FDTD Analysis of a Large Scale Energy Transmission Array Antenna

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1. Introduction

The finite-difference time-domain (FDTD) method [1-3] is a versatile and efficient tool for the solution of Maxwell's equations in complex structures for any time dependence. In this paper, we show analytical methods and computer simulation of a large-scale phased array antenna. The FDTD technique is employed to estimate beam scanning characteristics. Each antenna element is excited by a feeding probe based on the specified phase differences among the array antenna. For this purpose, a coaxial feed model [4] gives us an easy and fast way to analyze antenna characteristics. The phased array antenna under consideration is consisting of cavity-backed slot antenna elements. It is being developed for an energy transmission antenna system in the space solar power satellite [5]. The cavity-backed slot antenna element is thought to be one of the most suitable elements for the wireless transmission of microwave energy, and especially for space solar power satellite such as SPS2000 [6] and another experimental system SSPS [7]. The energy transmission antenna is referred to a spacetenna. Here we consider an antenna element and an array antenna module in the spacetenna operating at the frequency of 5.8 GHz. First, we describe the configuration and dimensions of the antenna element and the FDTD model analyzed. Second, we present radiation patterns and beam steering characteristics of the large scale phased array antenna consisting of 576 elements. Finally, a brief summary of this paper is provided.

2. Geometry and Modeling of Antenna Element

Figures 1 and 2 show a configuration of an energy transmission antenna system and an antenna element. The antenna characteristics are defined in the SSPS concept [7]. The spacetenna is a flat shape of 24 m by 22 m and regularly filled with array antenna modules. The spacetenna includes four hundred modules. Each of them has a square shape of 1 m by 1 m regularly filled with cavity-backed slot antennas and contains 572 elements. Hence, there are about two hundred thousand elements in the spacetenna. Antenna elements include microwave circuits operating at the frequency of 5.8 GHz. We proposed a cavity-backed slot antenna depicted in Fig. 3. This type of antenna has enough mechanical strength and the ability of low profile. Moreover, it is possible to radiate thermal energy effectively and keep the temperature of the element low. Liner polarization is assigned to elements and the bandwidth of the antenna element is not specified since the sinusoidal wave at the frequency of 5.8 GHz will be used.

Suppressing the grating lobes during the beam scanning and obtaining easily impedance matching, we define the dimension of the antenna element as d_x = d_y = 42 mm (0.812λ), where λ denotes the wavelength at the frequency of 5.8 GHz. The upper limit of the antenna height is specified as high as less than 50 mm (0.97λ). The term of antenna height means the total height of an antenna element and microwave circuits. We design antenna elements of 15 mm (0.3λ) high. The cavity-backed slot antenna is excited by a probe. Figure 3 shows the geometry and the dimension of the antenna element. h denotes the cavity height. P_f and P_h denote the probe location and its height. ℓ_s and w_s denote the slot length and width, respectively. The long edge of slot is separated by 12 mm from the center of cavity top plane.

Figure 4 shows input characteristics of antenna elements. In the figure a solid line denotes the experimental result and a dashed line denotes the computed result. It is found that the computed $|S_{11}|$ is less than -30 dB at the frequency of 5.8 GHz when ℓ_s = 24 mm, w_s = 3 mm, P_f = 7.5 mm and P_h = 12 mm. On the other hand, Figure 5 draws the radiation patterns. The absolute gain is about 7 dBi at 5.8 GHz in the *xz*-plane. It is found from these figures that the computed results agree well with the experimental results.

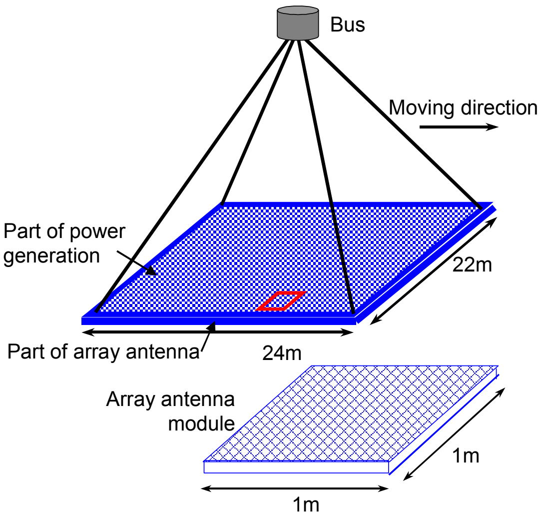

Figure 1. Space solar power satellite.

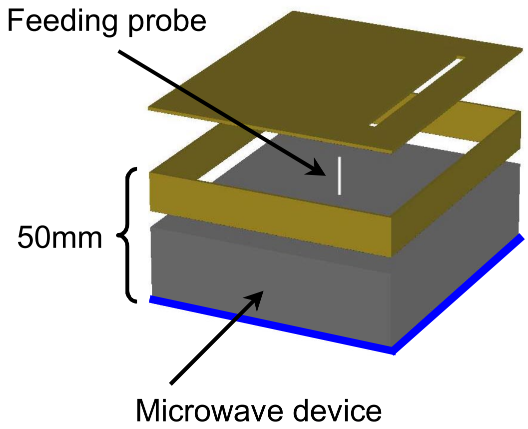

Figure 2. Antenna structure.

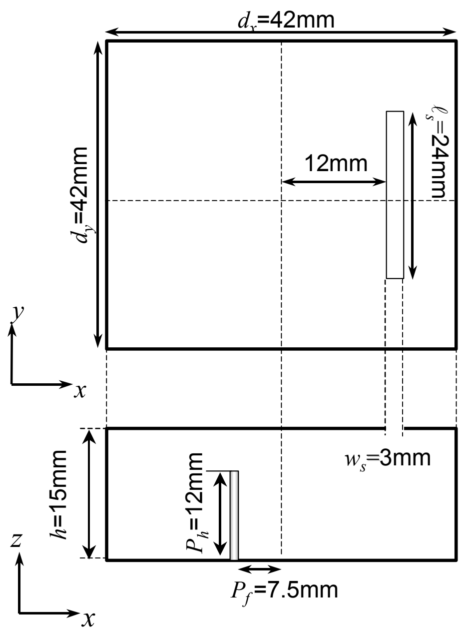

Figure 3. Antenna excited by a probe.

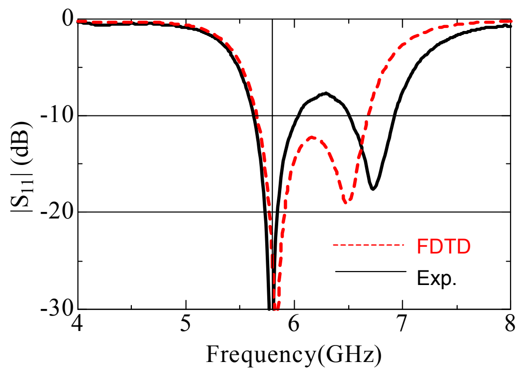

Figure 4. Input characteristics.

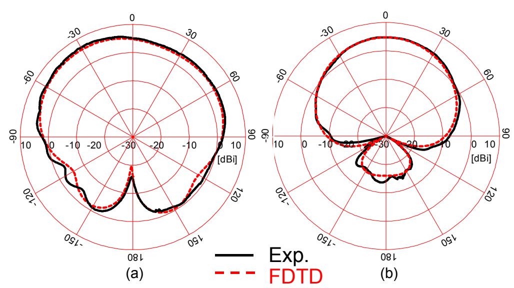

Figure 5. Radiation Patterns.
(a) *xz*-plane, (b) *yz*-plane.

3. Computer Analysis of Beam Steering

Now we analyze beam steering characteristics of a large scale phased array antenna. Here the array antenna module in the SSPS is simulated using the FDTD technique. Figure 6 shows 576-element array antenna. In order to develop the FDTD formulation for the model of a large scale phased array antenna, the problem space including the antenna is quantized by Yee cells (cubical cells) [1]. We use 1.5 mm cubical cells (Δ=1.5 mm) [8]. On the outer boundary, the FDTD algorithm employs the second order absorbing boundary condition proposed by Higdon [9] to simulate the field sampling space extending to infinity by suppressing reflection off the outer boundary.

To analyze the antenna characteristics, the excitation for a wire-fed antenna geometry is performed using a feeder model depicted in Fig. 7. It is a coaxial model that simulates a coaxial feeding cable. As seen in the view of the coax, a gap voltage is introduced in the coaxial center conductor, and standard FDTD relations are used within the coax to propagate the fields toward the antenna. The coaxial line has a characteristic impedance of 50 Ω. The square shaped and air-filled coaxial line illustrated in Fig. 7 is used. It is approximated by 2×2 cells in the xy-plane and 30 cells along the z-axis. As the cell size Δ is chosen to be 1.5 mm, the radius of the coax outer conductor is equal to Δ. For a wire oriented in the z-direction, the excitation electric field relates to the source voltage $V_{ij}(n)$ of the (i, j)-th element according to the expression

$$V_{ij}(n) = \sin\left(2\pi f_o n \Delta t - \psi_{ij}\right) = \sin\left(2\pi \frac{n}{256} - \psi_{ij}\right) \quad (1)$$

$$\psi_{ij} = \frac{2\pi}{\lambda}\left(x_i \cos\phi + y_j \sin\phi\right)\sin\theta \quad (2)$$

where n is a positive integer, (x_i, y_i) denotes the element coordinates when the origin of coordinate system corresponds to the center of array antenna, and the phase ψ_{ij} relative to the coordinate origin should be though in the voltage source for steering the beam direction of (θ, ϕ). In this work the time step size Δt is chosen as $(256 f_o)^{-1}$ where f_o is equal to 5.8 GHz. The radius of the inner conductor, R, is chosen as 0.52 mm so that the characteristic impedance of the coaxial cable is 50 Ω [4].

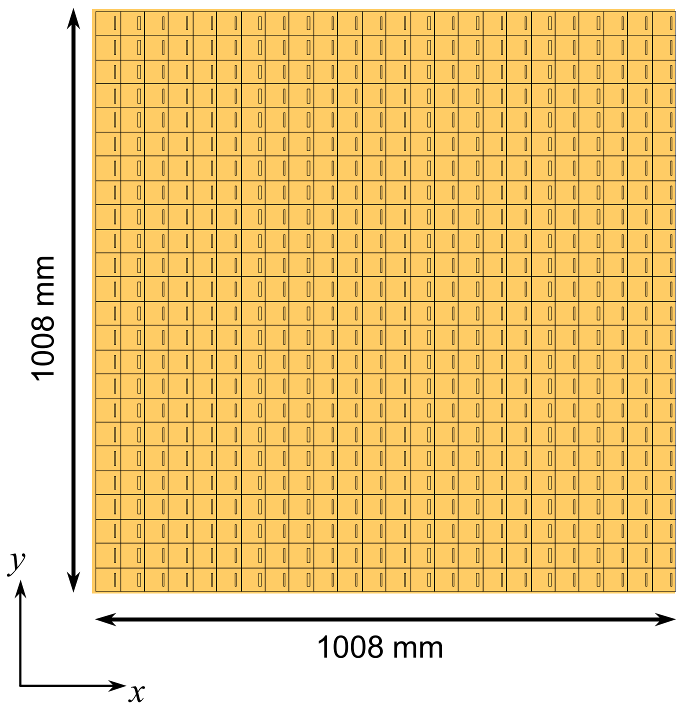

Figure 6. 24×24 (576)-element planar array antenna.

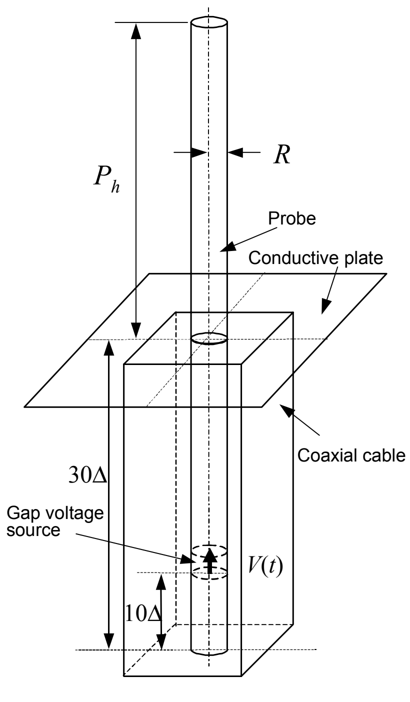

Figure 7. FDTD feed model (coaxial model).

Figure 8 shows computed radiation patterns of the 576-element planar array antenna where the antenna parameters used are the same as those in Fig. 3. The main beam is steered to the directions of (θ, ϕ) = (0, 0) and (10, 0) and directed to the specified directions. As a result, it is found that the FDTD technique shown in this paper gives a good estimation. Here, we used the supercomputer SR8000 in Hokkaido University for the FDTD simulations.

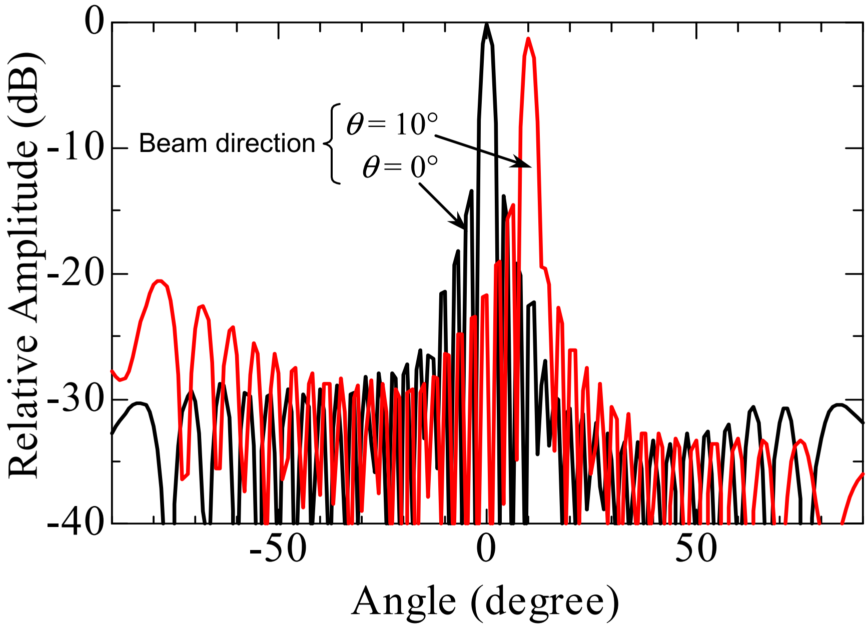

Figure 8. Radiation patterns of the array antenna. $\phi = 0°$

4. Summary and Conclusion

The purpose of this paper is to estimate the beam steering characteristics of the large scale array antenna. The array antenna consisting of cavity-backed slot antenna elements which we plan to use as an element for the microwave energy transmission antenna (spacetenna) in the solar power satellite are tested. First we showed the geometry and dimension of the antenna element satisfying the specifications. We used the FDTD technique taking into account the feeder geometry and the phase shift. It is concluded that the useful FDTD technique is established for the design of the energy transmission antenna system.

Acknowledgements

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