Phase-Controlled Magnetron Development for SPORTS: Space Power Radio Transmission System

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Abstract

Since the first proposal of a Space Solar Power Station (SPS) in 1968, many different types of SPS have been proposed. Some of them are designed with microwave power transmission (MPT) technology based on a microwave power transmitter with microwave tubes. The microwave tubes, such as klystrons or magnetrons, have high efficiency (> 70%) and high power output (over 1 kW). We show a new concept for a microwave transmitter with phase-controlled magnetrons (PCM), for satisfying both requirements of high efficiency and beam control. We also propose a new phased-array system with the phase-controlled magnetrons for the SPS.

We use the injection-locking technique and phase-locked-loop (PLL) feedback by controlling an anode current for the phase-controlled magnetron. We can stabilize and control the frequency and phase of the microwave emission of the phase-controlled magnetron. However, we have a power loss after the phase-controlled magnetron for SPS use, because the output power from one antenna is designed to be less than 1 W in a recent SPS design, and we have to insert a power divider and phase shifters after the phase-controlled magnetron. In order to decrease the power loss after the phase-controlled magnetron, we have recently proposed some new concepts, and have developed a phase-controlled magnetron array called SPORTS (Space POwer Radio Transmission System) in FY2000 and FY2001 at Kyoto University.

1. Introduction

Microwave power transmission (MPT) technology is one of the most important technologies in the Space Solar Power System (SPS). The dc-RF-dc conversion efficiency, the accuracy of the microwave beam control, and the cost of the microwave power transmission system are especially important. We believe that a magnetron is well-suited for the microwave power transmission system of the SPS [1], especially a small experimental SPS, because its dc-RF conversion efficiency is high (> 70%) and it is very inexpensive (< $5). Weight is also important for a space system, because it strongly affects cost. The weight-power ratio (g/W) of the magnetron system, which includes the dc-dc converter and heat radiation, is smaller than that for a semiconductor amplifier system, because the output power of the magnetron is high (> 1 kW). Of cause, the magnetron does have some unsuitable characteristics for microwave power transmission including a communication system. It has been difficult to control the frequency and the phase of the microwave output of the magnetron, because it is just a microwave oscillator.

One result of our study is to show that the output microwave spectrum of a magnetron depends on the stability of the dc power source and the filament current [2]. If we use a stabilized dc power source for the magnetron and turn off the filament current after stable oscillation occurs, the spectrum, including low frequencies and high frequencies, is quiet and pure, and it is adequate for use in a microwave power transmission system (Figure 1). The main frequency, the high frequency, and the low frequency were measured by a spectrum analyzer with a spiral antenna, a horn antenna, and a current probe, respectively. The harmonics did not show great improvement between turning on the filament current and turning it off. This is because the harmonics of the magnetron are caused by distortion of the fundamental, and the distortion is independent of the effect of the filament current. However, almost all spurious emissions are suppressed except some spiky noise. The cause of the other spurious signals is complex; however, we consider that it is enough to suppress interference. However, there remains the problem of the frequency shift caused by heating of the magnetron; still, the spurious emissions are suppressed.

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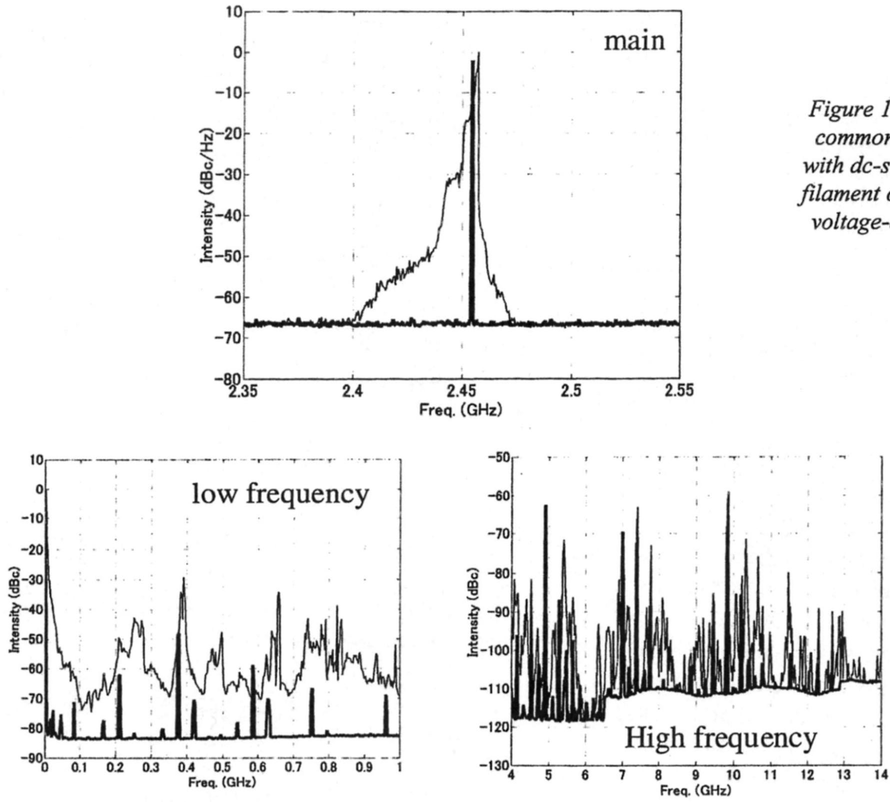

Figure 1. The output spectrum of a commonly used magnetron (bold: with dc-stabilized power supply and filament off; normal: with half-wave voltage-doubler power supply and filament on)

Therefore, in order to stabilize the magnetron frequency and to control its phase, we have developed a phase-controlled magnetron (PCM) with injection locking and phase-locked-loop (PLL) feedback obtained by controlling the anode current of the magnetron (Figure 2) [1]. We use a commonly used, inexpensive magnetron for the phase-controlled magnetron. The phase of the magnetron can be tuned in several different ways. One is to change the magnetic field by using an external coil [3]. Another is to change the anode current flow. We have chosen the anode current control, because the range of frequency control and phase control is wider with anode current control than is

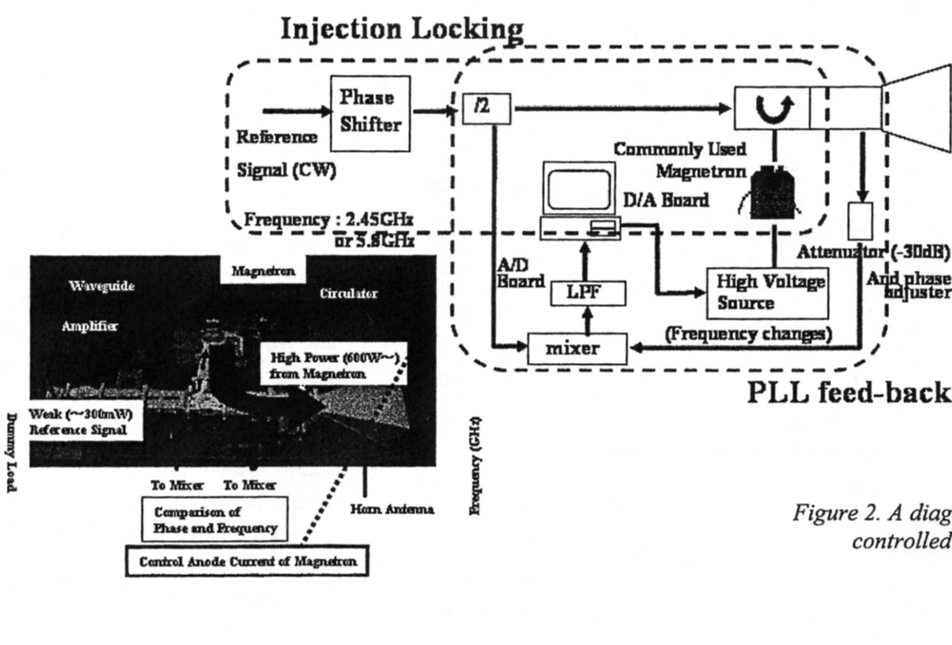

Figure 2. A diagram of the phase-controlled magnetron

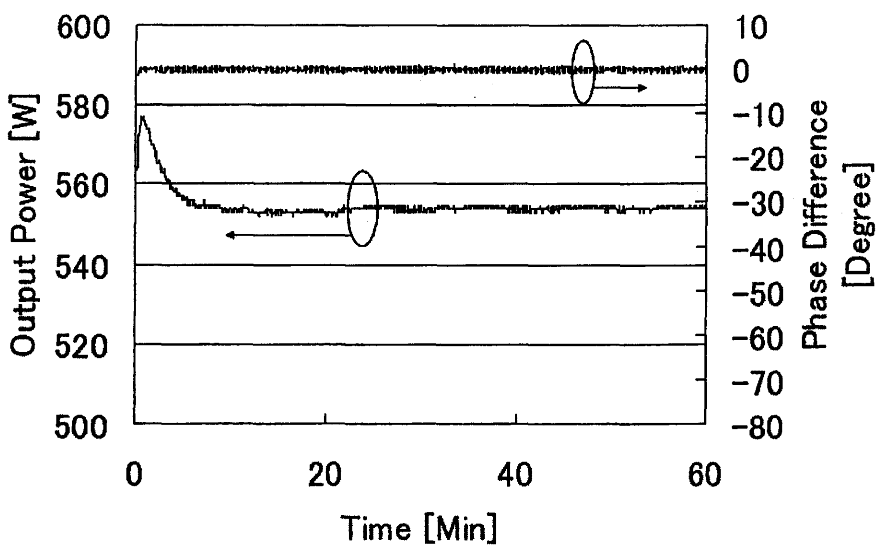

Figure 3. The time dependence of the phase and power of a phase-controlled magnetron.

possible with control of the magnetic field. Figure 3 indicates the time dependence of the phase and the power output of the phase-controlled magnetron. After an initial time delay, the output power and the phase of the phase-controlled magnetron's output are stabilized. We have carried out a phased-array experiment with the phase-controlled magnetrons, and we successfully controlled the beam direction with the phase-controlled magnetrons [4].

Based on the phase-controlled-magnetron technique, we have developed some microwave power transmission systems for equipment at Kyoto University. One is a 2.45 GHz system called SPORTS-2.45 (Space POwer Radio Transmission System for 2.45 GHz), and the other is a 5.8 GHz system called SPORTS-5.8 (Space POwer Radio Transmission System for 5.8 GHz). The phase-controlled magnetron has characteristics of high efficiency, high power, high voltage, and small weight-power ratio. However, for some SPS applications, the high-output-power advantage of the phase-controlled magnetron is weakened, because the output power from one antenna is designed to be less than one watt in a recent SPS design [5]. Therefore, we have to put a power divider and phase shifters before the antenna, in order to control the beam direction electrically and to suppress grating lobes. Commonly used power dividers and phase shifters have a large power loss. However, the SPS must have a low-loss microwave power transmission system because of cooling problems in dissipating generated heat, and cost considerations. The SPORTS system has therefore been developed with means for decreasing the power loss after the phase-controlled magnetron, in order to realize a beam-control system.

There is no law regarding the use of the frequency for microwave power transmission. Only the ISM (Industrial, Scientific, and Medical) band is now open for microwave power transmission. We would like to use microwaves for power transmission from space to the ground because of (system and propagation) efficiency and cost. 2.45 GHz and 5.8 GHz belong to the ISM band, and these are microwaves. Therefore, we have chosen the frequencies of 2.45 GHz and 5.8 GHz. If other microwave frequencies become available for microwave power transmission, we will use the new frequencies.

2. SPORTS-2.45

SPORTS-2.45 is composed of four subsystems (Figure 4): a phase-controlled magnetron phased array as a microwave transmitter subsystem, a microwave receiver (rectenna array), solar panels for dc supply, and a near-field scanner for measurement. SPORTS-2.45 was designed and developed at Kyoto University as a test bed for a space microwave power transmission experiment in FY2000.

The solar panels provide 8.4 kW of dc power to the microwave transmitter subsystem, composed of a phased array with twelve phase-controlled magnetrons. The design specifies 200 V dc, as would be suitable in space use. For the phase-controlled magnetron of the SPORTS-2.45, we used a cooker-type magnetron, 2M234, made by Matsushita Co. Typical characteristics of the 2M234 are as follows: the frequency (matched load) is 2.455 GHz; the peak anode voltage is 3.85 kV; the average output power (matched load) is 550 W. We always turn off the filament current during power transmission after stable oscillation occurs. We achieved a frequency stability of better than 10^{-8}, relative to the frequency stability of an input reference signal. The transmitted microwave power and frequency were 4 kW and 2.45 GHz, respectively. One reference signal was divided and injected into each phase-controlled magnetron through a phase shifter. This was the first phase-controlled magnetron array in the world.

The SPORTS-2.45 system has two different types of antenna arrays. One is a twelve-horn antenna array, with low power loss but with a limited narrow-beam scanning capability. The gain of each horn antenna is 17.73 dB. The other antenna is a 96-dipole antenna array with reflector and

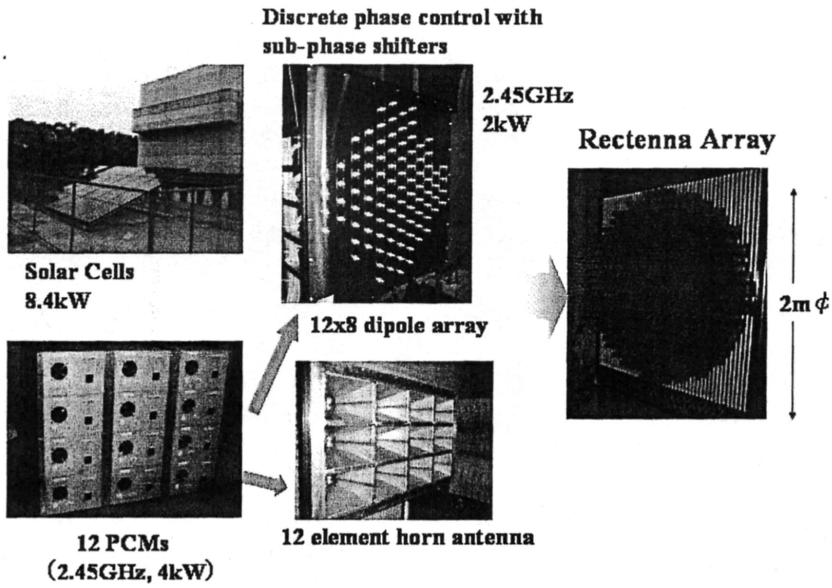

Figure 4. The SPORTS-2.45 system.

sub-phase shifters. The sub-phase shifter can control the phase of a microwave signal with only the options of $-60°$, $0°$, $+60°$. It is a 96-antenna array with twelve eight-way power dividers and 96 sub-phase shifters, with which the microwave beam can be scanned into a much wider range of directions. We have shown that we can keep high beam-collection efficiency when we control a beam to a two-times-larger direction with the sub-phase shifters in the SPS system [1].

For target detection, we use a retro-directive system with a CW pilot signal of 400 MHz in the SPORTS-2.45. We use three receiving antennas for the pilot signal, and we calculate the direction of a target with a computer. We put the receiving antennas in triangular locations, and the element spacing of the receiving antennas is 1.3 m (1.7λ). We can easily change the frequency of the pilot signal by hardware and software changes because we calculate the direction of the target with a computer. We succeeded in detecting the target under conditions of power transmission with the phase-controlled magnetrons.

The rectenna array is composed of four types of rectennas, which are placed accordingly for optimum microwave input power, yielding the highest RF-dc conversion efficiency [6] in the presence of a spatially-varying gradient power density of the microwave beam. All rectennas in an array cannot be of highest RF-dc conversion efficiency because the RF-dc conversion efficiency of the rectenna has an input-power dependence. We use a Yagi-Uda antenna and a power divider for the rectenna. The maximum RF-dc conversion efficiency of each rectenna was 77.7%, 75.7%, 73.0%, and 68.6% with 1 W, 2.1 W, 4.1 W, and 6.7 W of input microwave power, respectively

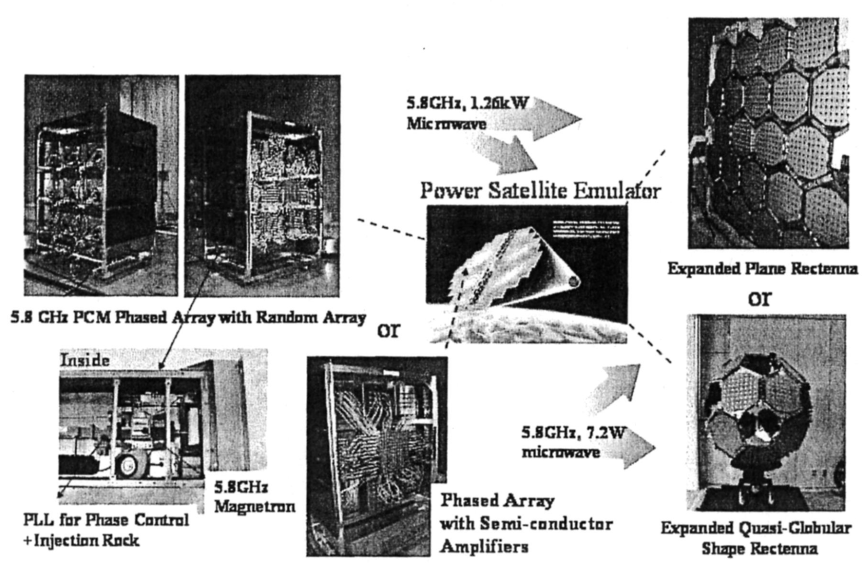

Figure 5. The SPORTS-5.8 system

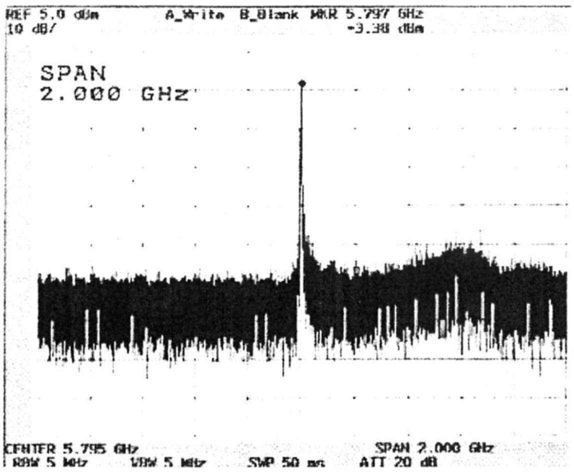

Figure 6a. The output spectrum of the 5.8 GHz magnetron of SPORTS-5.8 (the span is 2 GHz)

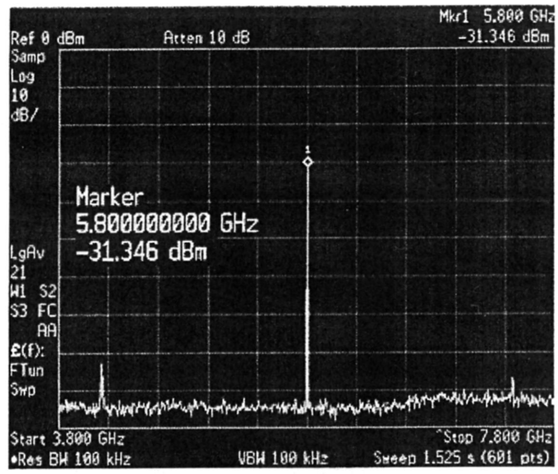

Figure 6b. The output spectrum of the semiconductor amplifier of SPORTS-5.8 (the span is 4 GHz).

[7]. There are 2,692 rectenna elements, and the diameter of the rectenna array is approximately 2 m.

3. SPORTS-5.8

In FY2001, we also developed SPORTS-5.8, with 5.8 GHz magnetrons for the phase-controlled magnetron (Figure 5). SPORTS-5.8 is composed of several transmitting subsystems and rectenna arrays. The main microwave transmitting system is composed of nine phase-controlled magnetrons, based on a newly developed magnetron with a frequency of 5.8 GHz. Typical performance values of the 5.8 GHz magnetron, developed by Matsushita Co., are as follows: the frequency (matched load) is 5.800 GHz; the peak anode voltage is 4.0 kV; the average output power (matched load) is 300 W. We always turn off the filament current during power transmission after stable oscillation occurs. Four-stage eight-way power dividers were developed to distribute the microwave power from one phase-controlled magnetron to 32 microstrip-antenna elements. The transmitted microwave power from the 288 antennas was over 1.26 kW. In the main transmitter system, we adopted a random array, in order to decrease the level of grating lobes and to decrease power loss after the phase-controlled magnetron. The power loss after the phase-controlled magnetron was below −1.5 dB.

For target detection, we use a retro-directive system with a pilot signal of 4.8 GHz that is modulated with a spread spectrum [8]. We use four receiving antennas for a pilot signal, and we calculate the direction of a target with a computer. This does not respond to fake or wrong signals, because direct-sequence spread-spectrum is used for the signals. It is expected to be more reliable in the presence of noise and power transmission. The pilot signal can be modulated, e.g., for sending information on power reception and authentication. This is a useful technique, even for a single receiving site. It has been confirmed that the new direction-finding system for multiple spread-spectrum pilot signals works well. Figure 7 shows the result of direction finding with a modulated spread-spectrum pilot signal in the SPORTS-5.8 system [9]. The distance between Tx and Rx was approximately 4 m. We used two receiving antennas for the pilot signal, which were put in the horizontal plane with a spacing of 0.5λ. The error in the direction finding

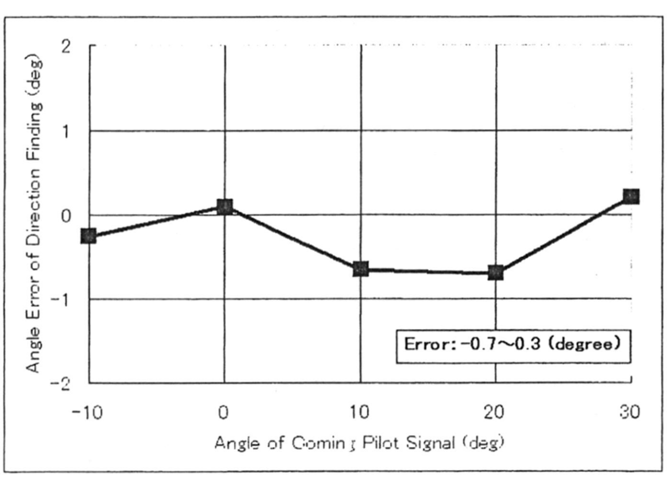

Figure 7. The result of direction finding with a modulated spread-spectrum pilot signal [9].

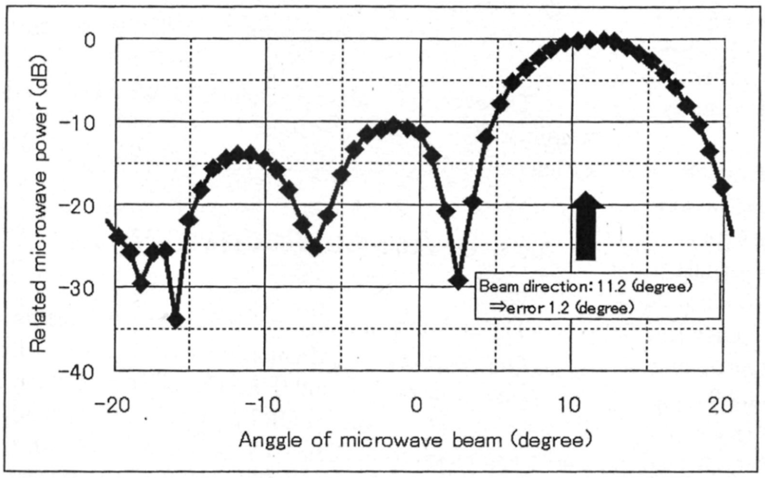

Figure 8. The result of beam forming with the retro-directive system [10].

was below 0.7°. This is sufficient for the final SPS system because we use a large number of the direction-finding systems in the SPS, and the direction-finding error is expected to be much smaller in total.

We have another, alternative microwave power transmission system in the SPORT-5.8. It is called a "beam-forming subsystem," with one semiconductor amplifier, power dividers, 144 four-bit phase shifters, and 144 (12 × 12) microstrip antennas. The performance characteristics of the semiconductor amplifier are as follows: the frequency is 5.77 GHz; the frequency stability is better than 1.4 ppm; the saturation output microwave power is 26.9 W; and the saturation gain is 8.5 dB. The total microwave power emitted from the antenna array through the power dividers and phase shifters is over 7 W. Figure 8 shows the result of beam forming with the retro-directive system with a distance of 4 m. The element spacing of the transmitting antenna was 0.7λ. The error of direction finding and beam forming was below 1.2°. We can use the same retro-directive system both for the beam-forming subsystem and for the transmitting subsystem. We can carry out experiments concerning beam forming with the subsystem.

We show spectral data for the 5.8 GHz magnetron and the semiconductor amplifier of the SPORTS-5.8 system in Figure 6. Unfortunately, the parameters of the measurements were different between Figure 1 and Figure 6, and we can not exactly compare these data. However, there is no interference from these transmitting systems with the retro-directive system, and we experimentally succeeded in detecting the target with the retro-directive system with a 4.8 GHz pilot signal.

We have two types of rectenna array in the SPORTS-5.8. We emulate a small experimental satellite with rectennas, and both rectenna arrays can be stored in a small shape and expanded. The same rectenna element is used for both arrays, and only the shape of the arrays is different. One is a plane rectenna array, and the other is a quasi-globe-shaped rectenna array. The maximum RF-dc efficiency of the rectenna element is over 71.8% with 100 mW of 5.8 GHz microwave input power and with a 200-ohm load.

4. SPORTS-5.8 options

The SPORTS-2.45 and SPORTS-5.8 systems were developed with the concept of "high efficiency beam control." In order to decrease the loss after a phase-controlled magnetron array with high efficiency, we use a sub-phase-shifter system for SPORTS-2.45, and a random array for SPORTS-5.8. Besides these experiments, we have developed two different types of microwave transmitters with a

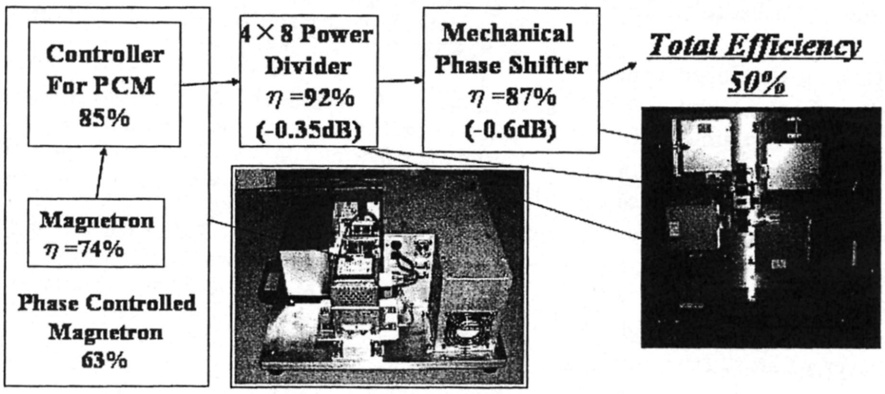

Figure 9. A diagram showing the efficiency of the SPORTS-5.8 option system.

frequency of 5.8 GHz. One uses three parabolic antennas, which form a one-dimensional phased array of parabolic antennas. We can decrease the loss after the phase-controlled magnetron because we do not need phase shifters after the phase-controlled magnetron in the parabolic phased array.

The other is a revised phase-controlled magnetron without the injection-locking technique and with a low-loss phase-shifter system. This is a circulator-less phase-controlled magnetron. The size of the circulator-less phase-controlled magnetron module is 400 mm × 400 mm × 150 mm. Its weight is below 13 kg, which includes the magnetron, dc/dc converter, waveguide, PLL control unit, and structure. The weight of the magnetron is only 0.6 kg, and the output microwave power is approximately 300 W. The weight/power ratio is below 43 g/W. The frequency stability of the SPORTS-5.8 option is approximately 10^{-5}; however, we can improve the frequency stability with an improvement in the performance of the PLL. For a low-loss phase shifter, we adopted a mechanical (moving dielectric substance) system, and its loss is –0.6 dB with analog phase shift. An efficiency diagram is shown in Figure 9. We have achieved 50% total efficiency of the microwave transmitter with beam control. The mechanical phase shifter, however, still has many problems: for instance, moving speed and lifetime.

We tried to decrease the size and weight of the SPORTS-5.8 option; however, we did not try to decrease the size and weight of both SPORTS systems. Generally speaking, the 5.8 GHz system is smaller than the 2.45 GHz system in microwave power transmission.

5. Conclusion

The SPS must have a low-loss microwave power transmission system with beam control because of the cooling limitation problem and cost considerations. Generally, the SPS has been designed with a microwave transmitting system with a phased array of over 80% efficiency. However, present microwave technology does not permit such a high-efficiency phased array. Our group focused on the magnetron as the microwave transmitter for microwave power transmission because of its cost, efficiency, and weight. We have developed the phase-controlled magnetron and its phased arrays, called SPORTS.

The SPORTS systems have been developed with concepts to decrease the power loss after the phase-controlled magnetron, in order to realize a low-loss beam-control system. The concepts are the "sub-phase shifter," "random array," "parabolic phased array," and "mechanical phase shifter." The SPORTS systems also include a retro-directive system for target detection, a beam-forming subsystem with a semiconductor amplifier, and receiving rectenna arrays. The SPORTS systems have achieved totally high efficiency with beam control; however, we are still trying to increase the efficiency and stability of the phase-controlled magnetron, and trying to decrease power loss after the phase-controlled magnetron with the SPORTS systems.

The eventual goal is a practical SPS. We work towards a microwave power transmission system with higher efficiency and lighter weight at Kyoto University.

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