Analysis of Huge-scale Periodic Array Antenna for SSPS Using Impedance Extension Method

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***Abstract*— An extreamly large scale periodic array antenna is required for the power transmission in the space solar power systems. Analysis of the array antenna is important to estimate radiation property of the array antenna, but a full-wave analysis requires too much computer memory and too long CPU time. In order to overcome this difficulty, the impedance extension method is proposed as a method of approximate analysis for a huge periodic array antenna. The active impedance and radiation pattern of the array antenna are presented. It is shown that the edge effect of the array antenna is very small in a huge array by error analysis of the active impedance and the radiation field for the impedance extension method.**

I. Introduction

Exhaustion of the energy source including fossil fuel has become one of the most serious problems in recent years. As one of the approaches to solve the problem, research on the SSPS (Space Solar Power Systems), which generates the power by solar cells mounted on geostationary satellite and transmits the power to the earth with microwave, has attracted considerable attention as described in [1], [2]. In order to transmit the microwave power from the SSPS to the earth, a huge array antenna composed of hundreds of millions of elements is used to obtain an extremely narrow beam width of microwave. Therefore, beam width, actual gain pattern and edge effects of a huge periodic array antenna have to be analyzed for the design of practical use of SSPS.

Many efforts have been made to analyze electromagnetic property of the periodic array antenna. Ishimaru et al. [3] proposed a finite periodic structure method for the analysis of a finite array antenna and compared the active impedance of 11×11 element dipole array antenna over a ground plane obtained by the proposed method with exact solution and infinite periodic structure. Hansen and Gammon presented the effects of the active impedance of finite-by-infinite array antenna consisting of dipole elements with a ground plane [4], [5]. They also proposed a Gibbsian model to express the edge effects of the active impedance [6], [7]. It has been also reported that the active impedance is independent of a number of elements and E-plane impedance can be modulated form depending on the radius of elements [9]. Although so many results of the active impedance of a periodic array antenna have been reported in these papers, analysis for the actual gain pattern and systematic analysis of the array antenna have not been reported yet.

Meanwhile, many researches of methods for the huge array antenna have been carried out. One of these researches is the acceleration of Method of Moments (MoM)[10], [11]. MoM is a popular method to analyze antennas as well as conducting scatterers, but the CPU time and memory are proportional to N^3 and N^2, respectively, when Gaussian elimination is used to solve a $N \times N$ MoM matrix, where N is the number of unknown coefficients in MoM. Therefore, analysis of large antenna whose hundreds of millions of unknown is almost impossible and it is important to develop a much efficient method to analyze such a huge scale antenna.

In this paper, properties of active impedance of a periodic array antenna reported in previous papers are explained briefly. Impedance extension method, which can be used for the approximate numerical analysis of a huge periodic array antenna using properties of the active impedance, is proposed. Finally, the validity of the proposed method is discussed by calculating the active impedance and actual gain pattern of two-dimensional periodic cross dipole array antenna.

II. Impedance Extension Method

Numerical results reported in previous papers [3]-[9] yield following properties of active impedance of a periodic array antenna.

1) Active impedance is almost independent of the distribution of feeding voltage.
2) Active impedance changes in the edge region, and is almost uniform in the central region.
3) Active impedance is almost independent of a number of elements, when the number of array elements is large enough.

From these properties, it is possible to expand the active impedance of a small periodic array antenna (called "small array") having N_x^o elements to a huge periodic array antenna (called "huge array"). Two dimensional periodic cross dipole array antenna having a ground plane for SSPS is shown in Fig. 1. In the Impedance extension method (IEM) shown in

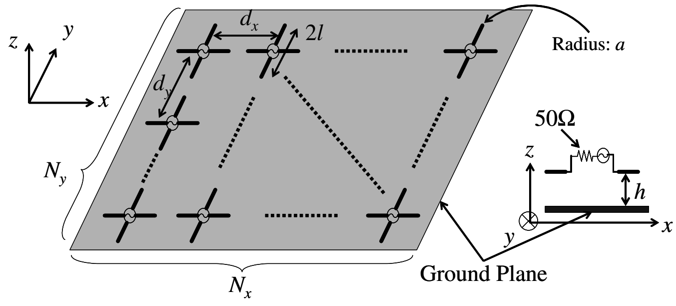

Fig. 1. Two dimensional cross dipole array antenna for SSPS.

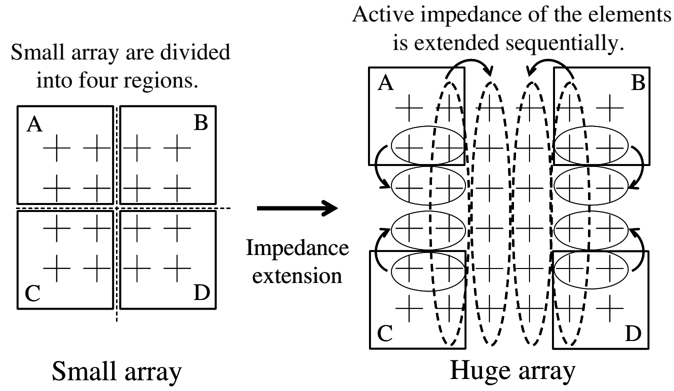

Fig. 2. Two dimensional impedance extension method (IEM).

Fig. 2, the elements of the small array are divided into four areas. Next, the active impedance of the elements is substituted into those of the elements in the corner region of the huge array. Finally, the active impedance of the other elements in the huge array is extended from that of the elements in the corner region. In the Infinite array method (IAM) shown in Fig. 3, on the other hand, the active impedance of the center element in the small array is substituted into the impedance of all elements of the huge array.

III. Numerical Results

A. Active impedance and actual gain of a huge array

The impedance extension method is applied to a huge array. Active impedance of a small array having $N_x^o = N_y^o = 50$ is extended to the huge array with $N_x = N_y = 200$. The length of each dipole, the radius of each dipole, the array spacing and the height of the array elements are $2l = 0.5\lambda$, $a = 0.00025\lambda$, $d_x = d_y = 0.75\lambda$ and $h = 0.25\lambda$, respectively. Each dipole is divided into 3 dipole segments in MoM analysis. As the feeding amplitude of the voltage of the array element, 10dB-tapered Gaussian distribution expressed by

$$V(n_x, n_y) = e^{-\frac{(x-\mu_x)^2+(y-\mu_y)^2}{2\sigma^2}} \quad (1)$$

is employed, where

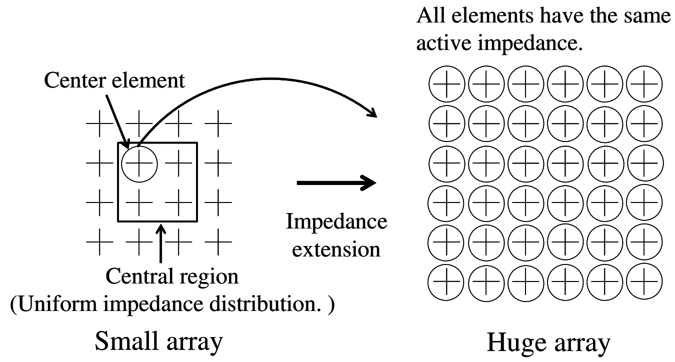

Fig. 3. Infinite array method (IAM).

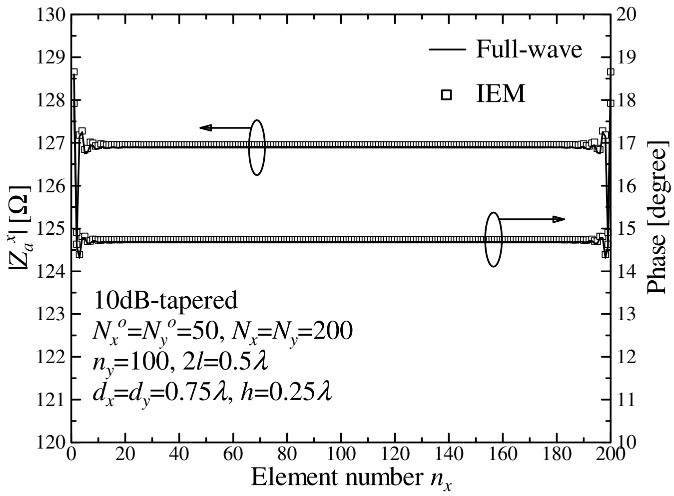

Fig. 4. Active impedance of 100th row.

$$\mu_x = \frac{d_x(N_x-1)}{2},\ \mu_y = \frac{d_y(N_y-1)}{2},\ x = d_x(n_x-1),$$
$$y = d_y(n_y-1),\ \sigma^2 = \frac{\{d_x(N_x-1)\}^2+\{d_y(N_y-1)\}^2}{8\log(\sqrt{0.1})}.$$

Since image method is used to include the effect of ground plane, the total number of elements to be analyzed is 80000. The current distribution of each array element is required to calculate the radiation field, and it is assumed that all elements have the same current distribution to that of the center element in the small array. Using this current distribution, actual gain pattern of the huge array is obtained.

Active impedance of dipole antennas along with x axis of 100th row obtained by the impedance extension method and full-wave analysis is shown in Fig. 4. Actual gain pattern of the array antenna is shown in Fig. 5. It is found that the active impedance and the actual gain obtained by the proposed method agree with those by the full-wave analysis very well.

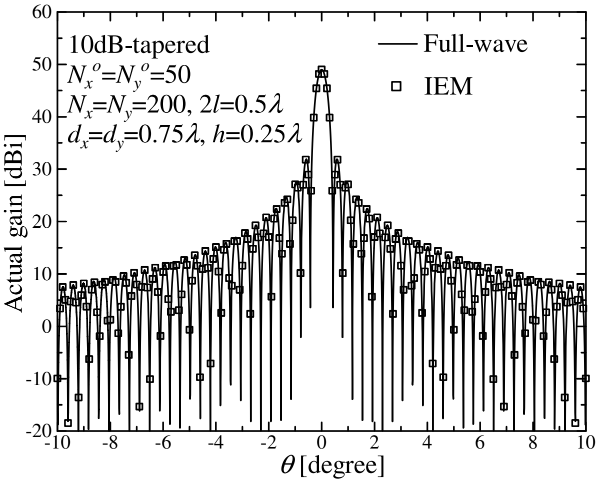

Fig. 5. Actual gain pattern obtained by impedance extension method and full-wave analysis.

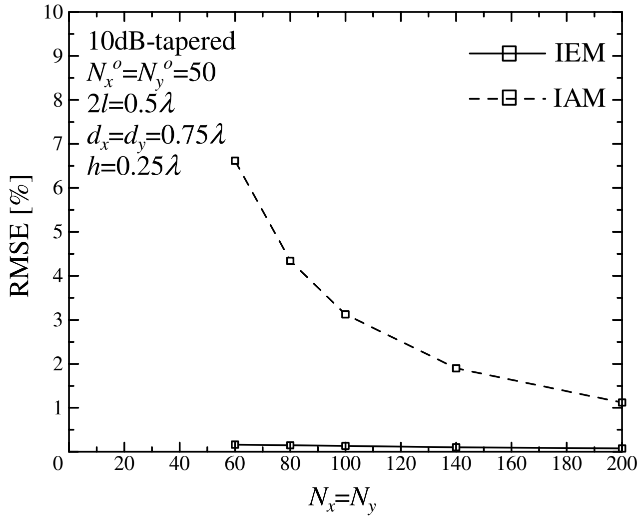

Fig. 6. RMSE of the active impedance.

B. Error of impedance extension method

Error of active impedance of two methods is estimated using following RMSE (Root Mean Square Error).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\left|Z_1^x(i,j) - Z_2^x(i,j)\right|^2}{(N_xN_y)^2}} \quad (2)$$

where $Z_1^x(i,j)$ is the active impedance of the element along with x axis obtained by full-wave analysis and $Z_2^x(i,j)$ is the active impedance of the elements along with x axis obtained by impedance extension method. RMSE of the two method is shown in Fig. 6. It is found that RMSE of the IEM, which takes into account for edge effects, is smaller than that of the IAM, which ignores edge effects. In addition, RMSE of the two method gradually decrease when a number of elements $N_x = N_y$ increases.

Error of the radiation field of two methods is also estimated using following equation.

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^{P}\left|E_1(\theta_i) - E_2(\theta_i)\right|^2}{\sum_{i=1}^{P}\left|E_1(\theta_i)\right|^2}} \quad (3)$$

where E_1 is the radiation field obtained by MoM, E_2 is the radiation field obtained with the impedance extension method and P is the number of sampling points of θ_i. Error of the radiation field of the two methods is shown in Fig. 7. It is found again that error of the IEM is smaller than that of the IAM. These results show that edge effects on the active impedance and the radiation field are negligible for the huge array antenna.

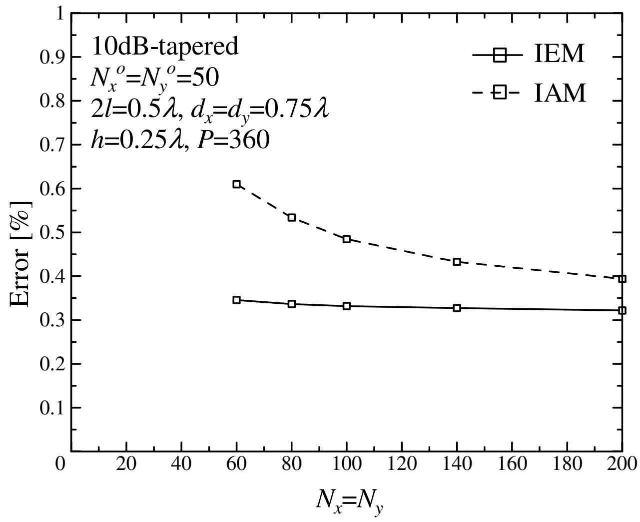

Fig. 7. Error of the radiation field.

IV. Conclusion

In this paper, properties of the active impedance of a periodic array antenna, which were reported in previous papers, were explained briefly. The impedance extension method based on these properties was also proposed as an approximate method for the huge array antenna. In the impedance extension method, the active impedance of the small array antenna obtained by MoM was extended to that of the huge array antenna. This method has two advantages. First, the CPU time and computer memory for analysis are independent of the array scale. Second, when the active impedance of the small array is once obtained, any huge array can be analyzed by the proposed method as long as it has the same array parameter excluding the number of elements N_x because the active impedance is almost independent of a number of elements and distribution of feeding voltage. The active impedance and the actual gain of the two dimensional huge array antenna were obtained by proposed method and high accuracy was confirmed. Furthermore, it was also found that edge effects of the huge array is negligible from the error estimation of the active impedance and the radiation field.

In-phase feeding distribution was assumed in this paper. However, the phase of the array element may be different from each other when beam is scanned. The validity of the present method applied to the array antenna with phase distribution will be given in the future work.

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REFERENCES

[1] P.E.Glaser, "Power from the sun; its future," Science, vol.162, pp.857-861, Nov. 1968.
[2] A.K.M. Baki, Kozo Hashimoto, Naoki shinohara, Tomohiko mitani, and Hiroshi Matsumoto, "Isosceles-trapezoidal-distribution edge tapered array antenna with unequal element spacing for solar power satellite," IEICE Trans. Commun., vol.E91-B, no.2, pp-527-535, Feb. 2008.
[3] A. Ishimaru, R.J. Coe, G.E. Miller, and W.P. Geren, "Finite Periodic Structure Approach to Large Scanning Array Problems," IEEE Trans. Antennas Propagat., vol.AP-33, no.11, pp.1213-1220, Nov. 1985.
[4] R.C. Hansen, and D. Gammon, "Standing Waves in Scan Impedance of Finite Scanned Arrays," Microwave and Optical Technology Letters, vol.8, no.4, pp.175-179, Mar. 1995.
[5] R.C. Hansen, and D. Gammon, "Standing Waves in Scan Impedance: E-Plane Finite Array," Microwave and Optical Technology Letters, vol.11, no.1, pp.26-32, Jan. 1996.
[6] R.C. Hansen, and D. Gammon, "A Gibbsian Model for Finite Scanned Arrays," IEEE Tans. Antennas Propagat., vol.44, no.2, pp.243-248, Feb. 1996.
[7] R.C. Hansen, "Finite Array Scan Impedance Gibbsian Models," Radio Science, vol.31, no.6, pp.1631-1637, Nov.-Dec. 1996.
[8] R.C. Hansen, Phased Array Antennas, Sec. 8.3, John Wiley Sons, 1998.
[9] R.C. Hansen, "Anomalous Edge Effects in Finite Arrays," IEEE Trans. Antennas Propagat., vol.47, no.3, Mar. 1999.
[10] R.F. Harrington, Field Computation by Moment Methods, New York, Macmillan, 1968.
[11] J.H. Richmond and N.H. Greay, "Mutual impedance of nonplanar-skew sinusoidal dipoles," IEEE Trans. Antennas and Propagat., vol.23, no.5, pp.412-414, May 1975.