Experimental Study on One-Dimensional Phased Array Antenna Including Lossy Digital Phase Shifters for Transmitting Power Maximization

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Abstract

A large-scale phased array antenna will be adopted as a microwave power transmitter of solar power satellites. The objective of the present study is to maximize transmitting power of a large-scale phased array antenna including lossy digital phase shifters. In the present paper, we describe a newly developed algorithm for transmitting power maximization, and demonstration experiments of a one-dimensional 12-elements phased array antenna including 4-bit lossy digital phase shifters. We confirmed effectiveness of the developed algorithm through the demonstration experiments as well as numerical simulations.

1. Introduction

A large-scale phased array antenna will be adopted as a transmitting antenna of solar power satellites (SPS) [1, 2]. One of the most important purposes of the SPS is to transmit electricity from space to the ground as efficiently as possible. In general, the transmission loss of the phase shifter depends on its phase shift. In most of the phased array antenna systems, amplitude difference through the lossy phase shifter among antenna elements is conditioned by a limiter circuit or an automatic gain control circuit. In the SPS situation, however, these conditioning circuits provide extra power loss. Therefore, it is important to find a solution for maximizing transmitting power of a phased array antenna including lossy phase shifters. Fakharzadeh et al. [3] proposed a beamforming method under the condition that an analog phase shifter provides nonlinear transmission loss depending on its phase shift.

The objective of the present study is to maximize the transmitting power of a large-scale phased array antenna including lossy digital phase shifters. In the present paper, we first describe a newly developed algorithm for transmitting power maximization. Then we describe demonstration experiments of one-dimensional 12-elements phased array antenna including 4-bit lossy digital phase shifters in order to validate the developed algorithm.

2. Algorithms for Transmitting Power Maximization of a Large-Scale Phased Array Antenna

Fig. 1 shows an alignment of a one-dimensional phased array antenna composed of N isotropic antenna elements with d spacing. Each antenna element includes a m-bit phase shifter, which can shift the output phase discretely in $180/2^{m-1}$-degree increment from 0 to 360 degrees (m: natural number). We assume that the phase shifter provides the amplitude attenuation of $\alpha_l (\alpha_l < 1)$ when the l-th-bit phase shifter is switched on (l: natural number, $1 \le l \le m$). Then, the transmitting power maximization problem can be expressed as the following discrete optimization problem (P):

$$A = \max_{\boldsymbol{x}} E^*(\boldsymbol{x}, \theta)E(\boldsymbol{x}, \theta), \text{ s.t. } \boldsymbol{x} = \left\{ x_{pl} \mid x_{pl} = 0,1 \right\}, \quad 1 \le p \le N \tag{1}$$

$$E(\boldsymbol{x}, \theta) = \sum_{p=1}^{N} \left\{ \prod_{l=1}^{m} \alpha_l^{x_{pl}} \cdot \exp\left(j \frac{2\pi d}{\lambda}(p-1)\sin\theta + j\pi \sum_{l=1}^{m} 2^{1-l} x_{pl} \right) \right\}, \tag{2}$$

where E is the radiated electric field, * shows the complex conjugate, θ is the direction angle shown in Fig. 1, p is a natural number, j is the imaginary unit, and λ is the transmitting microwave wavelength. Then the problem (P) is equivalent to the following discrete optimization problem (P'):

$$A' = \max_{x}\left|E(\boldsymbol{x},\theta)\right|, \tag{3}$$

because $E^{*}(\boldsymbol{x},\theta)E(\boldsymbol{x},\theta) = \left|E(\boldsymbol{x},\theta)\right|^{2}$.

The computational time becomes $O(2^{mN})$ to solve the problem (P') by enumerating all the possible variables, because the number of the decision variables x_{pl} is mN and each decision variable takes 0 or 1. When the number of antenna elements N becomes large, this enumerative approach takes too much time to solve the problem (P'). Therefore, we developed a new algorithm to obtain a near-optimal solution in a short computational time by applying the following real rotation theorem [4] to the problem (P'):

$$|z| = \max_{0\leq\xi<2\pi}\mathrm{Re}\{z\cdot\exp(\mathrm{j}\xi)\}, \tag{4}$$

where z is an arbitrary complex number. By replacing z by $E(\boldsymbol{x},\theta)$ and substituting Eqs. (2) and (4) into Eq. (3), the problem (P') can be eventually rewritten as the following problem (D):

$$A' = \max_{0\leq\xi<2\pi}\sum_{p=1}^{N}\left\{\prod_{l=1}^{m}\alpha_{l}^{x_{pl}}\cdot\cos\left(\frac{2\pi d}{\lambda}(p-1)\sin\theta + \pi\sum_{l=1}^{m}2^{1-l}x_{pl} + \xi\right)\right\}. \tag{5}$$

Note that the decision valuable of the optimization problem can be replaced by ξ. Assuming that ξ can take discrete values as follows:

$$\xi \in \Xi = \{2\pi k/K \mid k = 0,1,\cdots,K-1\}, \tag{6}$$

where K is an natural number, we can obtain a near-optimal solution in a computational time of $O(NK2^{m})$.

We can drastically reduce the computational time by the developed algorithm described above, when the number of antenna elements becomes large. Although the near-optimal solution of the problem (D) is not always the same as the optimal solution of the problem (P'), we confirmed that an appropriate K can make the approximation error small enough to be accepted.
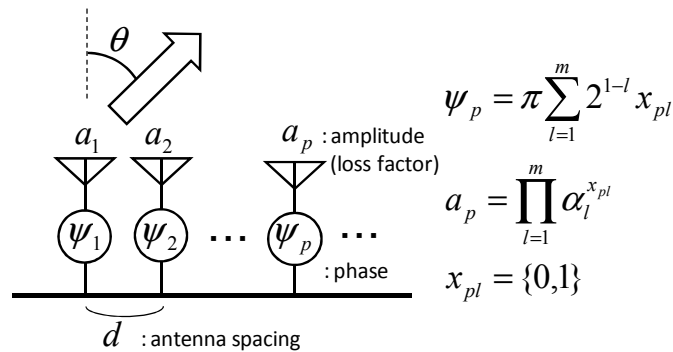

Fig. 1. Alignment of a one-dimensional phased array antenna.

3. Demonstration Experiments

We conducted demonstration experiments of a one-dimensional 12-elements phased array antenna in order to validate the developed algorithm. We fabricated 4-bit phase shifters whose transmission loss was different between two states. Then we measured beam patterns of the phased array antenna with and without using the developed algorithm.

3.1 Characteristics of Fabricated 4-bit Phase Shifters

The fabricated 4-bit phase shifters consist of two circuit types: hybrid-coupled-type phase shifters for 180-degree and 90-degree phase shifts, and loaded-line-type phase shifters for 45-degree and 22.5-degree phase shifts. The phase shift of each phase shifter takes place by switching on/off PIN diodes HSMP-4890 mounted on the circuit.

Table 1 shows measurement results of the fabricated phase shifters with respect to transmission losses and phase difference between two states. The measurement data are the average values of the 12 fabricated phase shifters. All types of the fabricated phase shifters involved the larger transmission loss when the PIN diodes were on-state than off-state. These characteristics are matched with the premises for the amplitude attenuation described in Sec. 2. These data were utilized as the initial data to calculate beam patterns of the one-dimensional 12-elements phased array antenna.

Table 1. Measurement results of the fabricated phase shifters (average values of the 12 phase shifters)

Designed phase shift [degree]	Transmission loss (off state) [dB]	Transmission loss (on state) [dB]	Phase difference between two states [degree]
-180	-1.19	-1.40	-181.8
-90	-0.91	-1.19	-90.3
-45	-0.41	-1.12	-44.1
-22.5	-0.38	-0.39	-22.2

3.2 Configuration of Demonstration Experiments

Fig. 2 shows a configuration diagram of the demonstration experiments. 12 antenna elements were horizontally aligned and each antenna element includes the fabricated 4-bit phase shifter. The transmission frequency was 2.45GHz, and the antenna spacing was 0.08 m ($\approx 0.65\lambda$). The transmitting microwave power from the phased array antenna was received by a standard horn antenna through a distance of 6m. The demonstration experiments were conducted in an anechoic chamber.
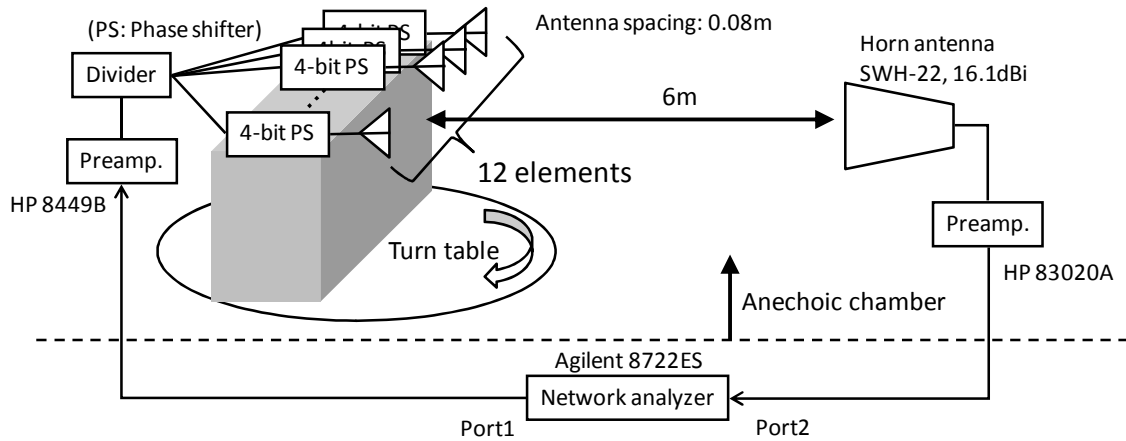

Fig. 2. Configuration diagram of demonstration experiments.

3.3 Results and Discussion

Fig. 3 shows beam pattern measurement and simulation results. The results in the beam directions of +5 and -5 degrees were shown in Fig. 3(a) and Fig. 3(b), respectively. The circle plots were obtained from the demonstration experiments and the lines were obtained from computer simulations. The red color shows the beam patterns obtained by using the developed algorithm, and the blue color shows those obtained by the conventional phase settings. The beam patterns were normalized by the maximum value of the beam pattern obtained by using the developed algorithm. The conventional phase settings are derived from the following equation when we assume the uniformly excited phased array:

$$\psi_p = -\frac{2\pi d}{\lambda}(p-1)\sin\theta. \tag{7}$$

From the measurement results, the developed algorithm provided greater antenna gain of 0.53 dB than the conventional phase settings, as shown in Fig. 3(a). This means the developed algorithm can prevent a transmitting power loss of 11% compared with the conventional phase settings. The measurement results in Fig. 3(a) agreed well with the simulation results. On the other hand, the measurement results show a gain decrease of 0.23dB by the developed algorithm when the beam was steered in the opposite direction, as shown in Fig. 3(b). The gain decrease is caused by the following reason: the number of antenna elements was not large enough to ignore the individual variability of the fabricated phase shifters. Therefore, the develop algorithms will work for increasing the transmitting power more effectively in a large-scale phased array antenna.
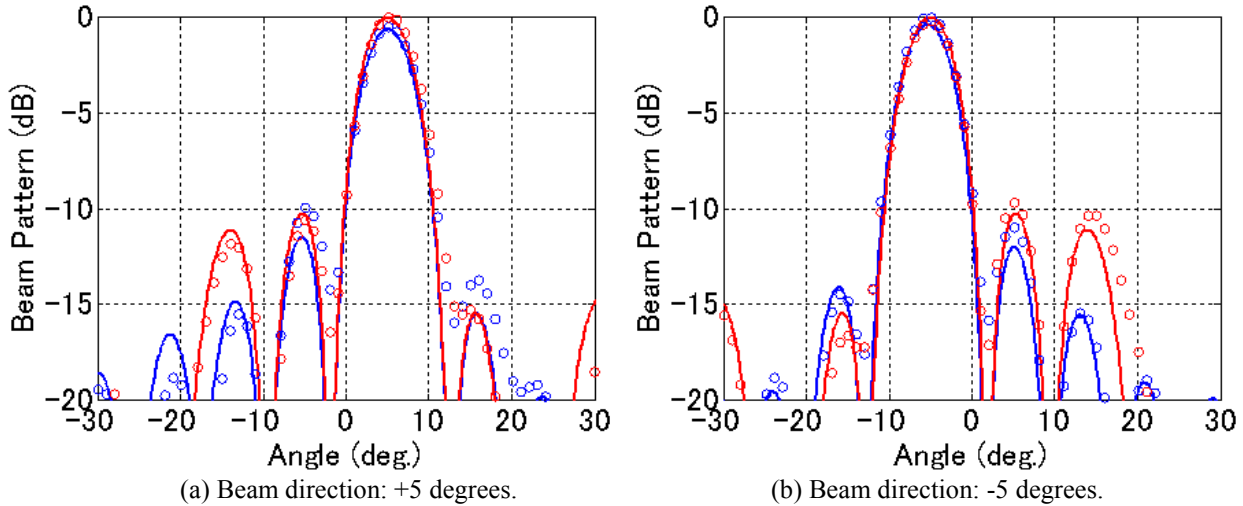

(a) Beam direction: +5 degrees.   (b) Beam direction: -5 degrees.

Fig. 3 Beam pattern measurement and simulation results of the one-dimentional 12-elements phased array antenna. (Circles: demonstration experiments, lines: simulations, red: developed algorithm, blue: conventional phase settings)

4. Conclusion

We confirmed effectiveness of the developed algorithm through the demonstration experiments as well as numerical simulations. The algorithm will contribute to maximizing transmitting power of not only the SPS transmitting antenna but also any other large-scale phased array antennas, for example, a phased array radar system.

5. Acknowledgments

6. References

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