Development of Phased Array for High Accurate Microwave power Transmission

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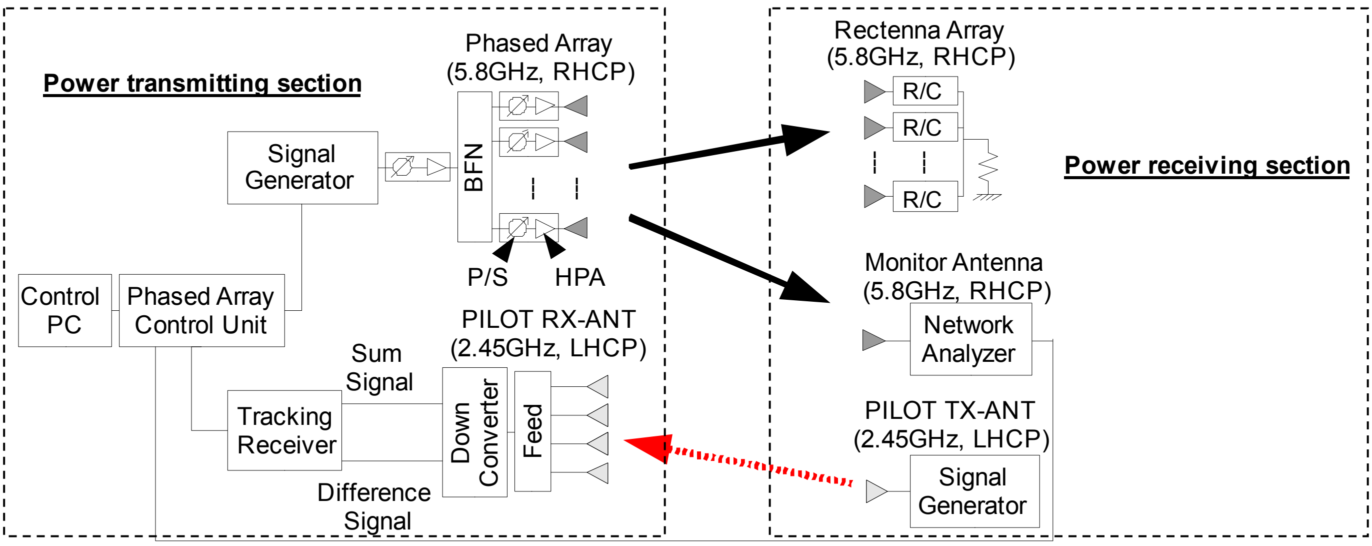
***Abstrtact* – A phased array with 1.5kW microwave output power has been developed and tested. Mitsubishi Electric Corporation and Kyoto University jointly developed this for the purpose of basic experiments of high accurate microwave power transmission. To realize this purpose, REV method as a calibration system of the complex electric field of an antenna element and software retro-directive system as a power receiving section tracking system is employed in the phased array. It has been found from measurements of radiation performance that a measured radiation pattern is in good agreement with a simulated result and beam steering accuracy less than 0.1degrees, corresponding to about fortieth of the beamwidth, is obtained due to REV method. Furthermore, a power receiving section tracking accuracy less than 0.4degrees rms (root mean square) is obtained due to software retro-directive system.**

***Index terms* – Phased arrays, power transmission, calibration**

I. Introduction

SPS (Solar Power Satellite/Station) is an alternative clean power generating system for use on earth. Collected solar power in space is transmitted to earth via microwave or laser and converted into direct-current power for use. To realize it, development of power transmitting system is one of the most important things, because it is required to have high power output capability, high accurate detection of a power receiving section and high accurate beam control to this direction. Mitsubishi Electric Corporation (MELCO) has addressed development of this kind of microwave technologies. However, a power transmitting equipment aimed to study high accurate microwave power transmission has not been developed. MELCO and Kyoto University jointly developed a 256 elements phased array and measured this radiation performance. Each antenna element of the phased array has High Power Amplifier (HPA) and 5-bit digital Phase Shifter (P/S). Thus, the phased array can transmit 1.5kW microwave power and steer beam within 15 degrees of zenith. Furthermore, REV (Rotating Element electric field Vector) method [1] for a calibration of the complex electric field of antenna element and software retro-directive system for a power receiving section tracking are employed. Fig. 1 shows the block diagram of the developed phased array. A power transmitting section mainly consists of phased array for microwave power transmitting and a pilot receiving antenna for tracking a power receiving section. The power receiving section consists of rectenna array for microwave power receiving, a monitor antenna for the calibration of each antenna element and a pilot transmitting antenna for tracking.



HPA: High Power Amplifier, P/S: Phase Shifter, R/C: Rectifying Circuit

Fig. 1. Block diagram of developed phased array.

II. PHASED ARRAY CONFIGURATION

An appearance of the phased array is shown in Fig. 2. The phased array has 256 antenna elements. As shown in Fig. 1, microwave power is amplified by High Power Amplifier Modules (HPA-MDLs), so that each antenna element can transmit about 6W of microwave power. These HPA-MDLs mainly consists of HPA and 5-bit digital P/S. Phased Array Control Unit (PACU) sends control signals to P/Ss and set desired phase values. By using calibration and tracking systems described in the latter chapter, high accurate beam steering is achievable within 15 degrees of zenith. Furthermore, water cooling system not shown in the block diagram is equipped the phased array to keep HPA-MDLs low temperature

As an antenna element, single-fed circular microstrip patch antenna with small perturbation segments, shown in Fig. 3, is employed as a Right Handed Circular Polarization (RHCP) radiator. Every antenna elements are easily removable from phased array.

These 256 antenna elements are laid out in a triangular lattice, so that grating lobes don't appear when main beam is steered within 15 degrees of zenith. The length of the bottom side of the triangle dx is 0.74λ, while the height of the triangle dy is 0.85λ and the aperture area is 11.80λ× 13.92λ.

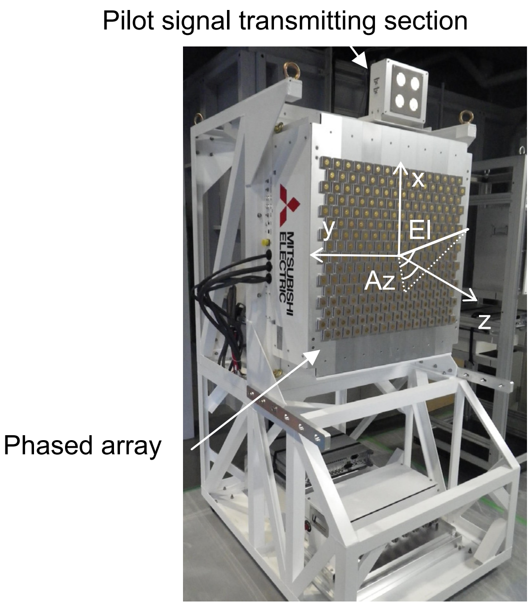


Fig. 2. Developed phased array.

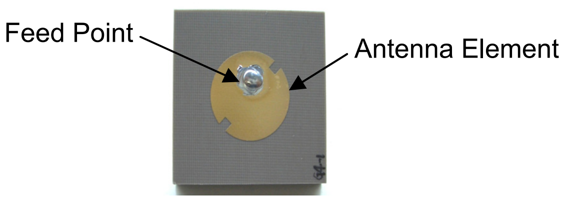


Fig. 3. Single-fed circular microstrip patch antenna with small perturbation segments.

III. HIGH ACCURATE BEAM CONTROL SYSTEM

In SPS system, a phased array has to have high accurate beam steering capability to prevent from radiating microwave power to undesired directions. To realize it, it is important to set a phase value of each element a desired value and accurately transmit microwave beam to a power receiving section. Therefore, a calibration system of complex electric field of the antenna element and a high accurate power receiving section tracking system are required. As a calibration system, REV method and as a tracking system, software retro-directive system is employed.

By using these systems, the phased array accurately can track a power receiving section and transmit microwave power to this direction.

A. REV Method

REV method (REV-I) is MELCO developed calibration system of the complex electric field of an antenna element. Each element including HPA-MDL has errors due to manufacturing tolerances, element failure and aging. Furthermore, mutual coupling between antenna elements causes the complex electric field of each antenna element to change. This is why a calibration system is required and REV method has performed not only in experimental field of phased arrays but also in space satellite's operation [2]. This has to be executed before and during microwave power transmitting operations. REV method has two remarkable features. First one is this method requires only amplitude measurement and second one is the complex electric field of an antenna element can be calibrated in an array operation, that is a calibration including excitation errors and mutual coupling is achievable. The first step measures the power output from a phased array when phases of multiple elements are successively shifted with a phase interval. The phase interval is 11.25dergees because 5-bit digital phase shifter is used. As a power monitor antenna, a cylindrical horn antenna is equipped in a power receiving section. Next, measured power variation is expanded into Fourier series to derive the complex electric field of the corresponding antenna element. However, there are two disadvantages of REV-I, which is a calibration error and calibration time. The calibration error is due to a phase error of P/Ss and it is difficult to avoid. The calibration time is directly proportional to the number of elements and bit number of P/S.

To overcome these disadvantages, other types of REV method are employed on the purpose of more accurate and faster calibration.

For more accurate calibration (REV-II) [3], not power of a phased array but complex electric field is to be measured. The first step measures the complex electric field output from the phased array when phases of multiple elements are successively shifted with 11.25degrees phase interval. Next, by summing measured complex electric fields of an antenna elements, the complex electric field of the corresponding

antenna element is derived. In this method, a calibration including phase error of P/S is achievable.
For faster calibration (REV-III), REV method is executed not for one antenna element unit but for sub-array unit. Sub-array is a group of some antenna elements and this group can be selected arbitrary. We select row/column sub-array.

B. Software Retro-directive System

To track a power receiving section, software retro-directive system is employed. In this system, phased array detects an angular direction of the power receiving section and steer beam to this direction due to amplitude mono-pulse system. For amplitude mono-pulse system, pilot signal is used. Pilot signal is microwave signal of Left Handed Circular Polarization (LHCP) and 2.45 GHz. This system consists of a pilot signal transmitting unit mounted on a power receiving section and a pilot signal receiving unit mounted on a power transmitting section. Both units are consisted of a pilot signal transmitting/receiving antenna and a feed circuit. These antennas are 4 elements array as shown in Fig. 4. As an antenna element, single-fed circular microstrip patch antenna with small perturbation segments is employed. The pilot signal receiving antenna simultaneously employs two beams: a sum beam in both azimuth and elevation planes and a difference beam in both planes. Fig. 5 shows a measured elevation radiation pattern of the pilot signal receiving antenna. As shown, the sum beam has peak level of main beam near an arrival direction of transmitted pilot signal. The difference beam has a sharp and deep null directed normal to the pilot signal receiving antenna.
First step transmit pilot signal from the pilot signal transmitting antenna. The pilot signal receiving antenna receives pilot signal with both sum and difference beams. A tracking receiver compares two signals converted to intermediate frequency by a down converter. Next, PACU process these signals and detect the arrival direction of pilot signal by amplitude mono-pulse system. This system gave us beam tracking accuracy of 0.4 degrees rms (root mean square).

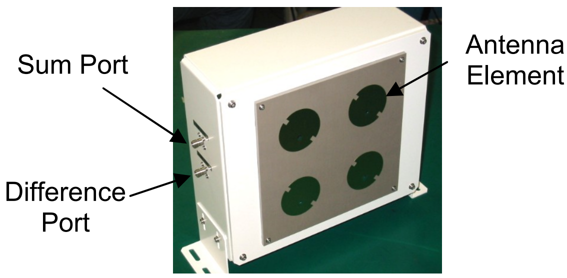


Fig. 4. Pilot signal receiving antenna.

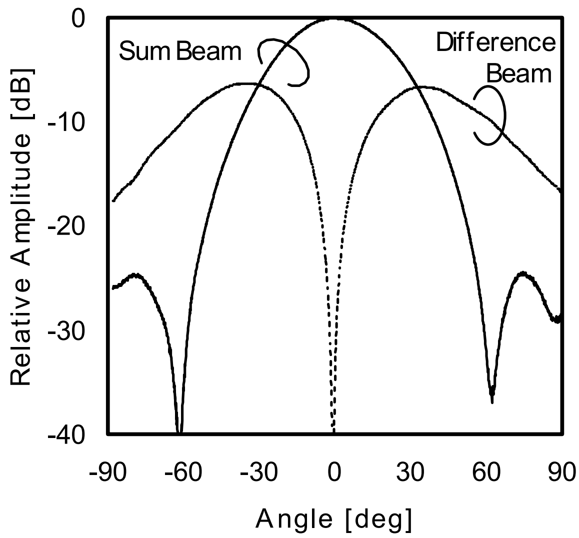


Fig. 5. Measured elevation radiation pattern of pilot signal receiving antenna.

IV. Experimental Result

Fig. 6 shows a radiation pattern of the phased array in elevation plane. In this figure, a measured radiation pattern before and after the execution of REV method and a simulated result are plotted. The radiation pattern before the execution of REV method is not in agreement with the simulated result and steering error of 0.1degrees was observed. The radiation pattern after the execution of REV method has deep null between sidelobes and is in good agreement with the simulated result. This is because excitation error of antenna element and the influence of mutual coupling are calibrated. Fig. 7 shows radiation patterns when main beam is steered to EL=-15, -10, -5, 0, 5, 10, 15degrees. In each beam steering angle, steering accuracy within 0.1degrees was obtained.

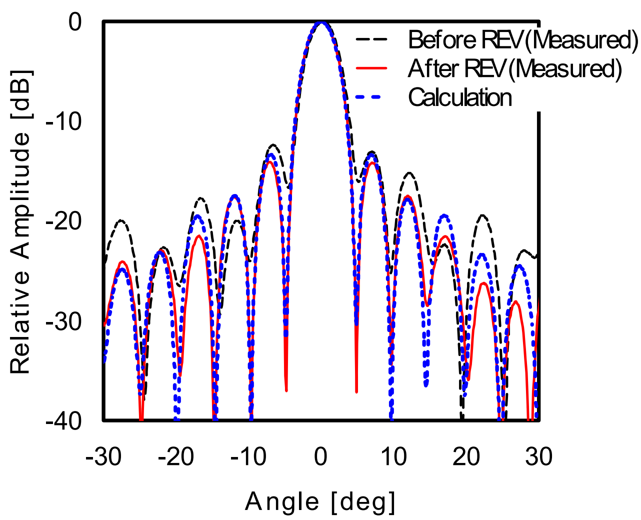


Fig. 6. Measured and simulated elevation radiation pattern.

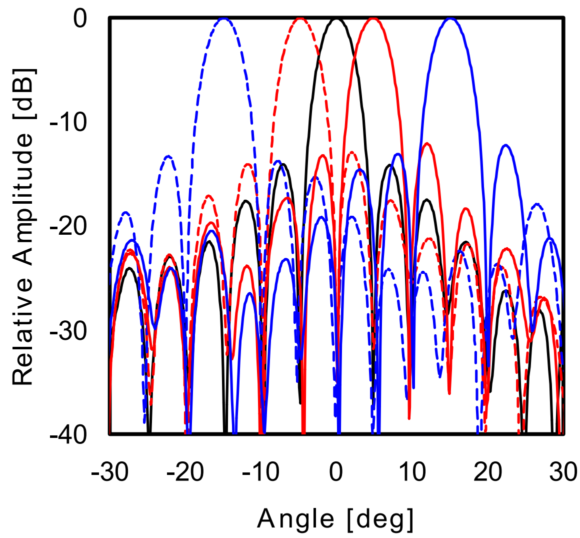


Fig. 7. Measured elevation radiation pattern of phased array (beam steering angle: EL=-15, -5, 0, 5, 15degrees(AZ=0degrees)).

V. Conclusion

MELCO and Kyoto University have jointly developed a phased array for the purpose of basic experiments of high accurate microwave power transmission. This phased array is 256 elements array and can transmit 1.5kW microwave power. To realize this purpose, a calibration system of complex electric fields of antenna elements (REV method) and a power receiving section tracking system (software retro-directive system) are employed. From radiation performance measurements, a measured radiation pattern has been in good agreement with a simulated result. In addition, beam steering accuracy less than 0.1degrees, corresponding to about fortieth of beamwidth, was obtained. This is because REV method has calibrated complex electric fields of antenna elements. Furthermore, beam tracking accuracy less than 0.4degrees rms has been obtained. These show the effectiveness of REV method and software retro-directive system.
Therefore, the developed phased array has achieved high accurate microwave power transmission and we will conduct basic experiments about higher accurate microwave power transmission and clarify improvements to existing technology for the realization of SPS.

References

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