A Study on Evaluation Method for Beam Profile of Phased Array by Using Two-Dimensional Measurement Equipment

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1. Introduction

Research and development of microwave power transmission (MPT) has become increasingly active in recent years [1,2]. After the resonator-coupled wireless power transfer system was developed in 2007 [3], MPT became widely recognized as one of the various wireless power transmission methods along with it. Wide-beam MPT systems like RF-IDs, which use wireless power to drive sensor tags and other devices, are moving toward full-scale social implementation, as evidenced by the fact that Japan will revise its ministerial ordinance in 2022 [4].

On the other hand, the beginning of MPT research in earnest was the narrow-beam MPT (power beaming) between fixed points in 1964 [5], and the expectation of a sustainable society through space-based solar power system (SSPS) [6] has continued to greatly encourage research. Many experiments of power beaming on the ground [7-9] have been conducted even in the 21st century, and further experiments are planned in the future [10]. In addition, the concept of power beaming of energy from offshore wind power generation on the ground as a step toward space is also being studied [11]. Bidirectional power beaming like power transmission cables may be realized by using reversible devices that switch between amplifier and rectifier functions [12,13].

For power beaming with high intensity, the beam forming is most important to reduce spillover power, not only from the viewpoint of transmission efficiency, but also from the viewpoint of radio interference. Research was conducted on the aperture distribution to maximize transmission efficiency [14] and on low-leakage beamforming based on Gaussian beams [15,16]. Design of power amplifiers [17] and simplification of power feeding circuits [18] during sidelobe reduction was also proposed. Power beaming often uses a lens-like focusing phase [19] since the receiving antenna is placed in a near field. In addition, flat-top beams [20] was developed for conversion efficiency at the rectenna.

Some of the authors previously proposed a both-side retrodirective system to dynamically minimize spillover in real-world situations [21,22]. Retrodirective systems typically re-radiate power signals in the direction of arrival by inputting the received pilot signals into the phase conjugate circuit of each antenna element [23,24]. In a both-side retrodirective system, spillover is minimized by repeating the propagation between the beamed pilot signal and the power signal. It has been suggested that this system may automatically avoid obstacles that scatter or absorb radio waves when they enter the beam [25].

The above beam convergence has so far been confirmed only by simulation, and experimental verification of the principle is needed. Thus, the authors have developed a two-dimensional measurement equipment for beam convergence experiments [26]. This device can reveal the beam profile distribution by inserting a probe into a parallel-plate waveguide with many holes. In addition, the two-dimensional system can greatly reduce the number of antenna elements and power feed circuits by sandwiching a linear array antenna between parallel plates.

Although the distance characteristics of power transmission between fixed points [27-29] are well known, care must be taken because beams propagating in two-dimensional space diffuse differently [30]. Previously, power transmission using a two-dimensional waveguide sheet [31] has been proposed, but the distance characteristics of beam propagation have not been described. As for beam measurement techniques, the method of measuring the near-
field pattern [32] is well known, but it is not possible to measure the entire beam profile. On the other hand, in the field of metamaterials, a mechanical sweep of the probe [33,34] has been used to measure beam scattering, and the proposed method is suitable for achieving a wider range of measurements at a lower cost.

In this paper, the theory on the two-dimensional beam propagation characteristics is described first and the consistency with experimental results using the developed measurement system is shown. Then, the measured results of low-leakage beam profiles when using Gaussian amplitudes are discussed.

2. Two-Dimensional Propagation Theory

2.1 Consideration of theoretical equations

A parallel-plate waveguide is a two-plate structure. The propagation distance of electromagnetic waves is longer than in free space. As shown in Fig. 1, electromagnetic waves spread spherically from a single point in free space. However, it is expected to spread two-dimensionally in a parallel-plate waveguide. Therefore, the behaviors of electromagnetic waves in two dimensions are investigated.

![Fig. 1 Propagation in free space and parallel plate.](image)

The transmission efficiency \( \eta_0 \) including near field can be expressed by the following approximation formula [29]

\[
\eta_0 = 1 - e^{-\tau'},
\]

where \( \tau' \) is calculated by the Friis’ transmission formula in free space. It is given by Eq. (2).

\[
\tau' = \frac{\lambda^2 G_t G_r}{(4\pi D)^2} = \frac{A_t A_r}{(\lambda D)^2}.
\]

Here, \( G_t \) and \( G_r \) are the gains of the transmitting and the receiving antennas, \( A_t \) and \( A_r \) are the effective antenna apertures of the transmitting and the receiving antennas, \( \lambda \) is the wavelength, and \( D \) is the distance between the antennas. The Friis’ transmission formula is a calculation formula for the case of an electromagnetic wave radiated from a point source in free space, which diffuses spherically and attenuates in accordance with the surface area of the sphere.

In a parallel plate waveguide, the antenna is sandwiched by two conductor plates. By analogy, for the propagation in parallel plate, the electromagnetic wave diffuses circularly, and the propagation formula can be expressed as

\[
\tau' = \frac{L_c L_r}{\lambda D},
\]

where \( L_c \) and \( L_r \) are the lengths of the line antenna [30]. The transmission efficiency \( \eta \) in parallel plate waveguide including near field can be expressed by eq. (4) using the parameter \( \tau' \).

\[
\eta = 1 - e^{-\tau'}
\]

(4)

2.2 Suppression of TE- and TM-modes

In free space, only TEM-mode wave can propagate. On the other hand, TE-, TM-, and TEM-mode waves can propagate in parallel-plate waveguide [35]. To construct a two-dimensional measurement equipment, it is necessary to suppress TE1- and TM1-modes, at least. The cutoff frequency \( f_c^{(i)} \) of the TEi- and TMi-modes in parallel-plate waveguide is given by

\[
f_c^{(i)} = \frac{k_c^{(i)}}{2\pi \sqrt{\varepsilon \mu}} = \frac{1}{2d \sqrt{\varepsilon \mu}},
\]

where \( \mu \) and \( \varepsilon \) are the magnetic permeability and the dielectric constant in vacuum, \( d \) is the gap between parallel plates and \( k_c^{(i)} \) is the cutoff wavenumber of mode order \( n \) expressed as

\[
k_c^{(i)} = \frac{n\pi}{d} \quad (n = 0, 1, 2, \cdots).
\]

This time, to construct a two-dimensional measurement equipment operated in 5.8 GHz, the gap between parallel plates is set to 22 mm, which is smaller than the cutoff wavelength 25.84 mm calculated by (5) and (6).

2.3 Verification of theoretical equation

To confirm the theoretical formula for two-dimensional propagation, the authors analyzed the propagation in a parallel-plate waveguide using the electromagnetic simulation software HFSS. The simulation model of parallel-plate waveguide is shown in Fig. 2. The waveguide width is 300 mm, and the length is 1,000 mm. The gap between plates is 22 mm. The transmission distance can be swept from 2 mm to 1,000 mm by 2 mm steps. In addition, PML boundaries were set at all edges of the waveguide to prevent unwanted reflections. The array antenna consists of four to six elements and is fabricated on a substrate Megtron6 made by Panasonic with a relative permittivity of 3.34 and a thickness of 0.75 mm.

![Fig. 2 Simulation model of parallel plate waveguide.](image)
In the simulation, the dielectric loss is set to $\tan \delta$ of 0.0037, and the copper conductivity is set to $58 \times 10^6$ S/m. The measurement uses array antennas with the same number of elements for both transmission and reception.

The results of the simulations and calculations for the 4-element array antenna are shown in Fig. 3. Both results are close at distances over than 250 mm. The reason for the low efficiency at short distances might be caused by the coupling between the antenna elements. The low efficiency at 60 mm is because the signals from each receiving antenna are combined in out-of-phase. The ripple in efficiency is caused by multiple reflections between the transmitting and the receiving antennas. The overall 2% lower efficiency is due to dielectric losses in the antennas. A comparison of the results of the calculations with the losses excluded is shown in Fig. 4. The simulation results and the theoretical equation are in perfect agreement at long distances.

3. Fabrication of 4-Element Experiment System

A measurement can provide an understanding of the characteristics of the waveguide. Figure 5 shows the fabricated waveguide. A copper plate with 1,000 mm long and 300 mm wide was used. On one of the plates, 624 holes with diameter of 4.2 mm were punched with interval of 20 mm to observe the electric field distribution. Since the diameter is sufficiently small comparing the half-wavelength of 5.8 GHz, there is no influence on propagation.

The fabricated components are shown in Fig. 6. The antenna, power divider, and phase shifter are connected by coaxial cables and connectors. The power divider is made of Pasternack. The antennas are supported by a copper board.

By adjusting the phase, all transmitting antenna elements are excited with the same amplitude and phase. The input phases to the antennas are shown in Fig. 7. The phases of receiving antennas were adjusted in the same way. The patch antenna is designed to resonate at 5.8 GHz in the waveguide.

The antenna characteristics in the waveguide are shown in Fig. 8. The return loss of the antenna elements was larger than 15 dB at 5.8 GHz. They were enough for the experiment.
In addition, an electric field probe was fabricated. Figure 9 shows the phase-stabilized cable and the electric field probe. The probe length is 6.5 mm, which is one-eighth of a 5.8 GHz wavelength.

When measuring electric field distribution, it is necessary to prevent electromagnetic waves from radiating out of the waveguide and causing reflections. Therefore, radio wave absorbers are attached to the edges of the waveguide. Two types of absorbers were prepared. Figure 10 shows the two types of absorbers, pyramid-shape and wedge-shape.

4. Experiment with 4-Element Array Antenna

The electric field distribution was measured and compared with simulations for 4-element array antenna system. A Keysight E5071C vector network analyzer was used for the measurements. Fig. 11 shows the results of the comparison. Note that the values of the electric field were scaled to compare with the measurement results so that the maximum values of the electric field are coincided and are set to 0dB.

Figures 11(a), (b), (c) show the electric field distributions obtained by simulation and measurements. The results were drawn by a graphic software for comparison. Figure 11 (a) shows the simulation result. It is confirmed that the beam is formed, and the power is reached to the far end. But sidelobes are observed up to 100 mm. Figure 11 (b) shows the measurement result when a pyramid-shape absorber is used. The result shows good agreement with the simulation. However, standing waves are observed between 420 mm and 920 mm. It is because that the absorber cannot absorb the electromagnetic wave sufficiently. Figure 11 (c) shows the measurement result when a wedge-shape absorber is used. Since the length of wedge was large for this measurement equipment, the measurement area becomes narrower. However, it showed a very good result. Standing waves were suppressed enough.

The measurement results showed good consistent with the simulation. And, because the wedge-shape absorber showed the better performance, the wedge-shape absorber will be used in the subsequent experiments.

Next, experiment to measure the transmission efficiency was conducted using two array antennas. Figure 12 shows the experimental set-up to measure transmission efficiency. 4-element array antennas are placed as facing each other. Absorbers are placed in both sides of the receiving antenna to suppress reflections. The measurement was carried out by 20 mm steps. The calibration was conducted at the ends of the cables connecting to the divider and the combiner, and the losses of the divider and the combiner, measured by direct connection without antennas, were subtracted.

The experimental results are shown in Fig. 13. The gray line denotes the measured raw value. The efficiency is lower than the theoretical value. This is because the device losses...
are included. The green line denotes the result excluding device losses, which shows very good agreement with the simulated results. In the long distance, it is also agreed with the theoretical value. And no fine ripple of efficiency due to multiple reflections was not observed, because the measurement interval was 20 mm.

As a result, it is confirmed that the derived theoretical equation (4) is effective and the experiment using a two-dimensional measurement equipment can clarify the propagation characteristics of array antenna.

5. Experiment with 16-Element Array Antenna

To establish an evaluation method for converging beam of both-side retrodirective systems, which is the final objective of this study, a 16-element two-dimensional measurement equipment was developed. Figure 14 shows the developed equipment.

16-element two-dimensional measurement equipment using copper plates with 1 m wide and 2 m long. On one of the copper plates, 4,416 holes were punched for electric field measurement. Experiments were conducted to measure the electric field of the microwave beam using a 16-element patch array antenna.

Figure 15 shows the 16-element patch array antenna and the components to be mounted on the equipment to measure the microwave beam. The antenna board comprising eight elements is fabricated on a single substrate. The devices used were a 16-element patch array antenna, semi-rigid cables with phase trimmer, attenuators for Gaussian beam formation, field probe, and a phase-stabilized cable. All input phases for antenna elements were adjusted by phase trimmer to be in-phase.

In the experiments, two types of beam shape are measured. The first one is a uniform excitation, where all input signals are the same amplitude and in-phase. It’s a simple excitation, but sidelobes will be generated and the microwave power is somewhat diffused. Figure 16 shows the uniform excitation circuit.

The second one is a Gaussian beam excitation. The input for each antenna was adjusted by an attenuator to form a Gaussian beam. In this study, the attenuator was selected to form a Gaussian distribution with 20 dB taper. Figure 17 shows the Gaussian beam excitation circuit. The designed attenuation values with the antenna numbers are shown in Table 1.

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Table 1  Designed attenuation values [dB].
Figure 18 shows the measured amplitude curve when a power divider, cables, and attenuators are connected. The attenuators were adjusted to be coincided with the target amplitude curve.

![Graph showing measured and designed amplitude curves.](image)

**Fig. 18** Measured and designed amplitude curves.

The electric field distribution was measured by using Keysight E5071C vector network analyzer. Figure 19 shows the inside of the 16-element two-dimensional measurement equipment. Wedge-shape absorbers are attached to all edges of the parallel plate. The levels of each measurement result are adjusted so that the maximum values of the electric field are coincided with the simulation values and are set to 0dB.

![Images showing inside of measurement equipment.](image)

(a) Before closing the waveguide  (b) After closing the waveguide  **Fig. 19** Inside of 16-element two-dimensional measurement equipment.

Figure 20 (a) shows the simulation result of the uniform excitation. Sidelobes are observed as in the case of 8 elements. The field strength is spotty up to about 800 mm. This is because of the interferences of electromagnetic waves radiated from the antenna. After 800 mm, the beam is formed toward the far end and the power is somewhat diffused.

Figure 20 (b) shows the measurement result of the uniform excitation. Figures 20 (a) and (b) showed excellent agreement.

Figure 20 (c) shows the simulation result of Gaussian excitation. A converged beam was formed, and strong field was observed at the far end.

![Simulation and measurement results of uniform excitation.](image)

(a) Simulation result of uniform excitation  (b) Measurement result of uniform excitation

![Simulation and measurement results of Gaussian excitation.](image)

(c) Simulation result of Gaussian excitation  (d) Measurement result of Gaussian excitation

**Fig. 20** Electric field distributions in the 16-element experiment system.

6. Conclusion

To evaluate the performance of a both-side retrodirective system by experiment, the authors proposed a two-dimensional measurement equipment using a parallel plate...
waveguide. Propagation in the parallel plate waveguide was clarified by the theory, and the transmission performance was confirmed by simulation. By using the proposed equipment, the electric field distribution in the waveguide can be measured by electric probe and the measured results can be visualized. Two types of measurement equipment were developed, a 4-element experiment system for principle verification and a 16-element measurement equipment to evaluate beam convergence. The experiment to measure the transmission efficiency was also conducted using two array antennas. The measurement results showed excellent agreement with the simulation results. As a result, it is confirmed that the derived theoretical equation is effective and the experiment using a two-dimensional measurement equipment can clarify the propagation characteristics of array antenna. Therefore, the effectiveness of proposed 2-dimensional measurement equipment for evaluation of beam convergence was confirmed.

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References


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