Design of Cavity-Backed Slot Antennas Using the Finite-Difference Time-Domain Technique

Manabu Omiya, *Member, IEEE*, Takashi Hikage, *Student Member, IEEE*, Norio Ohno, Kenich Horiguchi, and Kiyohiko Itoh, *Senior Member, IEEE*

***Abstract*—A cavity-backed slot antenna is thought to be one of the most suitable elements for the wireless transmission of microwave energy. A design technique is developed for the cavity-backed slot antenna using the finite-difference time-domain (FDTD) method. The technique is effective in characterizing antenna performance such as the input impedance and the far-field pattern since it takes into account the geometry of the feeder as well as the cavity. In this paper, we present a method that overcomes difficulties when the FDTD method is used to design the antenna. Moreover, we discuss how to determine the calculation parameters used in the FDTD analysis. Several numerical results are presented, along with measured data, which demonstrate the validity, efficiency, and capability of the techniques. The paper proposes a new prediction method for frequency characteristics of the cavity-backed slot antenna, which applies computational windows to time–sequence data. It is emphasized that windowing the slow decaying signal enables the extraction of accurate antenna characteristics. We also discuss how to estimate antenna patterns when we use a sinusoidal voltage excitation.**

***Index Terms*—Cavity resonators, FDTD technique, slot antennas, solar power satellite.**

I. Introduction

A CAVITY-BACKED slot antenna [1] satisfies the requirements of flush mounting as well as small size and light weight. Moreover, when it is used in an array configuration, it produces small mutual effects and thus is a suitable element in large antenna array systems such as a phased-array antenna [2]. For reasons mentioned above, we propose using a cavity-backed slot antenna as the microwave energy transmission antenna element for the solar power satellite (SPS) [3]. Now, we make an attempt to develop a cavity-backed slot antenna element whose geometry satisfies the conditions specified in [3]. Accordingly, we should develop an efficient technique of design, which allows us to consider the cavity geometry and the feed structure.

The method of moment (MoM) has been proposed as a technique of design for the cavity-backed slot antenna [2], [4]. It analyzes the antenna as a boundary value problem which is a set of integral equations for the electric field distribution on the slot and current distribution of the feed line. These analyses deal with the cavity-backed slot antennas with an infinite ground plane of a perfect electric conductor. Furthermore, it is assumed that the antenna and slot are excited by known volume electric and magnetic current densities inside the cavity or possible electric surface current density on the aperture. Therefore, it is difficult to evaluate the input impedance of the model, which has an arbitrary feed structure inside the cavity using these methods. Radiation patterns are given in the half-space over the infinite ground plane of the perfect electric conductor since the ground plane is placed surrounding the slot. In order to analyze complex, finite, and discontinuous antennas, we should use the geometrical theory of diffraction (GTD) [5] incorporated into the MoM. Moreover, a technique using hybrid finite-element method (FEM)/MoM and GTD was presented to analyze the radiation characteristics of cavity-fed aperture antennas in a finite ground plane [6].

Recently, the finite-difference time-domain (FDTD) technique has gained a lot of attention as a method for analyzing electromagnetic fields in the time domain [7]. The technique presents dynamically and visually the variation of the electromagnetic field in the transient state as well as in the steady state. The availability of the FDTD methods to evaluate antenna characteristics has also been shown in [8]. We present a technique to design a cavity-backed slot antenna using the FDTD method. We provide solutions to problems encountered in the analysis using the FDTD technique. Moreover, the procedure of specifying FDTD parameters for evaluation of antenna characteristics is shown.

The paper is divided into four sections after this introduction. Section II describes FDTD formulation and modeling of a cavity-backed slot antenna. In Section III, we compare the experimental results of input characteristics with analytical ones. Moreover, we comment on suitable windowing functions to estimate the antenna characteristics using the FDTD technique. In Section IV, we show analytical results of the radiation patterns. We also present the method of specifying parameters for the FDTD calculation after we discuss time periods related to radiation pattern analysis. Finally, a brief summary of this paper is provided in the last section.

II. Modeling of a Cavity-Backed Slot Antenna and FDTD Formulation

Fig. 1(a) shows the geometry and dimensions of an antenna element designed from experimental trials. We obtain a return loss of 22.6 dB at the frequency of 2.45 GHz. This frequency will be used for energy transmission in the SPS. The dimen-

Manuscript received December 11, 1996; revised December 19, 1997. This work was supported by Grant-in-Aid for Developmental Scientific Research (A)(2) 06505002 from the Ministry of Education, Science and Culture of Japan.

The authors are with the Graduate School of Engineering, Hokkaido University, Sapporo, 060-8628 Japan.

Publisher Item Identifier S 0018-926X(98)09717-8.

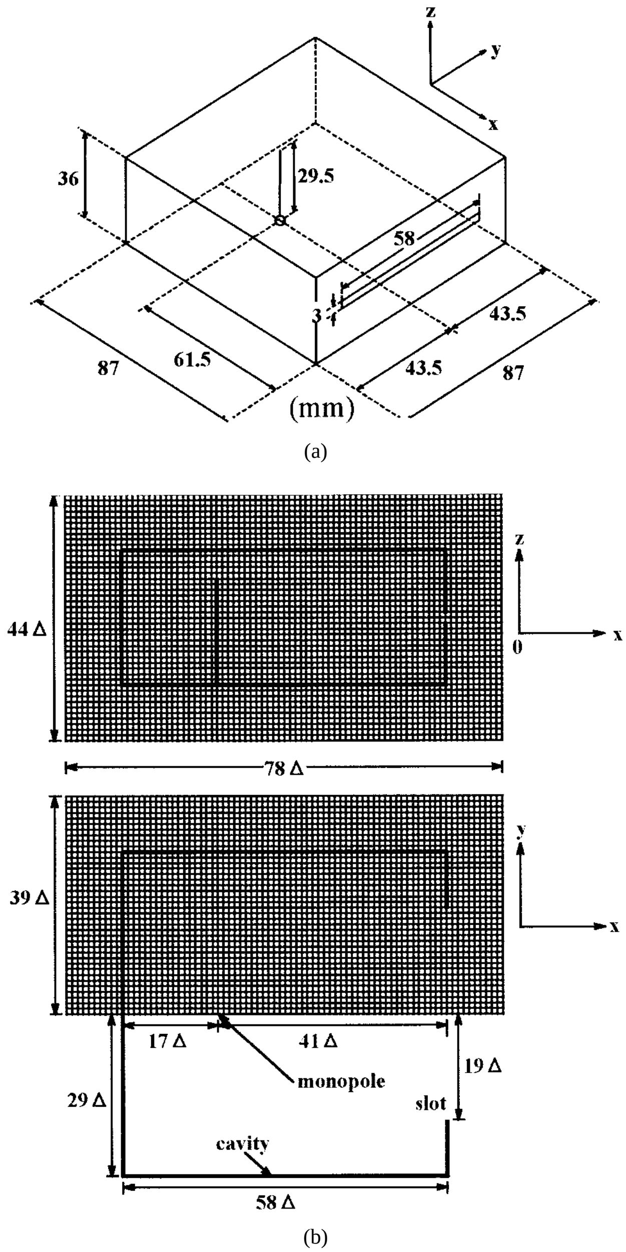


Fig. 1. (a) Geometry of the cavity-backed slot antenna. (b) FDTD grid used to model the antenna by Yee cells.

sions of the cavity are chosen under the assumption that the TE_{101} mode is excited in the cavity. In order to excite the cavity, a monopole element is used which is located in the cavity. The separation between the slot and the monopole is 61.5 mm which corresponds to a half wavelength. The length of a monopole is a quarter of wavelength (29.5 mm).

In order to develop the FDTD formulation for the model, the problem space including the antenna is quantized by Yee cells (cubical cells) [7]. Since the model is symmetric with respect to the xz-plane including the monopole element, only half of the problem space is used in the FDTD formulation. Fig. 1(b) shows the model and the problem space quantized by Yee cells for applying the FDTD method and also depicts sectional views of xz and xy plane. We use 1.5-mm cubical cells (Δ =1.5 mm). A square in the figure represents the section of a cell. The cell size Δ corresponds to 0.0123λ, where λ denotes the wavelength at 2.45 GHz. The slot width of 3.0 mm gives the restriction on the cell size.

There are ten cells between the antenna and outer boundary in each direction of the axis coordinates. Consequently the number of cells are 78 in the x direction, 39 in the y direction and 44 in the z direction. The wire is modeled by 19 cells and the slot by 2 $\times$ 38 cells. 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 reflections off the outer boundary. In order to include the effects of the relatively small wire radius, the magnetic fields surrounding the electric field components along the wire monopole axis are calculated [10]. Here the wire radius is set at 0.5 mm. In order to excite a cavity, a voltage source is located on the wire axis at the base of the monopole where it joins the cavity. In the computational simulations we use a Gaussian pulse or a sinusoidal wave. The time-step size Δt is given by $(2^8 f)^{-1} = 0.319\Delta/c$, where f is the frequency of 2.45 GHz, and c is the speed of light in free-space. The time-step size provides accurate results and stability [11]. We assume that the wire and the cavity are composed of perfect conductor.

III. Input Characteristics

We evaluate the input impedance using the FDTD method. For the impedance computations a Gaussian pulse of the from

$$V^n(I_0, J_0, K_0) = \begin{cases} \exp\left\{-\left(\frac{n-N_0/2}{T}\right)^2\right\} \\ (N_0/2 - 2^7 \le n \le N_0/2 + 2^7) \\ 0 \qquad \text{(otherwise)} \end{cases} \tag{1}$$

is used. Here n is a positive number, N_0 is the maximum number of time steps, the cell at (I_0, J_0, K_0) is located at the antenna feed point, and T is $32/\pi$. From (1), the pulse will exist from $n = N_0/2 - 2^7$ until $n = N_0/2 + 2^7$; approximated as zero outside this range, with peak value at $n = N_0/2$. The Gaussian pulse at truncation (at $n = N_0/2 \pm 2^7$) will have a value of 3.06×10^{-68}. Thus, at truncation the pulse is almost zero. Then the current in the wire of the source model can be obtained using a discretized form of Ampere's law that assumes the form

$$\begin{aligned} &I^{n+1/2}(I_0, J_0, K_0) \\ &\quad = \Delta\big[H_x^{n+1/2}(I_0, J_0 - 1, K_0) - H_x^{n+1/2}(I_0, J_0, K_0) \\ &\qquad + H_y^{n+1/2}(I_0, J_0, K_0) - H_y^{n+1/2}(I_0 - 1, J_0, K_0)\big]. \end{aligned} \tag{2}$$

The transient time-domain current through the base of the probe due to the Gaussian source voltage computed using FDTD is shown in Fig. 2 for $N_o = 2^{16}$. It is clear from the figure that the amplitude of the current doesn't converge to zero after 2^{16} iterations since the electromagnetic field generated in the cavity exists for a long time. The time histories of the voltage and current are discrete Fourier transformed, and the input impedance versus frequency is determined. As a result, calculating the frequency characteristics with the current waveform shown in Fig. 2 results in additive errors caused by the aliasing feature.

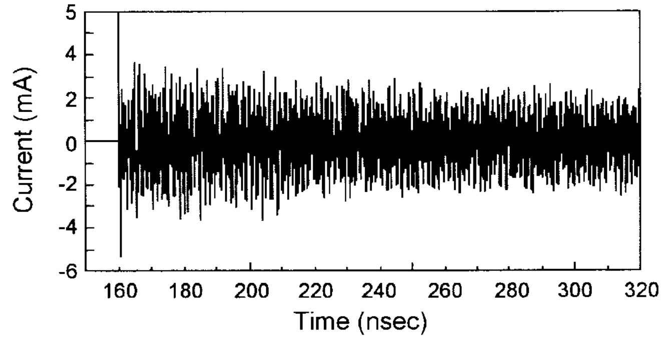
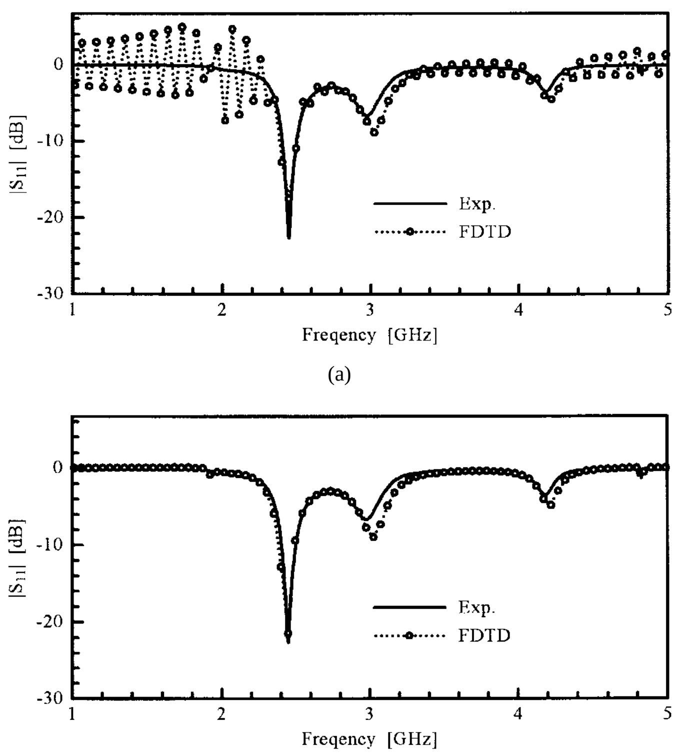


Fig. 2. Calculated current flowing in base of probe due to Gaussian pulse-voltage source.

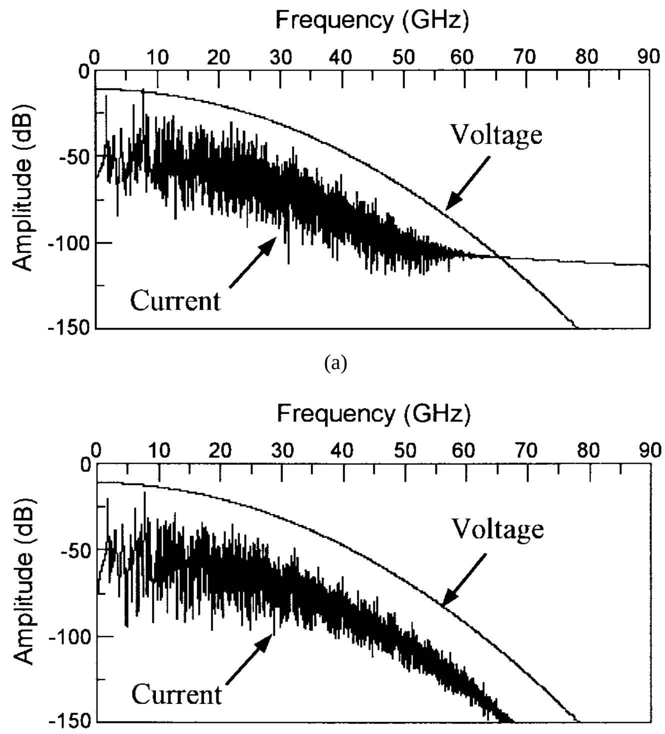


(b)

Fig. 3. Comparison of the FDTD computed and measured $|S_{11}|$ for the cavity-backed slot antenna. (a) Rectangular window. (b) Hanning window.

One approach to circumvent this problem is to extrapolate the time signature to late times after truncating the time iteration to a reasonable number of initial time steps. A number of methods [12]–[15] have been employed for extrapolation of FDTD signatures. However, the usage of these methods is not easy because of the parameter specification and restrictions of the models. We propose a method that applies computational windows to time-domain responses [16]. The effectiveness of computational windows for the FDTD analysis of input characteristics has never been reported. The windowed data give a reasonable estimation of input impedance although the approach does not contribute to the decrease of the total amount of time step.

Fig. 3 shows input characteristics where a solid line denotes the experimental result and circles connected by a broken line



(b)

Fig. 4. Frequency spectrum. (a) Rectangular window. (b) Hanning window.

denote the simulation result. Fig. 3(a) and (b) shows the characteristics using a rectangular window and a hanning window, respectively. It is clear from Fig. 3(a) that the simulation result is fluctuating.

Fig. 4 shows frequency spectra obtained from the Fourier transform of the voltage and current waveforms. Fig. 4(a) shows the spectra with the rectangular window. The spectrum of the voltage decreases with an increase in frequency. On the other hand, the current has the high aliased spectral levels that fold back into the low-frequency band. This spectral leakage occurs due to the discontinuity of the waveform at the boundary of the observed range, $n = N_0$, so the computational windowing technique is applied to decrease the discontinuity and prevent spectral aliasing. The simulation result in Fig. 3(b) that is calculated using the hanning window is in good agreement with the experimental result. Fig. 4(b) shows the frequency spectra computed with the hanning window. We conclude that the spectrum of the current decreases with an increase in frequency and windowing the slow decaying signal decreases the spectral leakage. Hence, it is valid to use the computational windows for the analysis of input characteristics. The most suitable window function for the numerical estimation of the input characteristics satisfies conditions that the differential values of the function at the boundaries of $n = 0$ and N_0 are continuous as well as the function itself. The conditions are also fulfilled by the Blackman window.

Next, Fig. 5 shows the relation between the number of iterations N_0 and input characteristics calculated with the hanning window, where we choose four kinds of the total number of time steps, $N_0 = 2^{16}$, 2^{15}, 2^{14}, and 2^{13}. It is

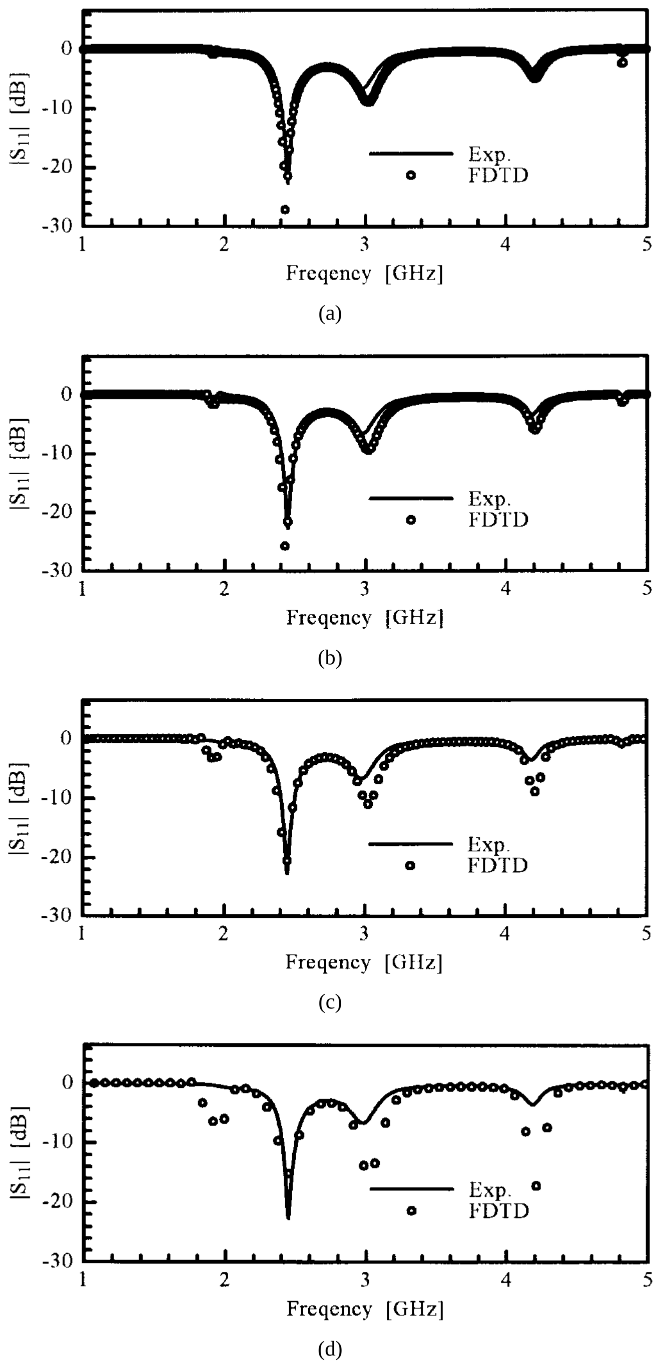


Fig. 5. Comparison of FDTD and measured results for the magnitude of the reflection coefficient. (a) $N_o = 2^{16}$. (b) $N_o = 2^{15}$. (c) $N_o = 2^{14}$. (d) $N_o = 2^{13}$.

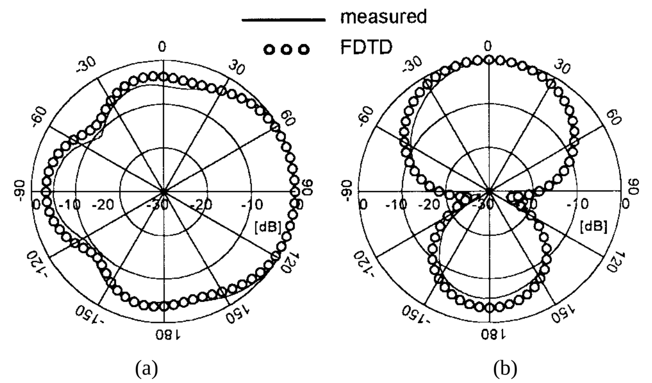


Fig. 6. Comparison of FDTD and measured data for radiation patterns at the frequency of 2.45 GHz. (a) E plane (xz plane). (b) H plane (xy plane). FDTD results at the 129th period.

clear from Fig. 5(a) and (b) that FDTD results agree well with measurements when N_0 is 2^{16} and 2^{15}. When N_0 is 2^{14} and 2^{13}, local minimum values of $|S_{11}|$ at the frequencies of 1.9 GHz, 3.0 GHz, and 4.2 GHz are more emphasized compared with measurements. Therefore, we conclude that the method requires as many as 2^{15} or 2^{16} time steps when computational windows are applied to the FDTD analysis.

IV. Far-Field Radiation Pattern

In this section, we evaluate far-field radiation patterns using the FDTD technique. For the computation of antenna patterns, it is necessary to have far-field data. These far-field data can be obtained from FDTD through the near- to far-field transformation [17]. This transformation is used to define equivalent magnetic and electric surface currents based on near-field data. In this section, we use the method with which radiation patterns are computed only at the frequency of 2.45 GHz [18]. The method uses the sinusoidal voltage excitation given by

$$V^n(I_0, J_0, K_0) = \sin(2\pi f \cdot n\Delta t) = \sin\left(2\pi \frac{n}{2^8}\right). \quad (3)$$

Where Δt is set to $(2^8 f)^{-1}$. The equivalent magnetic and electric surface currents vary sinusoidally in the steady state, so a set of complex electromagnetic fields is calculated at every period.

Fifteen cells are arranged from the surface of the analyzed model to the boundary of the problem space. The surfaces on which the equivalent magnetic and electric currents are computed is parallelepiped four cells in from the boundaries of the problem space because the outer three cells have been already used in order to apply the absorbing boundary condition.

Fig. 6 shows the antenna patterns of FDTD calculations and measurements. Fig. 6(a) and (b) indicates E plane (xz plane) and H plane (xy plane) radiation patterns at the frequency of 2.45 GHz. The solid line denotes the experimental result and circles denote the FDTD result at the 129th period. It is clear from the figures that the computed antenna pattern displays an accurate agreement with the experimental result.

Fig. 7 shows FDTD results of radiation pattern related to the period. In these figures a solid line denotes the antenna pattern at the 129th period and circles denote patterns at the second, third, fifth, and ninth period, respectively. Gains of radiation pattern in the fifth and the ninth periods are different from those at the 129th period by less than 0.52 and 0.39 dB's although there are differences of less than 4.79 dB between radiation patterns at the second and the 129th periods. The same results and conclusions are also obtained in the case of the E plane radiation pattern.

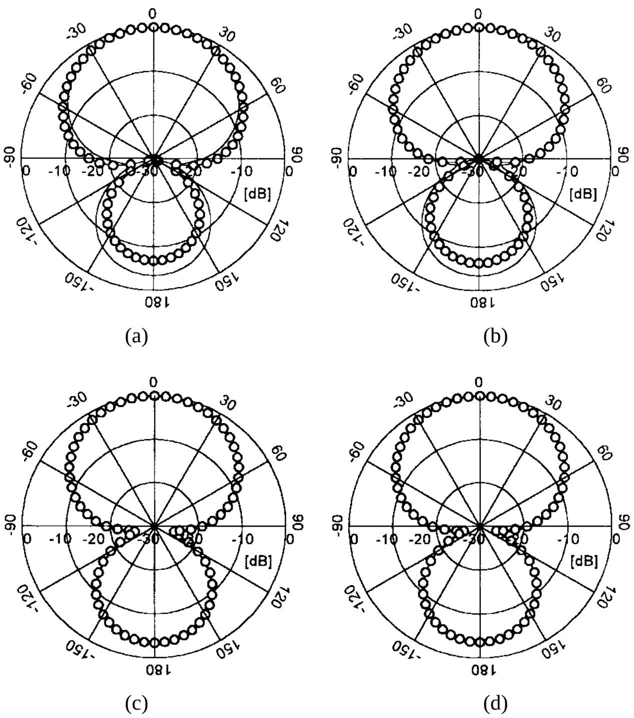


Fig. 7. FDTD results of the normalized radiation patterns at the frequency of 2.45 GHz for the cavity-backed slot antenna (H plane). Comparative data: solid lines obtained at the 129th period; circles obtained from data of the (a) second period, (b) the third period, (c) the fifth period, and (d) the ninth period.

V. Conclusion

The paper describes the numerical method to design a cavity-backed slot antenna, which is planed to be used as a microwave energy transmission antenna element for the solar power satellite. We propose to use the FDTD technique with which we can model precisely the cavity geometry and the feed structure located in the cavity. Moreover, we clarify the method of the analysis for the input characteristics and the radiation pattern using the FDTD technique.

In evaluating the input characteristics, we propose to apply the computation window to the current flowing through the feed point. The FDTD result has good agreement with the experimental result. And it is also clear that the method requires as many as 2^{16} or 2^{15} time steps to realize good estimations. As a result, windowing the slow decaying signal enables the extraction of accurate antenna characteristics. The FDTD result of the radiation pattern agrees with the experimental result very well. We also discuss how many periods are needed to estimate antenna patterns when we use the sinusoidal voltage excitation.

It may be concluded that the new design method of the cavity-backed slot antennas using the FDTD technique is verified. Moreover, we assure that the method is also useful to evaluate antenna characteristics for other types of cavity geometry and feed structure. We will report about these FDTD analysis results in the future.

References

[1] J. Galejs, “Admittance of a rectangular slot which is backed by a rectangular cavity,” *IEEE Trans. Antennas Propagat.*, vol. AP-11, pp. 119–126, Mar. 1963.

[2] A. Hadidi and M. Hamid, “Aperture field and circuit parameters of cavity-backed slot radiator,” *Proc. Inst. Elect. Eng.*, vol. 136, pt. H, no. 2, pp. 139–146, Apr. 1989.

[3] SPS2000 Task Team for Solar Power Satellite (SPS) Working Group, *English Summary of SPS2000 Project Concept—A Strawman SPS System—(Preliminary Edition)*, Sagamihara, Inst. Space Astronautical Sci., 1993.

[4] J. Hirokawa, H. Arai, and N. Goto, “Cavity-backed wide slot antenna,” *Proc. Inst. Elect. Eng.*, vol. 136, pt. H, no. 1, pp. 29–33, Feb. 1989.

[5] H. Shoki and K. Itoh, “Analysis of a slot antenna cut on a finite conducting plane (in Japanese),” *Trans. IEICE*, vol. J67-B, no. 12, pp. 1446–1453, Dec. 1984.

[6] C. J. Reddy, M. D. Deshpande, C. R. Cockrell, and F. B. Beck, “Radiation characteristics of cavity backed aperture antennas in finite ground plane using the hybrid FEM/MoM technique and geometrical theory of diffraction,” *IEEE Trans. Antennas Propagat.*, vol. 44, pp. 1327–1333, Oct. 1996.

[7] K. S. Yee, “Numerical solution of initial boundary value problems involving Maxwell’s equations in isotropic media,” *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 302–307, May 1966.

[8] R. Luebbers, L. Chen, T. Uno, and S. Adachi, “FDTD calculation of radiation patterns, impedance, and gain for a monopole antenna on a conducting box,” *IEEE Trans. Antennas Propagat.*, vol. 40, pp. 1577–1583, Dec. 1992.

[9] R. L. Higdon, “Numerical absorbing boundary conditions for the wave equation,” *Math. Computat.*, vol. 49, no. 179, pp. 65–90, July 1987.

[10] K. R. Umashankar, A. Taflove, and B. Beker, “Calculation and experimental validation of induced currents on coupled wires in an arbitrary shaped cavity,” *IEEE Trans. Antennas Propagat.*, vol. AP-35, pp. 1248–1257, Nov. 1987.

[11] A. Taflove and M. E. Brodwin, “Numerical solution of steady-state electromagnetic scattering problems using the time-dependent Maxwell’s equations,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 623–630, Aug. 1975.

[12] W. L. Ko and R. Mittra, “A combination of FD-TD and Prony’s methods for analyzing microwave integrated circuits,” *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 2176–2181, Dec. 1991.

[13] J. Litva, C. Wu, K. L. Wu, and J. Chen, “Some considerations for using the finite difference time domain technique to analyze microwave integrated circuits,” *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 438–440, Dec. 1993.

[14] V. Jandhyala, E. Michielssen, and R. Mittra, “FDTD signal extrapolation using the forward-backward autoregressive (AR) model,” *IEEE Microwave Guided Wave Lett.*, vol. 4, pp. 163–165, June 1994.

[15] J. Chen, C. Wu, T. K. Y. Lo, K. L. Wu, and J. Litva, “Using linear and nonlinear predictors to improve the computational efficiency of the FD-TD algorithm,” *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1992–1997, Oct. 1994.

[16] D. F. Elliott, Ed., *Handbook of Digital Signal Processing, Engineering Applications*. San Diego, CA: Academic, 1987.

[17] R. Luebbers, K. Kunz, M. Schneider, and F. Hunsberger, “A finite-difference time-domain near zone to far zone transformation,” *IEEE Trans. Antennas Propagat.*, vol. 34, pp. 429–433, Apr. 1991.

[18] T. Kashiwa, S. Tanaka, and I. Fukai, “Time domain analysis of Yagi—Uda antennas using the FD-TD method (in Japanese),” *Trans. IEICE*, vol. J76-B-II, no. 11, pp. 872–879, Nov. 1993.

Manabu Omiya (M’95) received the B.S.E.E., M.E., and Dr.E. degrees from Hokkaido University, Sapporo, Japan, in 1981, 1983, and 1989, respectively.

Since 1983, he has been on the Faculty of Engineering at Hokkaido University, where he is currently an Associate Professor of Electronics and Information Engineering. His special interests are in finite-difference time-domain techniques and solar power satellite system.

Dr. Omiya is a member of the Institute of Electronics, Information, and Communication Engineers, the Institute of Image Information and Television Engineers, and the Applied Computational Electromagnetics Society.

Takashi Hikage (S'98) received the B.S.E.E. degree from Hokkaido University, Sapporo, Japan, in 1997. He is currently working toward the M.S. degree in electronic engineering at the same university.

His current research involves finite-difference time-domain techniques and antenna elements for spacetennas of solar power satellites.

Mr. Hikage is a student member of the Institute of Electronics, Information, and Communication Engineers.

Norio Ohno received the B.S.E.E. and M.E. degrees from Hokkaido University, Sapporo, Japan, in 1995 and 1997, respectively.

He joined the Sony Company, Ltd., Tokyo, Japan, in 1997.

Kenich Horiguchi received the B.S.E.E. and M.E. degrees from Hokkaido University, Sapporo, Japan, in 1993 and 1995, respectively.

He joined the Mitsubishi Corporation, Ltd., Tokyo, Japan, in 1995.

Mr. Horiguchi is a member of the Institute of Electronics, Information, and Communication Engineers.

Kiyohiko Itoh (M'71–SM'96) received the B.S.E.E., M.E., and Dr.E. degrees from Hokkaido University, Sapporo, Japan, in 1963, 1965, and 1973, respectively.

Since 1965, he has been on the Faculty of Engineering at Hokkaido University, where he is a Professor of electronics and information engineering. From 1970 to 1971 he was with the Department of Electrical and Computer Engineering, Syracuse University, Syracuse, NY, as a Research Associate on leave from Hokkaido University. His special interests are in electromagnetic radiation, wave optics, mobile radio communications, and solar power satellites.

Dr. Itoh is a member of the Institute of Electronics, Information, and Communication Engineers and the Institute of Image Information and Television Engineers.