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Optimization of uniformly excited phased array for microwave power transmission

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1. Introduction

Solar power satellite (SPS) is paid attention to as a clean, inexhaustible large-scale base-load power supply since carbon dioxide is not exhausted. The expectation is great as renewable energy since the SPS is not affected by weather and can supply electric power as a base load for 24 hours a day. The SPS is a gigantic satellite designed as an electric power station orbiting in the Geostationary Earth Orbit (GEO) [e.g., 1]. The SPS sends a high power microwave to a ground power receiving site, where the microwave power beam is received by a rectenna (rectifying antenna) array. The rectenna array converts the microwave to direct current (DC) and is connected to an existing electric power grid. The power distribution transmitted from the antenna array elements in space has the Gaussian distribution with a 10dB taper in order to decrease sidelobe levels and achieve highly efficient transmission to the reception point [2]. It is a crucial problem that transmitting power is the maximum and a lot of heat is generated in the center of the array where heat radiation is most difficult. A method of decreasing the sidelobe under the uniform excitation has already been proposed for communications [3]. Since the transmission efficiency (ratio of the received electric power on the rectenna site to the transmitted power) was a critical factor for the microwave power transmission, we optimized the uniformly excited antenna array to satisfy not only the low sidelobe levels and also the high transmission efficiency, simultaneously.

2. Requirement for Microwave Power Transmission Beam and Advantage of Uniform Amplitude Excitation

When the microwave is transmitted from space, it is necessary to meet various requirements. For instance, the radiation outside of the rectenna site must be suppressed to decrease the electric power transmission loss, minimize the influence to human body and communications, and reduce the cost as much as possible. The electricity prices by SPS must be less or equal to existing commercial ones. Therefore, the formation of low sidelobe and highly efficient radiation is requested for the power transmission beam. The maximum sidelobe level falls only by -13 dB from the main beam level when the array antenna is excited with an equal amplitude although it is simple and its radiation efficiency is high. On the other hand, the maximum sidelobe level is less than -20 dB from the main beam level when it is excited with the 10dB Gaussian distribution taper where the excited power becomes 1/10 on the edge compared with the center. There is an advantage that a lot of electric power is concentrated in the center of rectenna site and the same electric power is obtained in a narrower area with high efficiency [4].

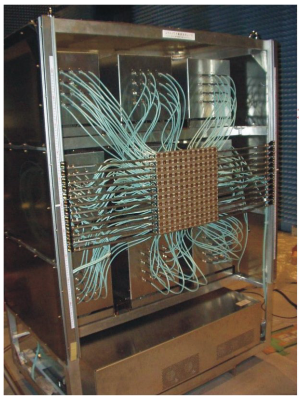
The array antenna array used in the present paper is to transmit power, the transmission efficiency is important, and the uniformly fixed excitation amplitude is preferred. The reasons for the uniformly fixed amplitude are; (1) the improvement of the radiation efficiency, (2) simple control of structure maintenance, and (3) heat problems.

3. Beam Optimization and its Verification

3.1 SPORTS 5.8 Beam Forming Subsystem

ISBN: 978-4-88552-223-9 C3055©IEICE

Frequency	5.8GHz band
No. of ant.	12×12 elements
Antenna element	Circular polarized square patch
Phase shifter	4 bits per element (Resolution: 22.5°)
Oscillator	FET
Output	150W (9 units)
Efficiency	Approx. 10%
Element spacing	0.6λ (up to 1.5λ is possible)
Sizes	1.4m x 0.9m x 2.0m



. Fig. 1. SPORTS 5.8: main specifications and photograph.

The beam forming subsystem of SPORTS 5.8 (Space POwer Radio Transmission System with 5.8GHz) [5] of our institute was used to evaluate the result of the beam formation experimentally. Its main specifications and photograph are shown in Fig. 1. The microwave power is fed from the semiconductor transmitter to each element via phase shifter for the beam formation. The element spacing was 0.6 wavelength and the radiation pattern was measured in the radio wave anechoic chamber for the microwave energy transmission experiments [6] (METLAB) in the present experiments.

3.2 Optimization Technique

The objective of the optimization of the radiation pattern is both the sidelobe suppression and the maximization of power in the receiving area. Therefore, mathematical techniques like linear or nonlinear programming which obtain the best points by maximizing or minimizing a single objective function in a solution space are insufficient. A multipurpose genetic algorithm (GA) to which a lot of researches have been done in recent years was used. This is because Pareto optimal solution set can be obtained by a single search since this GA searches for solution using two or more individuals and multiple purposes can be handled directly in each search stage in individual evaluation. Pareto optimal solution set contains all solutions that obtain good evaluation in various balances among purposes which have trade-off relation each other and more excellent solutions than the set does not exist in any points.

Fig. 2 shows the relation between the feasible region and the Pareto optimal solution set for two purposes. The trace or set of solutions closest to the global optimum solution within the feasible region is obtained. A designer can select the best point from the set based on his or her idea. The present analysis used a multipurpose GA called SPEA2 (Strength Pareto Evolutionary Algorithm 2) [7][8]. Its superiority to other algorithms has been confirmed in a variety of test functions.

Because the SPORTS 5.8 subsystem is uniform amplitude excitation, variables to be optimized are 144 excitation phases of the array elements. The power receiving area is assumed as a circle of 50cm in the radius from the center of the main beam in 3.2m distance from the transmitter. Received power was only evaluated with a grid of 101× 101 in the reception area of 4m × 4m due to the calculation time restriction.

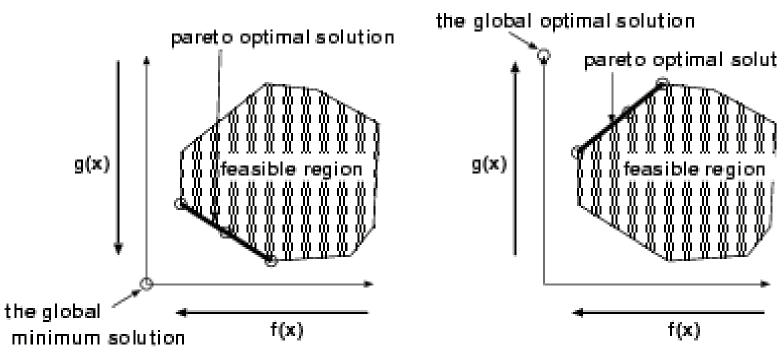


Fig. 2. Pareto optimal solution

The radiation pattern on the reception side was calculated by taking the radiation pattern of the patch antenna and transmission length of 3.2m into account. Two objective functions (1) to minimize the MSLL (Maximum SideLobe Level) and (2) to maximize the power in the reception area were used under the multipurpose GA.

3.3 Optimal Result

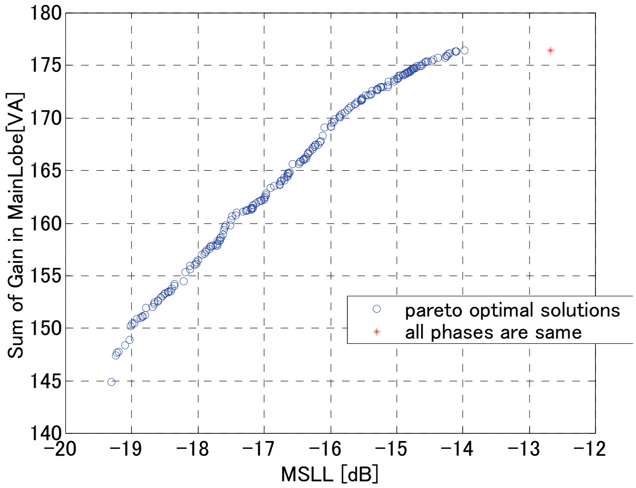


Fig. 3. Pareto optimal solutions of the radiation

The blue circles of Fig. 3 show the Pareto optimal solutions obtained by multipurpose GA for the broadside beam. A received power was normalized with the case (all phases are same) when all the elements are excited in-phase as a standard reference (100%) in the power receiving area. The red upper right point corresponds to the in-phase case, where MSLL is -12.68dB. The lowest MSLL = -19.31dB and relative received power was 82.3% among the optimal solutions. The sidelobe level was suppressed by 6.6dB compared with those of the in-phase case. The phases of the elements near the edges have greatly changed and sometimes become in the opposite phase with those of the center. The element in the center part greatly contributes to the main beam and the elements on the edges play a role to suppress MSLL.

3.4 Experimental Verification

a) **b)**

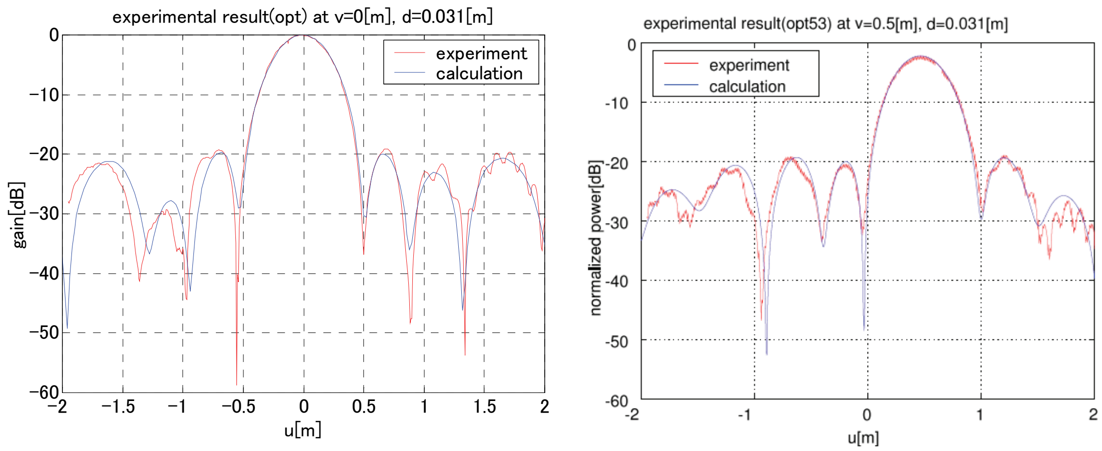


Fig. 4 Radiation pattern for the lowest MSLL. Red: experiment and blue: calculation.
(a) Broadside beam and (b) Off broadside beam

The phase distribution of the optimal solution was given to the phase shifters of the SPORTS 5.8 subsystem in order to examine whether actually the sidelobe levels had been suppressed. The solution with the lowest MSLL was used for the experiment. The result is shown in Fig. 4a. The experimental results (red) matched well with the calculated values (blue) and the MSLL is suppressed enough. The expected radiation pattern which suppresses MSLL was successfully obtained based on the optimization for the subsystem. The another optimal radiation pattern that suppresses MSLL most among Pareto optimal solution set when the main beam is shifted by 50cm to the side at the reception area from the broadside was calculated and its phase distribution was given to the subsystem. The results are shown in Fig. 4b. The experimental results again matched the calculation well. The satisfactory result was obtained not only to the broadside direction but also the off broadside direction. The obtained results are expected to be robust since such results were obtained even if the phase shifters include some errors. The influence of mutual coupling would be negligible at 0.6 wavelength element spacing for a square patch antenna.

5. Discussion and Conclusion

The PC cluster of Advanced Kyoto-daigaku Denpa-kagaku Keisanki-jikken (A-KDK) computer of our institute was used for the calculation of multipurpose GA for optimization. This system has 24 calculation nodes. Each node has Pentium III 1.0GHz CPU and 1GB memory. 12 nodes were allocated for this optimization. In the optimization of the broadside direction, the calculation time to obtaining a satisfactory Pareto optimal solution set was about 31 hours. At this time, the parameters of multipurpose GA were population size = 600 and maximum generation = 600. This calculation assumes the radiation pattern in the near field region and was relatively complex and time-consuming since the distance to the reception points are taken into account. No improvement was made to make the calculation faster. It is not practical to apply this algorithm to a SPS composed of an enormous number of elements. It is necessary to calculate by another new method with faster computers. It is important, however, that we have successfully obtained such optimal radiation patterns that maximize the received power and suppress MSLL.

The radiation pattern with uniform amplitude excitation on the beam formation subsystem of SPORTS 5.8 was optimized as a small-scale proof experiment under the assumption that the software retrodirective system will be adopted in a future SPS. The objectives of the multipurpose optimization were to maximize the power in the reception area and to minimize the MSLL simultaneously. The radiation patterns that suppress MSLL with high reception power were obtained and the results were experimentally confirmed. The MSLL were suppressed by about 6.6dB compared with in-phase excitation. It is expected that mutual coupling is hardly influenced when the element interval was 0.6 wavelength in the array antenna element spacing of square patch antennas since the experimental and calculated results matched well although this should be examined further.

Acknowledgments

This work was partly supported by Kyoto University 21COE Program, "Establishment of COE on Sustainable Energy System". Computation in the present study was performed with the KDK system of Research Institute for Sustainable Humanosphere (RISH) at Kyoto University as a collaborative research project.

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