from a bus system(single) which is located at 10 km upward. The panel consists of 400 subpanels of 100m×95m with 0.1m thickness. Each subpanel has 9500 power generation/transmission modules of 1m × 1m size. In each power module, the electric power generated by the solar cells is converted to the microwave power and no power line interface exists between the modules. The power module has thin film solar cells both on the upper and lower planes. The microwave transmitting antennas are on the lower plane. The module contains a power processor, microwave circuits, and their controller. Each module transmits a microwave power of 420W maximum. (Sasaki et al., 2006)

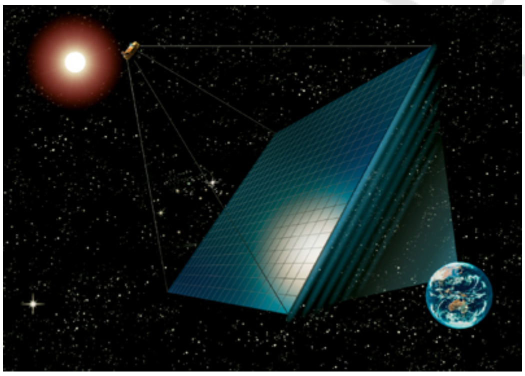

Figure 1: Single -bus type SSPS

2.2 Multi-bus type Model (FY2006)

In 2006, the multi-bus type of SSPS was newly proposed. Figure 2 shows the satellite structure of the multi-bus tethered SSPS. The new SSPS system has a multi-module structure. (see Figure 3)
In "Unit"SSPS, tethers link the bus system with the power generation/transmission modules.
So, a "Unit" SSPS is a small "single-bus type". Each "Unit" itself can transmit power(2.1MW) to Earth. Several "Units" are assembled to "Unit Assemly", and "Unit Assemly" s to "Multi-bus type"SSPS in a similar way.
The concept of this type is, so to speak, "Start Small, Let it Grow". (Yoshioka et al., 2011)

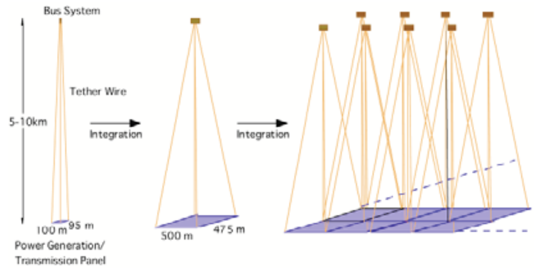

Figure 2: Multi-bus type SSPS

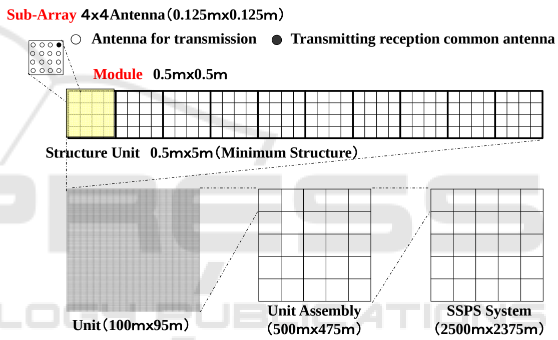

Figure 3: hierarchical structure of power transmitting panels

3 MPT GROUND EXPERIMENT MODEL

3.1 Total System

Figure 4 shows the outline of the MPT Ground Experiment Model, and Figure 5 shows its tree diagram. The model consists of three sections;

- Power Transmitting Section
- Power Receiving Section
- Beam Steering Control Section (JAXA)

As for Beam Steering Control Section, Japan Aerospace Exploration Agency (JAXA) is in charge of the section.

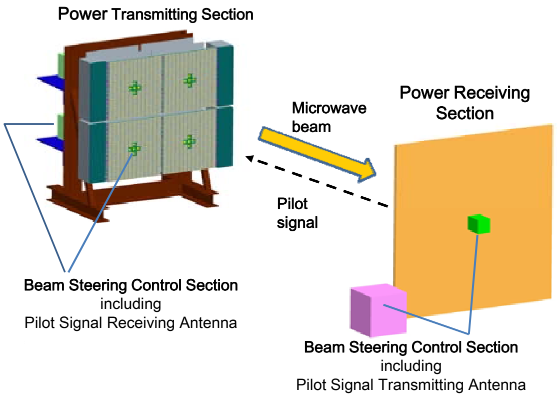

Figure 4: MPT Ground Experiment Model

MPT Ground Experiment Model

- Power Transmitting Section
  - Power Transmitting Panel
  - Reference Signal Control Master Unit
  - Power Supply
  - ......
- Power Receiving Section
  - Power Receiving Panel
  - Rectenna Control Unit
  - Battery Unit
  - Power Receiving Section Monitor & Control Unit
  - Power Supply
  - ......
- Beam Steering Control Section (JAXA)
  - Pilot Signal Transmitting Antenna
  - Pilot Signal Receiving Antennas
  - ......

Figure 5: Tree Diagram of Ground Experiment Model

To realize SSPS, each section needs to have following features;

for Power Transmitting Section,

- light weight and thin power transmitting modules (transportation and construction cost)
- high efficiency (heat discharge and power generation cost)

for Power Receiving Section,

- electrical robustness (stable operation and maintenance cost)
- high efficiency (power generation cost)

for Beam Steering Control Section

- beam steering control accuracy (safety)

To solve these problems, our solutions are;

for Power Transmitting Section,

- to develop a thin sub-array
- to apply highly efficient HPA to GaN HEMT, F-class amplifier

for Power Receiving Section,

- to find out the cause of rectenna damage
- to develop a highly efficient diode

for Beam Steering Control Section

- retro directive method (using pilot signal)
- rotating electromagnetic vector method (REV method)

Beam Steering Control Section has;

- Pilot Signal Transmitting Antenna (Power Receiving Section)
- Pilot Signal Receiving Antenna (Power Transmitting Section)

The microwave beam frequency is 5.8GHz, and the pilot signal frequency is 2.4GHz band. (Miyakawa et al., 2010)

3.2 Power Transmitting Section

3.2.1 Basic Design

The basic design concept of the power transmitting section is as follows;

- High power (kW-class)
- High efficiency of DC-RF conversion
- Thin phased array (Sub-array)
- Principled reference signal control

Tree diagram of Power Transmitting Section is shown in Figure 6. And the system block diagram of the power transmitting section is shown in Figure 7.

- Power Transmitting Section
  - Power Transmitting Panel
    - Power Transmitting Module (x4)
      - Sub-array (x76)
        - Antenna (x4)
        - HPA Module
        - Beam Forming Network (BFN)
      - Divider
      - First Stage HPA Module
      - BFN for Control Signal (BFNC)
      - Power Supply Card
      - Reference Signal Control Slave Unit
  - Reference Signal Control Master Unit
  - Power Supply

Figure 6: Tree Diagram of Power Transmitting Section

Four power transmitting modules, which are phased array antennas, constitute of the power transmitting section.

A sub-array is the minimum unit. It consists of a BFN, an HPA module(MDL) and four sub-array antennas. A BFN receives microwave, DC power and control signal, and feeds them to the HPA MDL. Each HPA MDL has a phase-shifter, a driver amplifier, a high power amplifier and so on. Then, it provides microwave to four sub-array antennas.

A power transmitting module has 76 Sub-arrays. The module size is 60cm square. One module can output more than 400W. So the power transmitting panel(4 modules) size is about 1.2m square and the output power is about 1.6kW.

Figure 8 shows the outline view of Power Transmitting Section. Pilot Signal receiving antenna is set in the center of each power transmitting module (PT module). It is used for beam steering control.

Each PT module transmits microwave beam to the right direction according to the phase control signal from the beam steering control section. A PT module generates microwave in accordance with the reference signal from RSC master unit. This microwave is amplified by HPA modules (first stage and sub-array) using DC power from the main power supply, and divided by the divider, distributed to the sub-array antennas, and then transmitted.

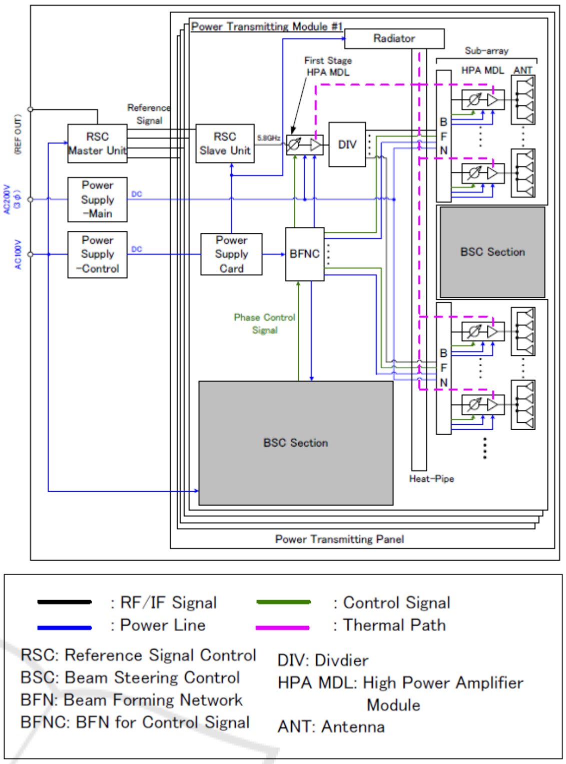

Figure 7: Block diagram of the power transmitting section

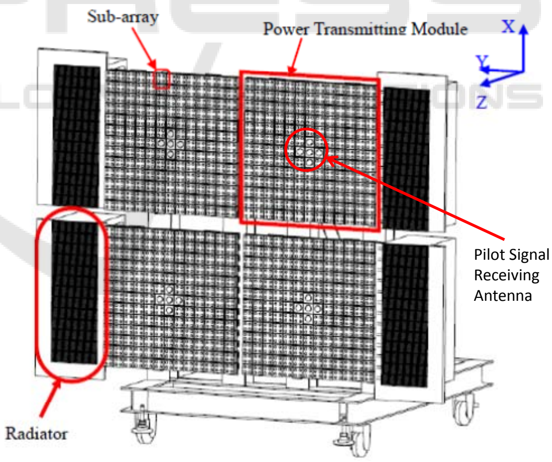

Figure 8: Outline view of power transmitting section.

As for SSPS, relative positions among the power transmitting modules may change. Power Transmitting Section has a function to simulate this situation by moving PT modules manually, for the purpose of verifying the effectiveness of the beam control method under that condition .

Table 1 shows the specifications of power transmitting section.

Table 1: Specifications of Power Transmitting Section

Item	Specification
Microwave Frequency	5.8GHz±75MHz
Power Transmitting Modules	Number: 4 Size: ≈0.6m x 0.6m Thickness: ≤40mm (Sub-array) Efficiency: ≥30% (PT module) Mass: ≤19kg (Sub-arrays)
High Power Amplifier (HPA)	GaN HEMT with F-class 76 HPAs (per PT module) Efficiency (PAE): ≥60% Ave.
Antenna Spacing	0.65λ (33.6±1 mm)
Phase Shifter	5 bit (MMIC)
Transmitting Power	≥400W (per PT module) ≥1600W (total)

As for the following items, our policy is;

- to get low loss Sub-array antenna for high efficiency, rather than for thickness.
- to get thin, light Sub-array structure
- to make a good balance between high efficiency and thickness of HPA module

GaN HEMT with F-class power amplifier is applied to the power transmission section. GaN HEMT has attracted much attention as the state-of-the-art 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 efficient amplifier is developed, in which 2nd harmonic at input side and 2nd and 3rd harmonic at outside are tuned with internal matching circuit. Very high Power Added Efficiency(PAE) 70%, with 7W output power was successfully obtained. Figure 9 is the photograph of hermetic sealed metal packaged GaN HEMT high efficienct amplifier. (Yamanaka et al., 2010)

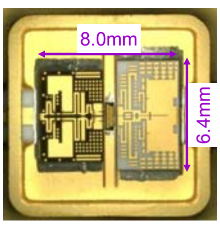

Figure 9: Metal packaged GaN HEMT amplifier

For space application, antenna thickness is very important parameter. Because the huge sized SSPS requires light weight for lower cost transportation and also requires the expansion structure in space.

Figure 10 is the ideal image of thin sub-array structure. Vertical circuit for the connection of the micro wave circuit board to the antenna array substrate was applied for the thickness reduction. The achievement of the thickness was 44.4mm in our early design. We are trying to reduce the thickness with keeping low loss performance. (Namura et al., 2010)

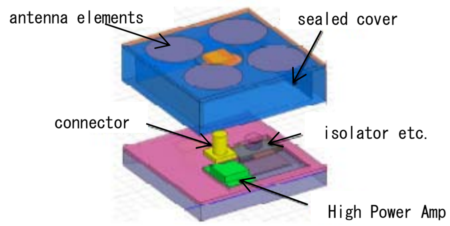

Figure 10: Sub-array radiation part structure image

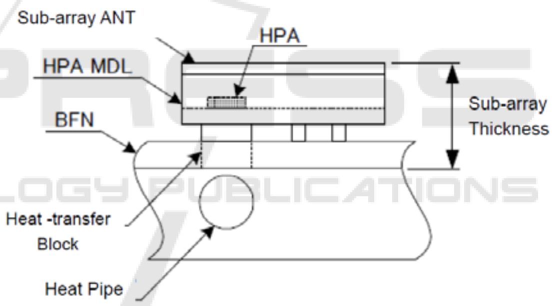

Figure 11: Sub-array thickness

According to above studies, a new design target is set as Table 2.

Table 2: Design Target (typical)

Item	Specification	Target
Output Power	≥400W per PT module	411W per PT module
Efficiency	≥30% as PT Section	35% as PT Section
Sub-array Thickness	≤40mm	34mm
Sub-array Mass	≤19kg	19kg

3.2.2 Element Test

In FY2011, a performance verification test of the HPA module(trial product, see Figure 12) was done. It consists of HPA module, Sub-array ANT, BFN etc. It became certain that all test results meet the design target (see Table 3).

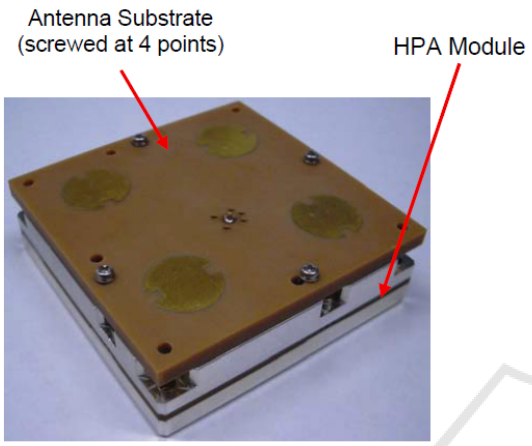

Figure 12: HPA module(trial product)

Table 3: HPA module(trial product) Test Result

Item	Design (average)	Test (average)
Output Power	≥6.1W	6.17W
Efficiency(PAE)	≥40.2%	41.50%
Accuracy of Phase-Shift	≤3deg rms	2.1deg rms
Spurious	≤ - 60dBc	- 65.7dBc
Size	62x62x14.6mm	62x62x14.6mm
Mass	92g	91.3g

We are going to examine the ongoing design of PT module(e.g., performance, size, mass, heat radiation) and make a prototype of sub-array.

3.3 Power Receiving Section

3.3.1 Basic Design

A tree diagram of Power Receiving Section is shown in Figure 13. And the system block diagram of the power receiving section is shown in Figure 14. Power receiving panel consists of 37 power receiving modules. The pilot signal transmitting antenna is set in the center module. (see Figure 15 and Figure 16)

- Power Receiving Section
  - Power Receiving Panel
    - Power Receiving Module (x37)
    - Panel Structure
  - Rectenna Control Unit
  - Battery Unit
  - Power Receiving Section Monitor & Control Unit
  - Ground Test Equipment
    - Remote Control Unit
    - Power Distribution Unit
  - Power Supply

Figure 13: Tree Diagram of Power Receiving Section

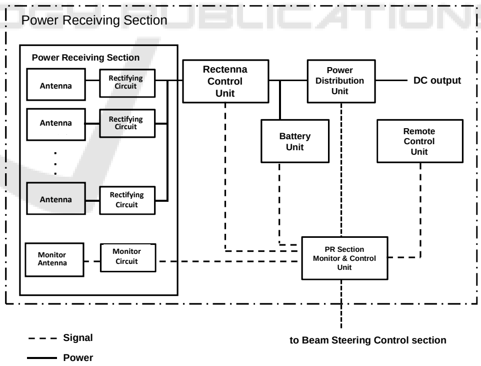

Figure 14: Block diagram of the Power Receiving Section

Table 4 shows the specifications of power receiving section. The diodes used in the power receiving module are "regular type"(commercialized product) .

The RF-DC efficiency(antenna to rectenna control unit) is estimated by efficiencies of :

- antenna polarization
- rectifying circuit
- rectenna control unit.

As a result, the RF-DC efficiency is estimated to be 56.8%.

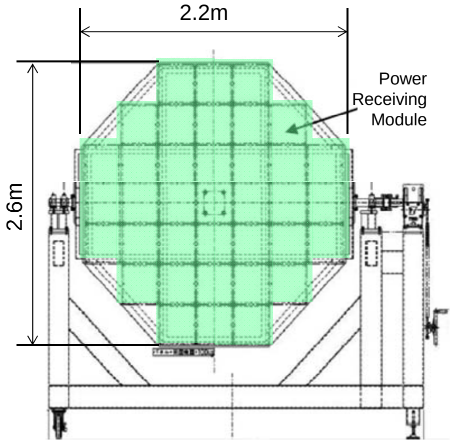

Figure 15: Power Receiving Section

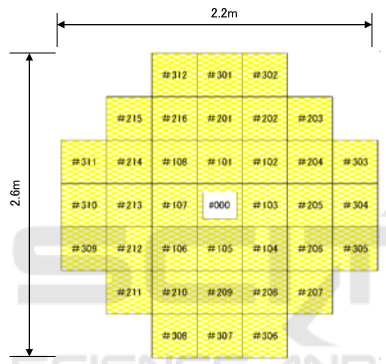

Figure 16: Power Receiving Panel (Rectenna Array)

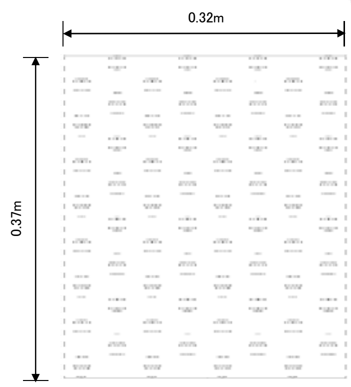

Figure 17: Power Receiving Module

Table 4: Specifications of Power Receiving Section

Item	Specification
Power Receiving Panel	Size : 2.6m × 2.2m
Power Receiving Module	Number: 37 Size: 0.37m x 0.32m
Diode type	Schottky barrier diode
RF-DC Efficiency	≥ 50% (Regular type, Power Receiving Panel) ≥ 80% (Advanced type, Rectenna Element)
Receiving Power	≥300W (estimated)

3.3.2 Element Test

Figure 18 is the typical block diagram of a rectenna. Self-bias rectifying circuit is used in a rectenna. This circuit has input filter, rectifying diode and output filter. Most of the power loss will be caused by the loss in rectifying diode. There have been several reports on the causes of the loss in diode. (McSpadden et al., 1998)

In parallel to designing power receiving module, we are trying to develop a high efficient Schottky barrier diode for rectifier using GaN material (Advansed type). In this development, an experimental evaluation of the manufacturing process and the manufacturing condition have been done. (Ozawa et al., 2010)

We are considering improvement of efficiency with studying parameters as follows:

- Cj_0: junction capacitance(zero bias)
- Rs: series resistance
- Vbi: built-in voltage
- Vbr: breakdown voltage

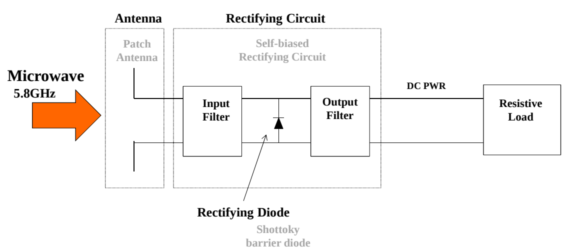

Figure 18: block diagram of a rectenna

A trial modelshows more efficiency than that of existing "Regular type". We continue making an effort to improve "Advansed type" diode.

4 MPT GROUND TESTS

We are planning the indoor and outdoor MPT tests. They wil be completed by fiscal 2014.

4.1 Indoor Test

Outline of the indoor(laboratory) test is shown in Table 5.

Table 5: Outline of the indoor test

Facility	anechoic chamber
Test Equipment	Power Transmitting Module × 4
Power Transmitting Distance	≥10 meters
Beam Pointing Accuracy	≤0.5 degrees (rms)
Microwave Frequency	5.8GHz±75MHz
Pilot Signal Frequency	2.4GHz band (Miyakawa et al.,2011)

4.2 Outdoor Test

Outline of the outdoor(field) test is shown in Table 6.

Table 6: Outline of the outdoor test

Facility	outdoor field
Test Equipment	MPT Ground Experiment Model (Power Transmitting Module × 4)
Power Transmitting Distance	≈ 50 meters
Transmitting Power	≈ 1.6kW (411W×4)
Power Flux Density @center, 50m	315W/m2±20% (estimated)
Output Power	≈ 0.3kW (estimated)

The objectives of the field test, or the demonstration, are;

- to transmit kW-class power
- to prove precise beam pointing accuracy(retro-directive, REV method)
- to demonstrate WPT (e.g., to feed electricity from rectenna to home electrical appliances

The energy electricity flux density at the receiving position center is calculated in Figure 19.

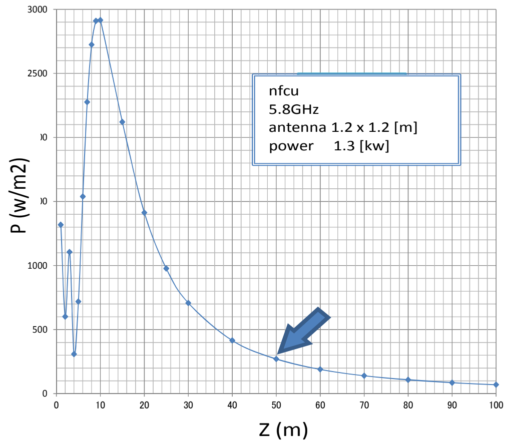

Figure 19: Electricity flux density

An energy distribution at 50m point is analyzed as shown in Figure 20. The black flame in the figure is shape of the receiving panel.

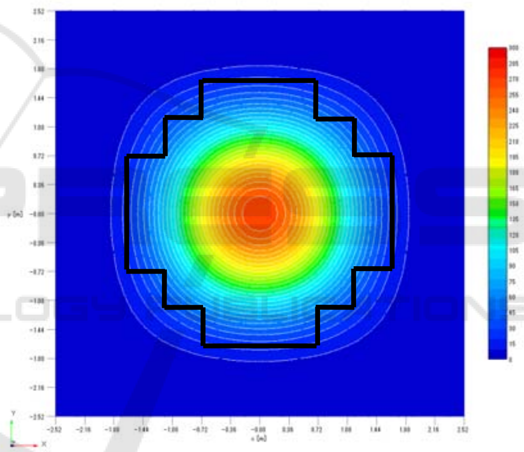

Figure 20: Energy distribution at 50m point

Figure 21 shows a WPT demonstration image. Layout of power transmitting/receiving sections is to be determined, avoiding any radio wave interference.

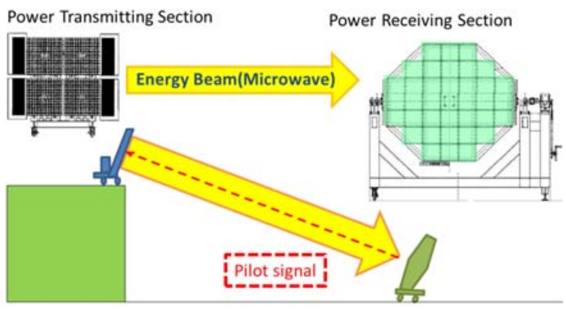

Figure 21: WPT Demonstration Image

CONCLUSION

Microwave Ground WPT project is currently going on. Basic design and element tests are in progress. We are planning to conduct the MPT ground experiment in FY 2014 in collaboration with JAXA. We have started to develop a concrete plan for the demonstration. And we should always be conscious that this ground demonstration is a preliminary step toward the next step of demonstration in space.

ACKNOWLEDGMENTS

The chairman of Microwave Power Wireless Power Transmission Technology Committee is Prof. Naoki Shinohara, Kyoto University. This committee consists of 12 members. Research and development related to the beam steering control section is shared with Japan Aerospace Exploration Agency, JAXA. J-spacesystems 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.

REFERENCES

Fuse, Y., Mihara, S., Saito, T., Ijichi K., Namura, K., Homma, Y., Sasaki, T., Ozawa, Y., Fujiwara, E., Fujiwara, T., 2011. *Microwave Energy Transmission Program for SSPS*, CHGBDJK.2 URSI GAS2011, Aug. 2011

McSpadden, Lu Fan, J., Kai Chang, K., 1998. *Design and Experimental of a High-Conversion-Efficiency 5.8-GHz Rectenna*, IEEE Trans. MTT, Vol.46, No.12, 1998, pp2053-2060

Mihara, S., Saito, T., Kobayashi, Y., Kanai, H., 2007. *Activities for the Realization of Space Solar Power Syatem at USEF*, S1-I-1408 URSI ISRSSP2007, Sep. 2007

Miyakawa, T., Sasaki, S., Yajima, M., Maki, K., Mihara, S., Fuse, Y., Saito, T., Ijichi, K., Homma, Y., Sasaki, T., Ozawa, Y., Fujiwara, E., Fujiwara, T., 2011. *Development Status of Microwave Power Transmission Demonstration on Ground for Space Solar Power Systems*, IAC-11-C3.2.2, 62nd International Astronautical Congress, Oct. 2011

Namura, K., Honma, Y., Sasaki, T., Samejima, F., Ishikawa, T., Fuse, Y., Saito, T., Mihara, S., 2010. *Studies on Transmission Subsystem for Ground WPT Experiment System*, 1S12 54th Space Science technology symposium, 2010

Ozawa, Y., Fujiwara, E., Fujiwara, T., 2010. *Study on technical demonstration model of microwave receiving System*, 1S14 54th Space Science Technology Symposium, 2010

Sasaki, S., Tanaka, K., Higuchi, K., Okuizumi, N., Kawasaki, S., Shinohara, N., Senda, K., Ishimura, K., 2006. A New Consept of solar power satellite: Tethered-SPS, Acta Astronica 60, 2006, p153-165

Strategic Headquarters for Space Policy, 2009. *Basic Plan for Space Policy*, June 2009

Yamanaka, K., Tsuyama, Y., Ohtsuka, H. Chaki, S., Nakayama, M., Hirano, Y., 2010. *Internally-Matched GaN HEMT High Efficiency Power Amplifier for Space Solar Power Stations*, WE3A-1, APMC2010

Yoshioka, K., Matsuoka, H., Hayami, H., Collins, P., Sasaki, S., Takano, T., Asakura, K., Nakano, S., 2009. *Essays on the Solar Power Satellite*, Keio University Press, 2009