Development of Active Phased Array with Phase-controlled Magnetrons

Naoki SHINOHARA, Junsuke FUJIWARA, and Hiroshi MATSUMOTO
Radio Atmospheric Science Center, Kyoto University
Gokasho, Uji, Kyoto, 611-0011, Japan
Email: shino@kurasc.kyoto-u.ac.jp

1. Introduction

During 1995-1997, NASA conducted a “Fresh Look” study of SSP (Space Solar Power or Solar Power Station/Satellite ; SPS) concepts and technologies. The SPS is a concept of a space solar power station with wireless power transmission (WPT) technologies to transmit generated electric power to the Earth. This study was a feasibility assessment of prospects for commercial generation of power in space for use on Earth. Throughout this study, the focus was to search out those concepts that have the potential to enable affordable production of energy for Earth in space. In response of the Fresh Look Study, during 1998 NASA conducted a $2M SSP Concept Definition Study (CDS). They conclude that the SSP should be capable of providing power at a cost of no more than about 5.5¢ - 7.5¢ per kWh for global markets to be viable in the far-term (2020 and later). Following action by the US Congress, a budget of $15M in FY 1999 was appropriated for SSP studies and technologies[1].

The SPS concept was proposed by P. E. Glaser in 1968 and a Reference System of the SPS was examined in the 1970s by DOE and NASA. However work stopped in 1980-1981 because of the cost-to-first power (> $250B (‘96,$)) , urgency faded as oil prices plummeted in the early 1980s, and etc.

From early 1980s, Japan is a top runner of studies of the SPS. In order to establish the WPT technologies via microwave (MPT) in space and to investigate the nonlinear plasma effects caused by the microwave power beam through the space plasma as well as the counter effects onto the microwave beam, our experimental group carried out two rocket experiments of 2.45 GHz microwave energy transmission in the ionosphere in 1983 and in 1993 in Japan, which is called MINIX (Microwave Ionosphere Nonlinear Interaction eXperiment)[2] and ISY-METS (International Space Year – Microwave Energy Transmission in Space)[3]. In the rocket experiments, we obtained new knowledge concerning nonlinear interactions between intense microwave and plasmas[4]. In many universities and laboratories, the MPT technologies are also studied and some field MPT experiments was carried out. ISAS proposes a small-size experimental SPS called SPS2000. 2nd Solar Power Satellite symposium was also held in Kyoto in 1999.

In this paper, we show results of development of a phase-controlled magnetron (PCM) with 2.45 GHz microwave and results of an active phased array with PCMs. The PCM can decrease costs of microwave transmitters. The magnetron is commonly used in microwave oven and is of very low cost with high efficiency. However, disadvantages of magnetron are (1) easy broken, (2) necessity of high voltage (several kilo volts), and (3) noisy spectrum. Our PCM system can offset the faults and can be used for an active phased array instead of semi-conductor amplifiers that have high cost. We developed the PCM for the MPT of the SPS and a space MPT experiment. However, the PCM can apply for communication technologies.

2. Development of phase-controlled magnetron(PCM)

In order to stabilize a frequency of a magnetron and to control a phase, we adopt a frequency locking technique with PLL-like feedback loop. The frequency locking is accomplished by operating the magnetron as a reflection amplifier[5], and can be used in coherent radar system.

A required power level of reference signal which is injected into the phase-controlled magnetron is about 10 to 13 dB below the RF output power of the magnetron. We could use a solid-state driver to produce the locking reference signal for a magnetron with the output power of hundreds of watts. Magnetron frequency is then automatically tuned to that of the locking signal. If this condition is met, there will be just 90 degree between the phases of the reference signal and of the magnetron RF output.

The bandwidth of lockable frequency depends on the input power level of the reference signal. The relation of the lockable frequency with the input power of the reference signal is described in Adler's equation[6]. For example, in case of a commonly used magnetron 2M236 whose frequency is 2.45 GHz, the frequency locking range depends on P_{in} / P_{out}. It is only 1.5 MHz when P_{in} / P_{out} is equal to –30 dB. If a condition of the magnetron such as the temperature of the device changes, the magnetron frequency changes as well. This prevents us from keeping the locking frequency. Therefore, a feed-back loop system has been proposed.

A magnetron can be tuned in several different ways. It can be tuned either internally or externally by a mechanical motion that changes the resonant frequency of the tube. It can also be tuned electronically in two different ways. One is to change a magnetic force by using an external coil[7]. The other is to change an anode current flow. Once the microwave phase from a magnetron becomes controllable, we could easily construct an active phased array with magnetrons. We developed a phase-controlled magnetron system with an anode current feed-back (Fig.1).

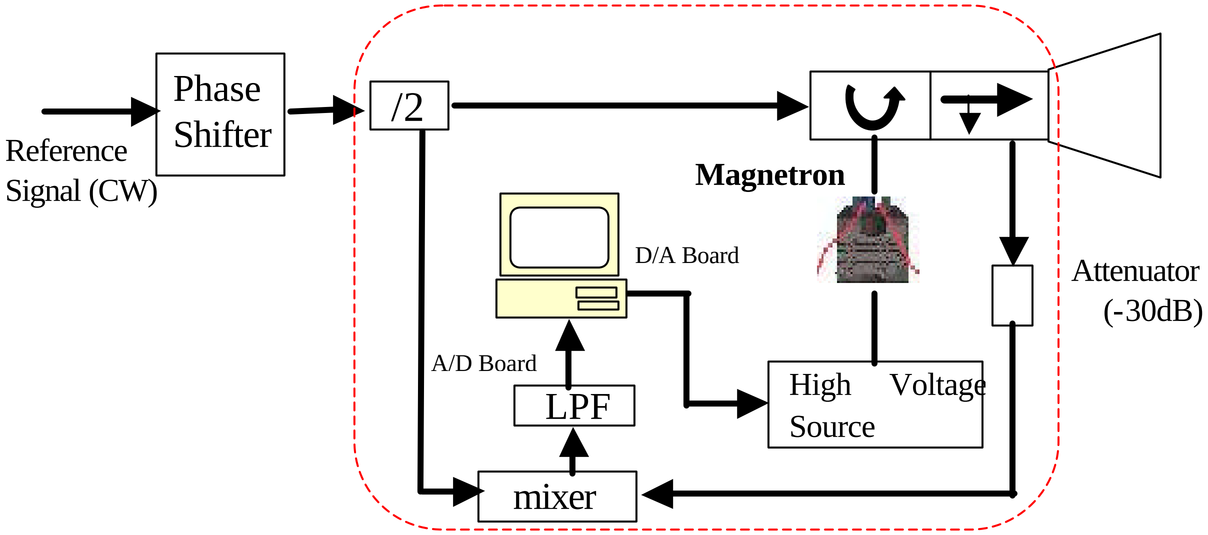


Fig.1 Phase-controlled magnetron system with an anode current feed-back

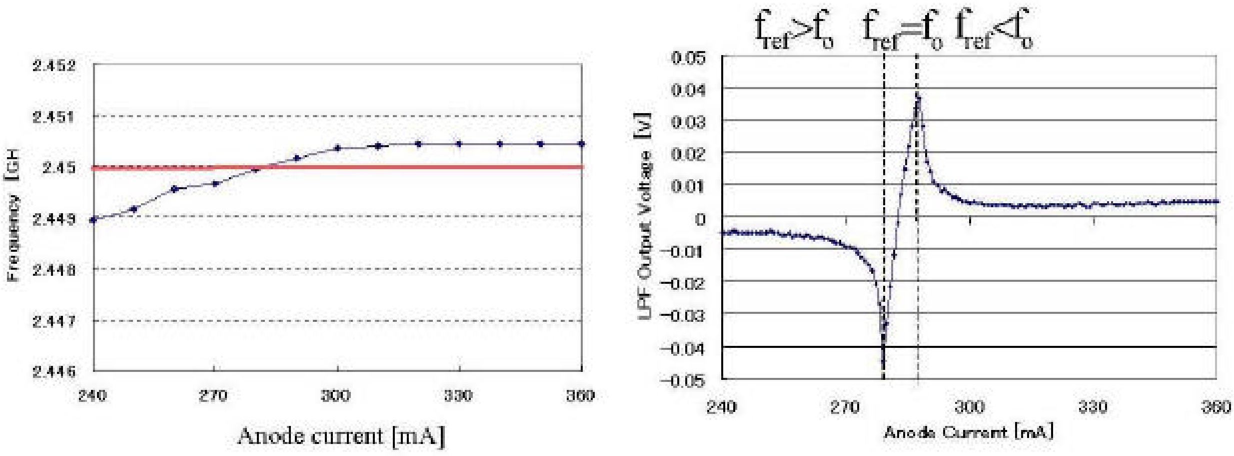


Fig.2 Anode current dependence of the frequency of the magnetron and of the LPF output voltage. Red line indicates the frequency of the reference signal. When the LPF output voltage reaches to zero, the magnetron frequency is locked at the frequency of the reference signal.

The frequency of a magnetron output microwave and a reference signal frequency are compared at a mixer. Through a LPF, we obtain a difference of two frequencies. Using the difference, we control an anode current and lock the magnetron frequency at the reference signal frequency. Figure 2 shows the anode current dependence of the output frequency of the magnetron and of the LPF output voltage. We can see the frequency of the magnetron is locked at 2.45 GHz, which is equal to that of the input reference CW signal when the LPF output voltage reaches to zero. A required power level of reference signal decreases to about 31 dB below the RF output power of the magnetron. After the magnetron frequency is locked at the reference signal frequency, we could control the phase with an inserted phase shifter.

3. Active phased array with the phase-controlled magnetrons

With two phase-controlled magnetrons shown in Figure 1, we have constructed an active phased array and have carried out a beam control experiment in METLAB (Microwave Energy Transmission LABoratory) of Kyoto University. In order to repress side lobes in the experiment of one-dimension array, we used two H-plane sectoral horns (Figure 3) with the aperture size of 41 X 10 cm. The element spacing is 10.5 cm (=0.86 λ). We designed and adopted the H-plane sectoral horn for the following reason ; (1)size of E-plane (array line) was decided by a size of waveguide WRJ-2 for 2.45 GHz microwave, (2) size of H-plane was decided by a maximum power density which rectennas (rectifying antenna) can receive in a space MPT experimental system as mentioned later. Experimental results are indicated in Figure 4. Lines with dots indicate the experimental results with the two PCMs and the H-plane sectoral horns. Lines without dots indicate theoretical results for the H-plane sectoral horns. The experimental results agree well with the theoretical results in main lobe. We have demonstrated the developed system in the 2nd Solar Power Satellite symposium.

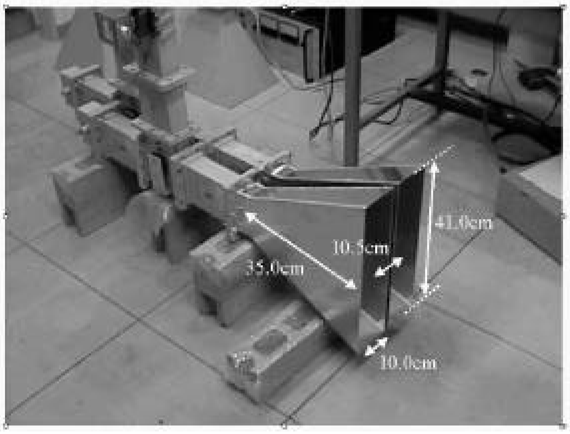
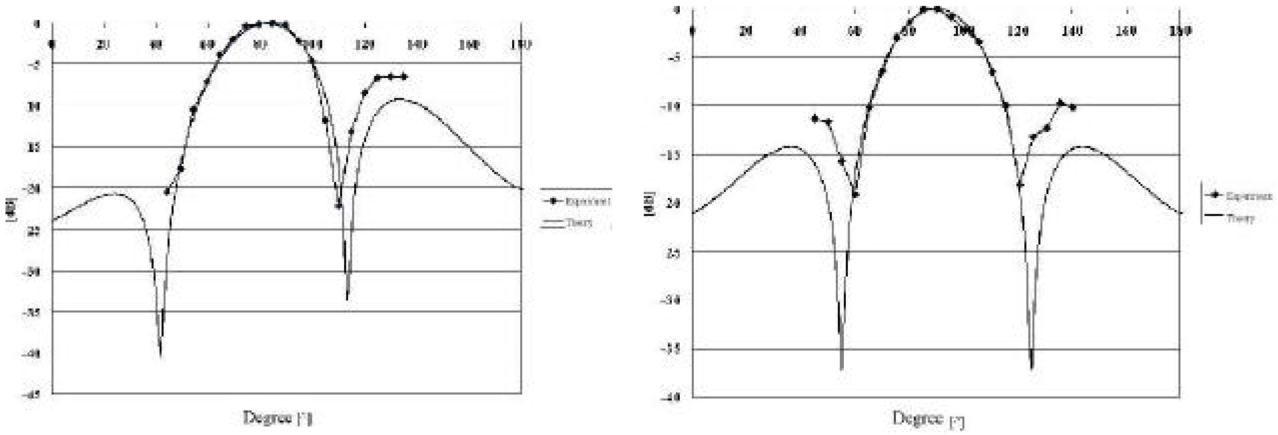


Fig.3 H-plane sectoral horns with PCMs



(a) (b)

Fig. 4 Directional pattern of an active phased array with two PCMs and two H-plane sectoral horns Lines with dots indicate experimental results. Lines without dots indicate theoretical results (a) Focal point is 80 degree (b) Focal point is 90 degree

In the active phased array with PCMs, we should notice that we need an extra isolator between an antenna and a PCM. If we do not use extra isolator, a magnetron does not be locked a reference signal Because the reference signal is weaker than a sneak microwave from next antennas. In future study, we should solve the sneak microwave problem.

The other future study is a spacing of array with PCMs. In the present system, we use waveguides WRJ-2 for 2.45 GHz and horn antennas because of high power over 600W from one PCM. With the horn antenna, a limit of the array spacing is $0.86\,l$. This wide spacing comes simply from the condition that a coaxial feeder and a small aperture antenna like a dipole in such a large power microwave. It is future work to decrease the element spacing in order to carry out an experiment with two-dimensional array in near future.

4. Conclusion

We have shown our recent study of an active phased array with PCMs. Using the PCMs, we have shown experimental results of controlling a microwave beam direction. It is the same result with semi-conductor amplifiers. A magnetron has higher output power and higher DC-microwave conversion efficiency and is much lower cost than the microwave semi-conductor amplifier. In the next step, we hope that we will carry out the space MPT experiment on International Space Station (ISS) with the PCM array in order to establish a stable system for space use under the ionospheric plasma condition and in order to carry scientific experiments concerning the interaction of the high power density microwave beam with the surrounding space plasma environments for the SPS.

The ISS project is in progress jointly by U.S.A, Japan, European Space Agency (ESA), Canada and Russia. The ISS will be a permanent, multipurpose manned facility built in orbit at an altitude of 400km. The Japanese Experimental Module Exposed Facility (JEM-EF) is on the ISS and is suitable for experiments on robotics and telescience, space power and space communications. We have proposed an MPT experiment on the JEM-EF with semi-conductor amplifiers to NASDA (National Space Development Agency of Japan) and JSUP (Japan Space Utilization Promotion Center) in January 1997[8], however, unfortunately it was not accepted for the first series of the JEM-EF experiments. Our study is conducted to design the space MPT experimental system.

Using magnetrons, it is easier and less expensive to achieve higher microwave power density compared to a system based on the semi-conductor microwave amplifiers. The present system provides more realistic system for a study of detailed nonlinear interactions between an intense microwave and ionospheric plasma. In order to carry out the space MPT experiment on the ISS, we have to improve the PCM system for space use.

Acknowledgement

This study was supported in part by a grant from Japan Space Utilization Promotion Center.

[References]

[1] http://procurement.nasa.gov/cgi-bin/EPS/sol.cgi?acqid=150#Amendment 01, “SPACE SOLAR POWER (SSP) EXPLORATORY RESEARCH AND TECHNOLOGY (SERT) PROGRAM, SOL NRA8-23”

[2] Matsumoto, H, and I. Kimura, ‘Nonlinear Excitation of Electron Cyclotron Waves by a Monochromatic Strong Microwave : Computer Simulation Analysis of the MINIX Results’, Space Solar Power Review, 6, pp.187-191, (1986)

[3] Kaya, N., H. Matsumoto, and R. Akiba, ‘Rocket Experiment METS Microwave Energy Transmission in Space’, Space Power, vol.11, no.1&2, pp.267-274, (1993)

[4] Matsumoto, H., Y. Hashino, H. Yashiro, N. Shinohara and Y. Omura, ‘Computer Simulation on Numerical Interaction of Intense Microwave with Space Plasmas’, Electronics and Communications in Japan, Part 3, Vol.78, No.11, pp.89-103, (1995)

[5] Sivan, L., ‘Microwave tube transmitters - microwave technology series 9’, Chapman & Hall, pp.183-188, (1994)

[6] Alder, R., ‘A study of locking phenomena in oscillators’, Proc. of the IRE, 34, pp.351-357, (1946)

[7] Brown, W. C., ‘The SPS transmitter designed around the magnetron directional amplifier’, Space Power, vol.7, no.1, pp.37-49, (1988)

[8] Matsumoto, H., K. Hashimoto, N. Shinohara, M. Fujita, K. Itoh, S. Sasaki, T. .Katagi, T. Itoh, J. G. Hawkins, and F. E. Little, ‘Microwave Power Transmission Experiment on JEM-EF of International Space Station’, Proc. of SPS’97, pp.231-236, (1997)