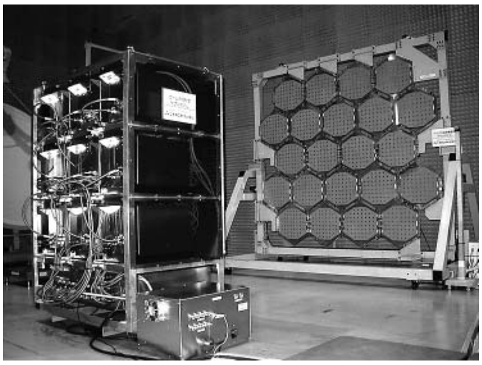

Technology and Applications of Microwave Power Transmission

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The microwave power transmission technology, a key technology for space solar power system (SSPS) which is being spotlighted as a technology capable of solving global environmental problem as well as the energy problem, is drawing attention as a technology applicable on the ground (for power transmission to solitary islands, remote areas, etc.). Mitsubishi Heavy Industries, Ltd. (MHI) has, therefore, undertaken a joint project with the Radio Science Center for Space and Atmosphere of Kyoto University, a leading institute in the world in the field of microwave power, and developed the microwave power transmission experimental equipment in view of applying the technology to space solar power satellite and ground receiving equipment. This paper describes the features of the technology and its future prospect.

1. Introduction

With the arrival of twenty-first century, space solar power system in which large scale solar power generated in space is wirelessly transmitted to the ground has been earnestly planned. This refers to a system that carries out wireless transmission of 1 to 10 GW electric power generated in the geostationary orbit of about 36 000 km altitude to the ground by using radiowave (microwave) of 2.45 GHz or 5.8 GHz. The microwave power received on the ground is then converted into electric power. This technology which consumes no fossil fuel for power generation is expected to solve the global warming problem as well as the energy problem. Furthermore, key technology of the microwave (wireless) power transmission, is drawing attention as a technology applicable to the space solar power system as well as the power transmission on the ground (viz. for power transmission to solitary islands, remote areas, etc.).

2. Outline of the System

The system consists of 3-subsystems given below (**Fig.1**).

(1) Microwave power transmission subsystem
(2) Beam forming and control subsystem
(3) Microwave receiving and power rectifying subsystem

The microwave power transmission subsystem is an power transmission system that uses magnetrons as microwave generators with high-efficiency and high-power. This system uses 9 units of magnetron for cooperative operation to realize high output of 1.26 kW or over.

The beam forming and control subsystem using semiconductor amplifiers is a transmission system aiming at high-precision beam control. This subsystem has realized high-precision beam control through phase control with 144 pieces of antenna.

The microwave receiving and power rectifying subsystem receives/rectifies the microwave transmitted from the aforementioned two transmission subsystems allowing visual confirmation of the received power through the lighting LED's. The subsystem is capable of monitoring the received voltage by means of a control computer by switching the setting of the Monitor Select Switch. Further, the subsystem is designed to be deployed to flat form from the state of several panels piled and stored.

3. Features of the Technology

3-1 Microwave power transmission subsystem

Overall efficiency is important for a microwave power transmission unit. In other words, it is utterly important in an SSPS how to generate maximum output on the ground from the power generated by the solar cell mounted on the satellite. The newly manufactured microwave power transmission subsystem adopts the magnetron with higher efficiency and higher output than the semiconductor as the unit for converting DC power into microwave power.

The newly developed unit (equipment) is designed to have several magnetrons carry out cooperative operation to control the transmission phase, allowing the transmission beam to be turned to a specific direction. The magnetron, generally used for heating in a microwave oven, etc., is lower in price, but because of the large noise it produces at the time of output, it needs some elaboration for multiple cooperation operation. MHI has therefore made effective use of the following characteristics of magnetron to reduce the output noise, leading

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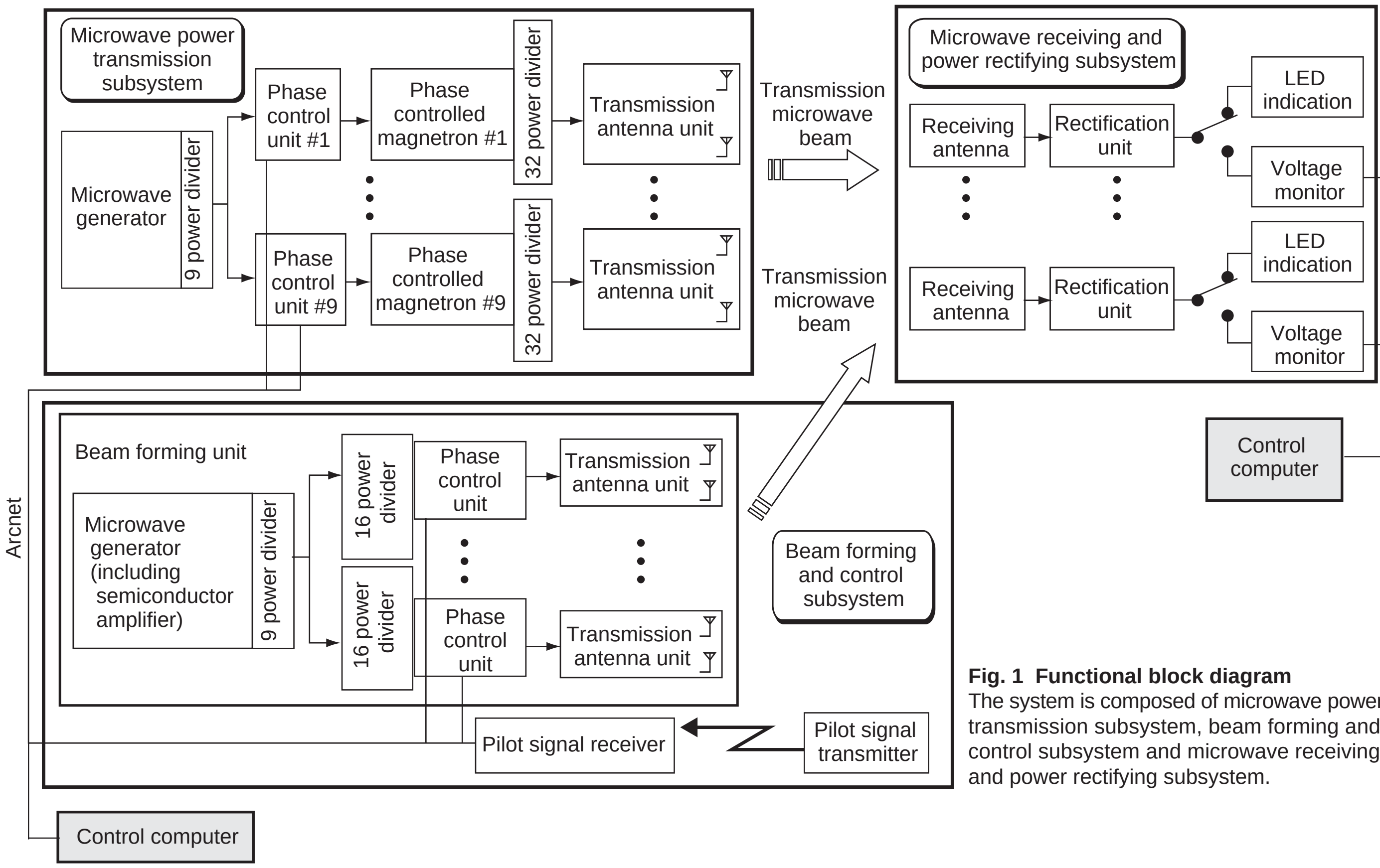


Fig. 1 Functional block diagram
The system is composed of microwave power transmission subsystem, beam forming and control subsystem and microwave receiving and power rectifying subsystem.

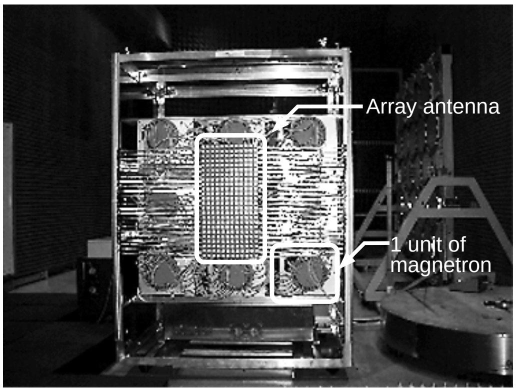


Fig. 2 Microwave power transmission subsystem
Transmits microwave power of 1.26 kW or over through 288 pieces of antenna by cooperative operation of 9 pieces of magnetron.

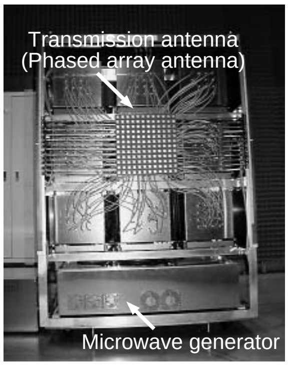


Fig. 3 Beam forming and control subsystem
Controls the output of 144 pieces of antenna using a low-loss phase shifter in order to carry out fine control of power transmission direction.

to a system capable of cooperative operation: (1) the output frequency varies according to the flowing current (plate <anode> current), (2) when the power of the certain frequency from outside (injection signal) is injection, the output gets synchronized with the frequency of the injection signal, and (3) the synchronized output has its phase determined by the difference between the output frequency when the power is not injection externally and the injection signal frequency.

Using the aforementioned characteristics, the output of one standard oscillator is branched to feed into all magnetrons to control the current in each magnetron in order to create a system with the output frequency and phase of multiple magnetrons standardized.

The newly manufactured microwave power transmission subsystem carries out cooperative operation of 9 units of magnetron, and uses 288 pieces of antenna to yield a power of 1.26 kW or over in total. **Fig. 2** shows the microwave power transmission subsystem.

The output of one unit of magnetron is divided to 32 pieces of antenna to be radiated into the space, and in order to minimize the attenuation during this time period, MHI has developed a radial type 32 power divider (with microwave wave-guided injection and coaxial output) having less loss than the conventional type. This has contributed to the realization of a high power feed efficiency of 70.5% to the antenna from magnetron output.

3-2 Beam forming and control subsystem

The beam forming and control subsystem is shown in **Fig. 3**.

This subsystem has the technical features given below in order to carry out forming of composite beam by radiating stable microwave from the phased array antenna and to allow high-accuracy pointing control of the beam.

This subsystem adopts PLL (Phase Locked Loop) synthesizer system with the oscillation frequency of a crystal oscillator as reference signal for its microwave generation unit to realize the stability with frequency deviation less than 10 ppm. Further, the generated microwave power is amplified by using 4 units of high-output semiconductor amplifier connected in parallel before being subjected to power synthesis by means of the impedance matching of the transmission line to generate high-power microwave.

MHI has developed radial type wave-guided power divider (9 divisions) and Wilkinson type power divider (16 divisions) to divide/supply the high-output microwave with low loss and at equiphase angle, and has applied them to the transmission lines to each antenna from the microwave generator.

MHI has developed and supplied a small-size, simple-structure and low insertion loss hybrid type 4-bit phase shifter capable of phase control between 0 and 337.5^{o} at intervals of 22.5^{o} through combination of line switching type (pre-stage) and reflecting type (post-stage).

The control of the phase shifter is executed by the function of switching the line equivalent to 0^{o} and 180^{o} in pre-stage according to 1-bit control signal by using an SPDT (Single Pole Double Throw) switch, and the function of phase control between 0^{o} and 157.5^{o} at intervals of 22.5^{o} by changing the impressed voltage of the varactor diode in the post-stage according to 3-bit control signal.

Further, the phased array antenna is designed to allow arbitrary setting of antenna element interval within the wavelength of 0.6 to 1 in order to conduct study on the improvement of radiation efficiency through optimization of radiated beam synthesis (such as reduction of extraneous radiation in directions other than the main radiation direction.)

The beam forming and control sub-system is further equipped with a pilot signal transmitter/receiver to inform of transmitted direction from the receiving side to the transmitting side. The pilot signal transmitter installed at the receiving side transmits signal to the pilot signal receiver at the transmitting side. The pilot signal receiver receives the signals using multiple receiving antennas, and calculates the angle of arrival of each pilot signal geometrically on the basis of the phase difference of signals received by each antenna before computing the position of the pilot signal transmitter. The principle of angle detection using pilot signal is shown in **Fig. 4**.

The pilot signal is diffused by PN (Pseudo Noise) signal (code) applying the frequency SS (Spread Spectrum) technology used also in wireless LAN, etc., so that only the signals with the PN codes same as PN codes at transmitting side and which can be put to correlative processing are selected and received. Furthermore, the frequency diffusion also improves the resistance against the noise.

3-3 Microwave receiving and power rectifying subsystem

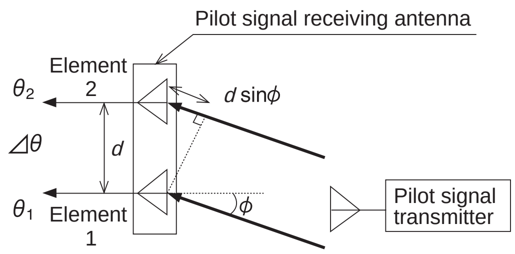
The microwave receiving and power rectifying subsystem receives and rectifies the microwave transmitted from the aforementioned microwave power transmission subsystem and beam forming and control subsystem using the receiving element called Rectenna. During this process, however, it is necessary, from the standpoint of security of the surrounding environment and human body, to reduce (minimize) the power density at the microwave receiving side, so that the antenna with large area is required to receive large electric power.

It is for this reason that the microwave receiving and power rectifying subsystem is basically composed of multiple panels connected by hinges so as to be folded compactly at the time of transportation and to be expanded into an antenna with large area at the place of installation, with each panel equipped on the surface with Rectenna to receive/rectify microwave power to convert into electric power and with a monitor board to monitor the state of receiving and further with signals and electric cables connecting these multiple boards (substrates).

This subsystem has the features given below.

(1) The subsystem is equipped with a latch (fixed) mechanism to control the expansion order or to retain the shape at the time of storage or after expansion, allowing expansion or storage operation by controlling the operating order.

(2) Each panel is equipped on its surface with a fixed Rectenna board, monitor board, latch mechanism, etc. connected accordingly by electric cables, while the



d : Space between elements
λ : Arrived signal wave length
θ_1 : Received signal phase of element 1
θ_2 : Received signal phase at element 2
$\Delta\theta$: Phase difference between elements 1 and 2
ϕ : Wave arrival angle (θ_1 - θ_2)

From the geometrical relationship in the above figure;

$$\Delta\theta = \left(\frac{2\pi}{\lambda}\right) d \sin\phi \rightarrow \phi = \sin^{-1}\left(\frac{\Delta\theta\lambda}{2\pi d}\right)$$

Fig. 4 Principle of angle detection using pilot signal
Detects the microwave arrival direction through the receiving phase difference of the multiple antenna.

panels can be stored and expanded with all these items intact. The expansion order (procedure) of this subsystem is shown in **Fig. 5**.

4. Achievements

4-1 Microwave power transmission subsystem

Fig. 6 shows the output spectrum of the phase-controlled magnetron and the phase difference between injection signal and output against the anode (plate) current.

Fig. 6 (a) shows the spread of spectrum due to self-oscillation of the magnetron before injection synchronization, while Fig. 6 (b) shows the spectrum getting synchronized and precipitous after the injection synchronization. Fig. 6 (c), on the other hand, shows the phase difference between injection signal and output against the anode current at the time of injection synchronization, indicating the frequency getting synchronized in the zone of "synchronization range" and the phase showing correspondence at point A. After this the anode current is controlled to phase status after this comes to A point. It has been confirmed that a stable phase control can be realized after the initial phase synchronization as shown in Fig. 6 (c).

4-2 Beam forming and control subsystem

The measurement result of the microwave beam pattern of the beam forming and control subsystem is given in **Fig. 7**, in which the beam pattern to 0^o direction shows almost bilateral symmetry with 0^o as the center. Compared with the main lobe with maximum beam intensity, the side lobe that ends up in extraneous radiation to directions other than the main radiation direction is substantially small at –13 dB or under, therefore the pattern indicates that most of the radiated power is included in the main lobe.

Thus, it has been confirmed in this subsystem that the formed composite beam corresponds with the theoretical pattern.

Further, when the radiated beam is controlled to $+10^o$ in horizontal direction, a main lobe with the radiation characteristics equivalent to those of the beam pattern

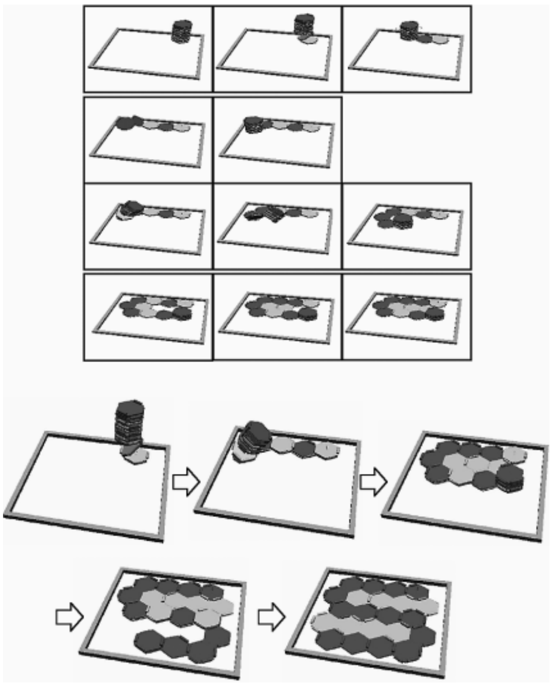


Fig. 5 Expansion order of planar-expansion Rectenna array
The piled up hexagonal panels are successively expanded to create a planar receiving unit (receiver).

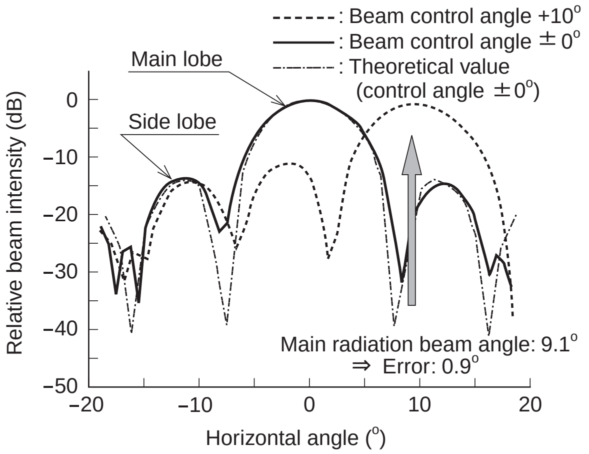
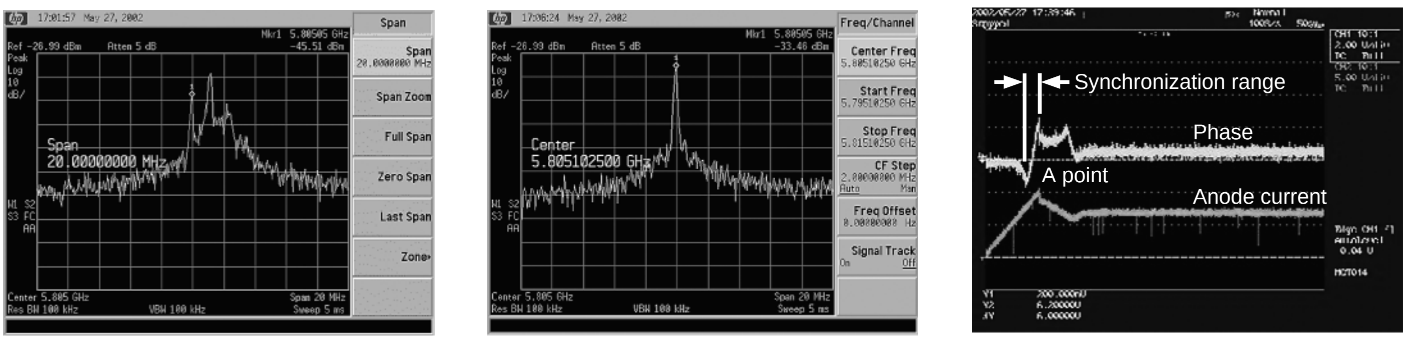


Fig. 7 Microwave beam pattern
The beam direction when set to $+10^o$ is found to be $+9.1^o$ when actually measured, with the error confined to 0.9^o.



(a) Before injection synchronization

(b) After injection synchronization

(c) Phase difference due to anode current control

Fig. 6 Phase shift control magnetron output spectrum and phase difference between injection signal and output against anode current
The output frequency gets synchronized by injecting magnetron standard signal, while the phase difference is unified by controlling the anode current.

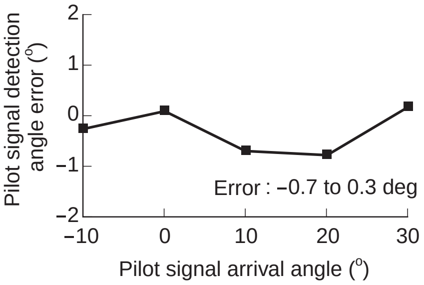


Fig. 8 Pilot signal receiver/transmitter detection angle error
The pilot signal receiver/transmitter error is slight at −0.7 to 0.3°.

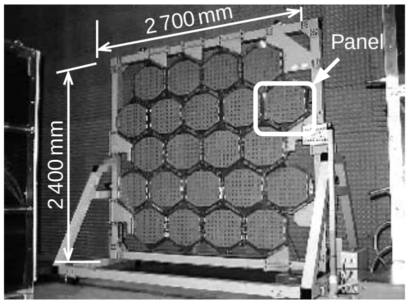


Fig. 9 Planar-expansion type receiving and rectifying subsystem
The expanded planar type receiving and power rectifying subsystem, composed of 22 pieces of panel

to 0° direction is found to be formed in the horizontal +10° direction, indicating that it is possible to form a composite beam by controlling the beam direction.

Furthermore, the main beam radiation angle is +9.1° against the beam control angle +10°, with the beam direction setting error being 0.9°. Since this error is considered attributed to the phase setting error of the phase shifter and the measurement error. The improvement in the phase setting accuracy of the phase shifter is the technical problem in the future.

Fig. 8 shows the characteristics of the pilot signal transmitter/receiver, indicating the pilot signal arrival angle detection error to be 0.7° or under. Improvement in beam control as well as in accuracy involves technical problem in the future, but the obtained result did conform to the specified ± 5° level.

4-3 Microwave receiving and power rectifying subsystem

The planar-developing Rectenna array structure composed of 22 panels and the pseudo-spherical Rectenna array structure composed of 20 panels were prepared to verify that they could actually be expanded (developed) and stored. **Fig. 9** shows the expanded planar type microwave receiving and power rectifying subsystem. It has been confirmed through the transmit/receive experiment using this subsystem that the microwave beam of narrow direction transmitted from the microwave power transmission subsystem and the beam forming and control subsystem is duly received by the desired panel causing the indication LED to light up.

Further, it has also been confirmed that the maximum power conversion efficiency of the Rectenna to be as high as 71.8%

5. Conclusion

The system was installed in the Microwave Energy Transmission Laboratory of Radio Science Center for Space and Atmosphere in Kyoto University in March, 2002, and is currently used for research and development of space solar power system (SSPS).

Through the development process of the system, we could establish the basic technologies essential to the development of future SSPS, such as the magnetron phase control technology, the low-loss microwave circuit technology and the beam control technology, etc. Further, we are making effective use of the acquired achievements and technologies through the development, and accumulating the technical experiences through the continual research and development on the elementary technologies regarding the space solar power system.

Besides, the microwave power transmission technology is expected to be applied not only to the key power supply to the SSPS but also to the power supply to the spacecraft in the orbit, to the power supply to the solitary islands and to the emergency power supply at the time of disaster, etc. Therefore the microwave power transmission is the hopeful technical field that has the possibility of development in new business in the future. We plan to proceed positively to carry on our research and development project and publicizing activities through cooperation with industrial, academic and administrative circles towards realization of the Space Solar Power System (SSPS).

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