Microwave Power Transmission Experiment on Ground for SSPS Demonstration

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For the microwave-type SSPS (Space Solar Power Systems), the most important subject to be verified towards the commercial SSPS is microwave power transmission from the orbit precisely to the rectenna on ground. This requires demonstration of the microwave beaming/pointing technology and verification of beam transmission through the ionosphere. The latter can only be verified by conducting a space experiment using a high-power microwave transmitter in orbit, but the former can be achieved by ground-based experiment. JAXA is now planning to conduct a microwave power transmission experiment on ground in cooperation with other research agencies and universities. The objectives of the experiment are, 1) to establish technologies to control a microwave power beam directing at a target rectenna, and 2) to establish technical readiness for the space experiment in the near future.

Key Words: Microwave Power Transmission, Space Solar Power Systems

1. Introduction

Two models of microwave-type SSPS (Space Solar Power Systems) have been proposed in Japan. One is a simple configuration using a power generation/transmission panel without the sun tracking mechanism. The typical example is the Tethered-SPS in which the power generation/transmission panel is suspended by tether wires and stabilized by gravity gradient force, which has been studied by USEF, called "basic model"[1)](Fig.1). The other is a combination of reflective mirrors with power generation solar array and microwave transmitter. The typical example is the formation flight model of reflective mirrors and power generation/transmission complex, which has been studied by JAXA, called "advanced model"[2)] (Fig.2). For these microwave-type SSPS, there are three important technologies to be developed; high efficiency power conversion from DC to microwave, microwave beaming, and high efficiency power conversion from microwave to DC. The target conversion efficiency from DC to microwave and vise versa is 80-85 %. This will be achieved in the near future based on the current state-of-art technologies. On the other hand, the microwave beaming technology targeting from 1 km size transmitting antenna in the geostationary orbit to several km size rectenna on ground is much challenging. Such a high-precision beaming/pointing has not been verified so far, although it is believed possible from a theoretical point of view. A retro-directive beam control for an antenna array is the most promising technology for SSPS microwave beaming that uses a beam-guiding signal (pilot signal) from the rectenna site.

JAXA is now preparing an experiment on the ground to demonstrate the high-precision beaming technology in the next several years. The basic concept of the experiment is to transmit a kilowatt-level microwave to a rectenna located typically at 100 m apart from the transmitter. The microwave beam is generated by the phased array antenna and the phase of microwave from each antenna is controlled using the pilot signal from the rectenna site so as that the beam is focused on

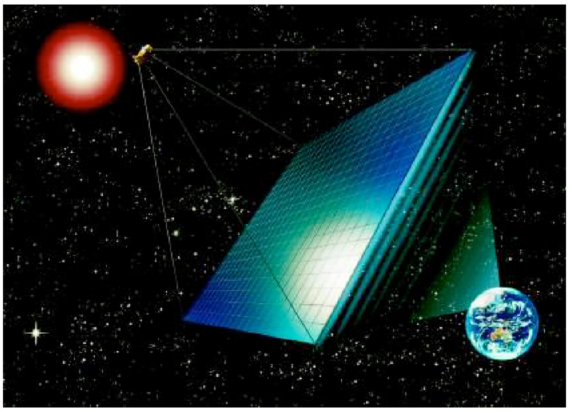

Fig.1 Conceptual image of earth pointing Tethered- SPS (basic model).

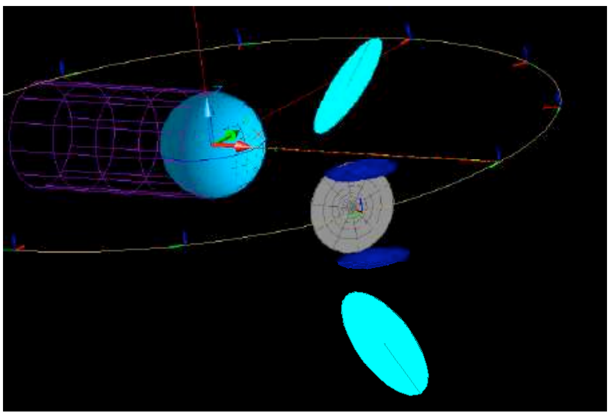

Fig.2 Conceptual image of sun-pointing SSPS using two free flying mirrors (advanced model).

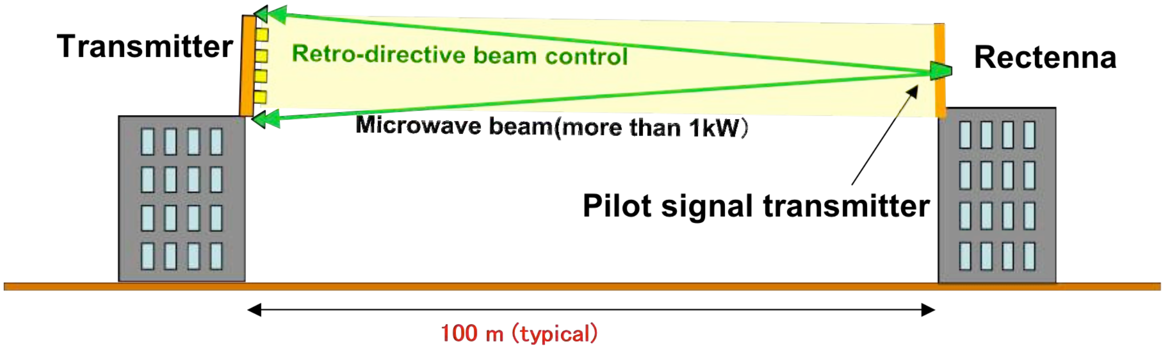

Fig.3 Configuration of the demonstration experiment.

the rectenna. There are several ideas for the retro-directive control combined with a feedback control using an information from the rectenna output power. The most promising method will be selected in the design phase, considering the future application for space use. Once the technology is verified and established in the ground experiment, we will enter the phase of space experiment in which a kW class microwave is transmitted from the low earth orbit to the ground site to demonstrate the microwave beaming/pointing technology for the SSPS application.

2. Demonstration Experiment

The basic configuration of the experiment is shown in Fig.3. The transmitter consists of 4 panels of antenna array that are movable to each other to simulate dynamic motion of large antenna in orbit. The space antenna will be composed of a number of rigid panels which are connected to each other. According to an analysis, random motion of each antenna panel less than ±2 degrees is acceptable from a standpoint of power collection on the ground[3]. The rectenna panels and a pilot signal radiator are located at about 100 m from the transmitting site. The rectenna output power is converted to the commercial AC power to operate household electric apparatus for publicity demonstration.

2.1. Microwave Transmitting System

The microwave transmitting panel is capable of 700 W radiation each at 5.8 GHz. Each panel, 0.8 m x 0.8 m will have 169 sets of sub-array consisting of 2 x 2 antennas, separating at 0.65 λ (wavelength). The thickness of the panel will be less than 10 cm. Each antenna transmits 1.04 W power and the amplifier for each sub-array will be 4.5 W. A phase shifter just before the amplifier is controlled so as that the microwave beam from the antenna array is directed to the rectenna by detecting the pilot signal. Software control will be adopted for the retro-directive control. The power efficiency of the amplifier will be more than 50% and the loss of phase-shifter will be less than 6 dB with 4 or 5 bits resolution. Totally 5 antennas will be used for detection of the pilot signal. For the microwave beaming from the 4 panels, the frequency and phase of the local oscillator in each panel needs to be synchronized or adjusted. There are several ways to synchronize them using a master oscillator in the transmitter site or an associated information from the rectenna site. The block-diagram of the transmitting system is shown in Fig.4. The total weight of one panel is estimated less than 30 kg. The power loss (or heat generation) in a panel will be 1kW, which requires a cooling system or low-duty operation.

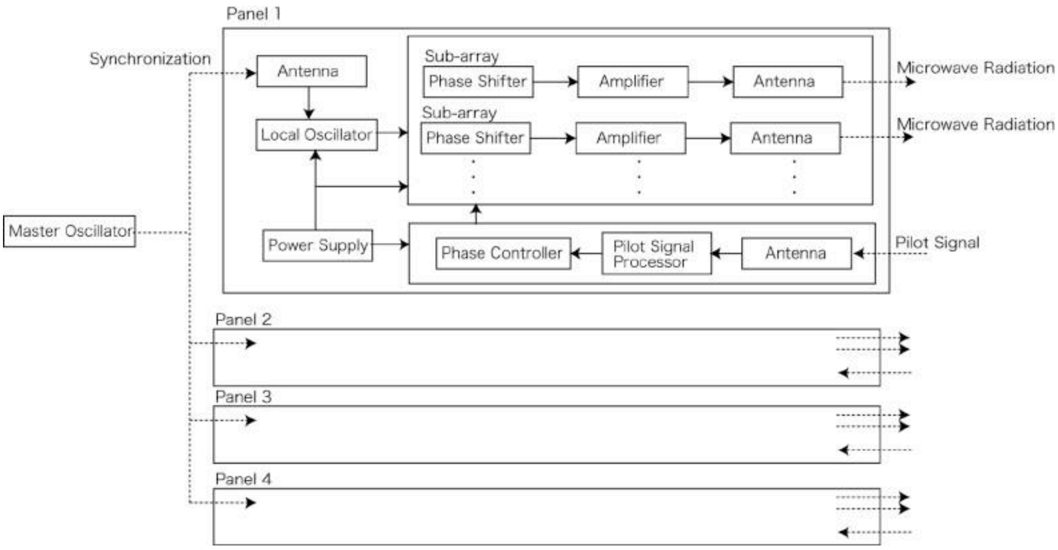

Fig.4 Block diagram of transmitting system.

2.2. Transmission Experiment

Each panel at 700 W will be tested in a shield room, but the system test using four panels at 2.8 kW ranging about 100 m is conducted in the open field. For the field experiment, a special consideration is required to avoid a multi-pass effect by the ground surface. The surface reflection would give disturbances in the phase of pilot signal when received at the transmitter site and jeopardize the beam pointing control. One idea to avoid the multi-pass effect is to conduct the experiment between two building as shown in Fig.3. Another idea is to use a hill and dale site, preferably near a damsite. The beam divergence from the 1.6 m x 1.6 m transmitting antenna consisting of four panels is about 4 degrees. The beam diameter at 100 m is about 7 m. An 8 m x 8 m size rectenna composing of 16 sheets of 2 m x 2m, which will be flexible type, are used to receive the microwave power. The power conversion efficiency of the rectenna is expected to be 75 %. The maximum power is 1.8 kW, which will be converted to the commercial power to be connected to the household electric apparatus, such as refrigerator, TV set, and vacuum cleaner. The planned specification of the experiment is summarized in Table 1.

Table 1 Specification of microwave power transmission experiment.

Transmitter configuration	4 panels movable to each other. 700W/panel, 30 kg/panel (typical),
Microwave transmission panel	169 sub-array/panel, 4 antennas/sub-array, 80 cm x 80 cm, 2-10cm thick microwave conversion efficiency 40 %
Microwave amplifier	5.8 GHz, 4.5 W, efficiency 50 %
Antenna configuration	0.65 λ spacing
Microwave beam control	Retro-directive control using a pilot signal from rectenna site
Phase control accuracy	4 or 5 bits
Rectenna configuration	16 flexible panels, 2m x 2m/panel, DC conversion efficiency 75%
Transmission range	100 m (typical)

2.3. Follow-on Experiment in Space

The major concerns about the microwave power transmission through the ionosphere are the non-linear effect for the high-energy density microwave beam and the effect of the ionospheric scintillation on the pilot signal, as shown in Fig.5. The space demonstration experiment will clarify the allowable power density for the microwave transmission and the scintillation effect on the retro-directive beam control.

JAXA has made conceptual study for the demonstration experiment in space[4]. The weight of the SSPS demonstrator is estimated as 200 kg. The subrecurrent orbit (47 revolutions per 3 days) at an altitude of 370 km is selected to compromise the requirements from the microwave power density and orbit maintenance operation. Figure 6 illustrates the configuration of the demonstration experiment . The attitude of the system is stabilized by the gravity gradient force between the bus system and the power generation/transmission panel which are connected by 4 30m-tether wires. The panel consists of 4 foldable power generation/transmission module. Each module

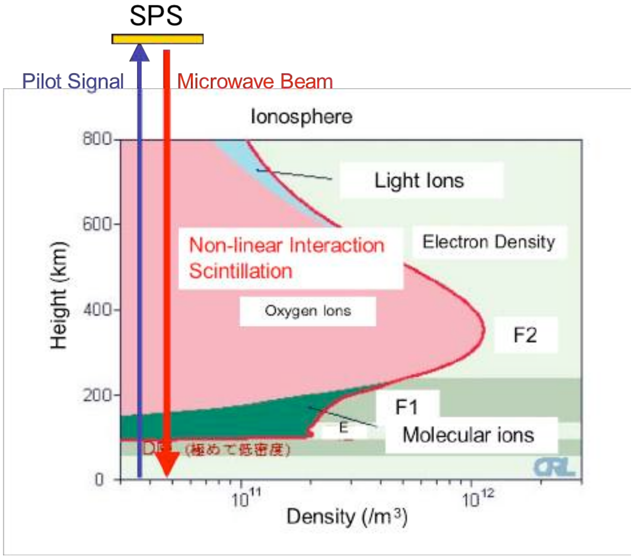

Fig.5 Possible interaction of strong microwave beam with the ionosphere.

is 0.8 m x 0.8 m wide and 0.1-0.02 m thick. The design of the microwave transmitter is equivalent to that of the ground demonstration experiment described in section 2.2. There is no electrical wire interface between the power modules. The bus system has a control and data management system and a propulsion system to keep the orbit. The microwave source signal is radiated from the bus system and is amplified by the 169 sets of the amplifiers up to 700W in each power module. The microwave circuit is designed to control the direction of the beam ± 10 degrees from the normal line of the panel. The total microwave power injected from the power generation/transmission panel is 2.8 kW. This level of the microwave power injection will generate a power density above 100 watt/m^2 for more than 50 m in the ionosphere. The power density on the ground is calculated as 0.8 μ watt/m^2. It is necessary to use a parabola to concentrate the microwave

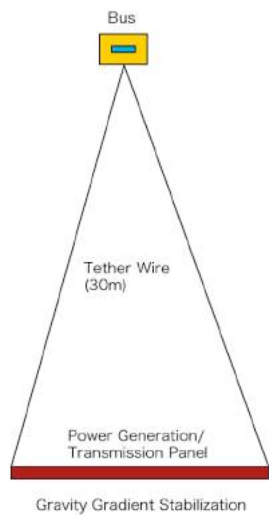

Fig.6 Configuration of the demonstration experiment in space.

power to be rectified by the existing diodes. About 2 m diameter antenna will give a power to illuminate one photo-diode. The interaction of the microwave beam with the ionospheric plasma is measured by a diagnostic package consisting of plasma probes and wave receivers. The package will have a TV camera to observe the dynamic behavior of the tether.

3. Summary

Microwave transmission experiment on ground currently planned in Japan is introduced. It will demonstrate the technologies to transmit a kW class microwave beam precisely at the rectenna located at about 100 m from the transmitter. The technologies verified in the ground experiment will be used to conduct the next-step kW class demonstration experiment from the low earth orbit to the ground. Once the microwave power transmission technologies are verified in the initial space experiment, we will enter the phase of a small scale SSPS of 100 kW class in which we will get a real power of kW class on ground.

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