Functionals in the Variational Method Applied to Equivalent Impedance Matrix of Metallic Posts Unsymmetrically Positioned in a Rectangular Waveguide

Takashi Toyama and Eikichi Sawado

Abstract—**New functionals for calculation of a variational method of equivalent impedance matrix elements of a metallic post have been proposed, in which the cross section shape of the metallic post can be arbitrary, and the post can be placed at an arbitrary position in a rectangular waveguide. The functionals are also applicable to a group of metallic posts placed unsymmetrically on the z = constant plane.**

I. Introduction

The topic of metallic posts in a rectangular waveguide has been treated by a variety of methods [1]–[11]. Among them, the variational method proposed by Schwinger [1] is characterized in two points. First, the equivalent impedance matrix elements of a metallic post in a rectangular waveguide operated at TE_{10} mode are expressed in such a functional that they are stationary with respect to arbitrary small variations of the current distribution on the post about its correct distribution. Second, the matrix elements are directly obtained without the calculation of the current distribution, due to the special form of the functional [1], [2].

Considering that, in the usual variational method, the stationary condition in the numerical treatment determines the expansion coefficients of the stationary function first, by means of which the stationary value of the functional is obtained, Schwinger's method is excellent for the reason that the matrix elements are directly obtained.

However, the application of Schwinger's method is restricted in that the cross section shape of the post must be symmetrical as follows.

In his method, the incident wave to the post is suitably chosen to satisfy the boundary condition on the side walls of the waveguide. The wave is scattered by the post, and the total field created by the incident wave and the scattered wave yields the field in the waveguide. The scattered wave is expressed as the sum of two Green's functions. Two types of summing are used, one making an even function, and the other an odd function on the z = 0 plane. The concept of the even and the odd function plays an important role in treating the scattering problem by the variational method of his theory. Since Green's function $G(r, r')$ gives the field at r produced by a current element of Dirac's delta function at r', both of the even and the odd functions, which are obtained by summing two Green's functions, require two current sources positioned symmetrically on the z = 0 plane. In addition, his treatment requires the boundary condition of the metal surface at any point where the current source exists. These two requirements determine the shape of the cross section of the metallic post to be symmetrical on the z = 0 plane.

Manuscript received July 16, 1991; revised January 15, 1992.
The authors are with the Department of Electrical Engineering, Tokyo Metropolitan University, Minami-Osawa 1-1, Hachioji-shi, Tokyo 192-03, Japan.
IEEE Log Number 9200852.

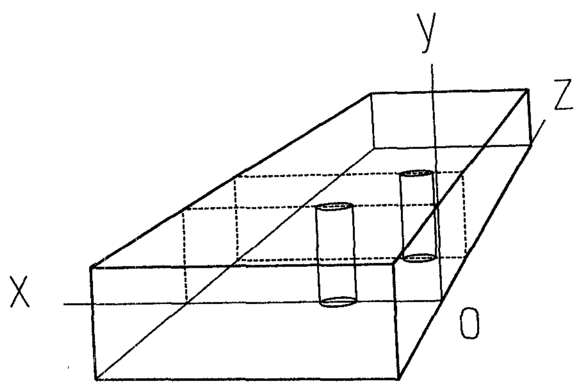


Fig. 1. A group of metallic posts unsymmetrically positioned in a rectangular waveguide.

The purpose of this paper is to remove the restriction of the functional of Schwinger's method, while maintaining its excellent form. The new functionals proposed in this paper can be applied to a metallic post, which has an arbitrary cross section shape and is placed at an arbitrary position. These functionals can also be applied to a group of metallic posts, which are positioned unsymmetrically as shown in Fig. 1.

II. The Variational Principle

According to Schwinger's method [1], when the following equation

$$h(x', z', x, z) = h(x, z, x', z') \tag{1}$$

holds, the following two equations

$$1/p = \int_c f(x', z')K(x', z')\, dS' \quad (2)$$

$$f(x_c, z_c) = \int_c h(x_c, z_c, x', z')K(x', z')\, dS' \quad (3)$$

are equivalent to the variational problem, in which

$$p = p(K) = \frac{\int\int_c h(x, z, x', z')K(x, z)K(x', z')\, dS\, dS'}{\left(\int_c f(x', z')K(x', z')\, dS'\right)^2} \quad (4)$$

is a functional, or a mapping from a function space of K into the field of scalars of p, and the correct K gives the stationary value of p.

From a mathematical point of view, h, p, f, and K can be anything. In Schwinger's method, and also in this paper, p is an element of impedance or admittance matrix, and K is the electric current distribution. Each element of impedance or admittance matrix is expressed in the form of (4) makes it possible to obtain the value of the element directly without the calculation of K.

Accordingly, the purpose of this paper is to find the functions f and h, or to determine the functional $p(K)$, which are applicable to the unsymmetrical cases.

III. Determination of the Parameters of an Equivalent Circuit

Using the voltage and current of an equivalent transmission line (see Appendix), the discontinuity is expressed by the impedance matrix, z_{11}, z_{12}, z_{21} and z_{22}. Since z_{11} is the ratio of V_{10} to I_{10} with I_{20} being zero, the following equations are obtained:

$$B = (1/\kappa a) \int_{ob} \sin(\pi x'/a) e^{-i\kappa z'} K(x', z')\, dS' \quad (5)$$

$$\cdot\, 1/((2i/\kappa a) z_{11})$$

$$= \int_{ob} \sin(\pi x'/a) \cos \kappa z' \, (K(x', z')/V_{10})\, dS' \quad (6)$$

where $(2i/\kappa a)z_{11}$ corresponds to p, and $\sin(\pi x'/a) \cos \kappa z'$ to $f(x', z')$ in (2). Since V_{10} is independent of x' and z', $K(x', z')/V_{10}$ can be assumed to be the current density $K(x', z')$.

In order to obtain the equation corresponding to (2), first, let us substitute (5) to the boundary condition (see Appendix). Then,

$$-A \sin(\pi x_{ob}/a) \cos \kappa z_{ob}$$
$$= (1/\kappa a) \sin(\pi x_{ob}/a) \sin \kappa z_{ob}$$
$$\times \int_{ob} \sin(\pi x'/a) e^{-i\kappa z'} K(x', z')\, dS'$$
$$+ \int_{ob} G(x_{ob}, z_{ob}; x', z') K(x', z')\, dS' \quad (7)$$

is obtained. Second, reforming the equation of V_{10} (see Appendix) as follows:

$$V_{10} - (i/\kappa a) \int_{ob} \sin(\pi x'/a)\, e^{+i\kappa z'} K(x', z')\, dS' = A \quad (8)$$

and multiplying (7) by (8), and then, after rearrangement the following equation is obtained:

$$-A \sin(\pi x_{ob}/a) \cos \kappa z_{ob} \cdot V_{10}$$
$$= A(1/\kappa a) \sin(\pi x_{ob}/a) \sin \kappa z_{ob}$$
$$\times \int_{ob} \sin(\pi x'/a) e^{-i\kappa z'} K(x', z')\, dS'$$
$$+ A \int_{ob} G(x_{ob}, z_{ob}; x', z') K(x', z')\, dS'$$
$$-A \sin(\pi x_{ob}/a) \cos \kappa z_{ob}$$
$$\times (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{+i\kappa z'} K(x', z')\, dS' \quad (9)$$

And finally, dividing (9) by $-A \cdot V_{10}$, we obtain,

$$\sin(\pi x_{ob}/a) \cos \kappa z_{ob}$$
$$= \int_{ob} h(x_{ob}, z_{ob}, x', z')(K(x', z')/V_{10})\, dS' \quad (10)$$

where

$$h(x, z, x', z')$$
$$= (i/\kappa a) \sin(\pi x/a) \sin(\pi x'/a) \sin \kappa z \sin \kappa z'$$
$$+ (i/\kappa a) \sin(\pi x/a) \sin(\pi x'/a) \cos \kappa z \cos \kappa z'$$
$$- G(x, z; x', z')$$
$$- (1/\kappa a) \sin(\pi x/a) \sin(\pi x'/a)$$
$$\times (\sin \kappa z \cos \kappa z' + \cos \kappa z \sin \kappa z') \quad (11)$$

Equation (11) satisfies (1), and then, this supports that (2) and (3) can be treated by the variational analysis.

Since (6) and (10) correspond to (2) and (3), respectively, the functions p, f and h in (4) are given as follows:

$$p = (2i/\kappa a) z_{11} \quad (12)$$

$$f = \sin(\pi x/a) \cos \kappa z \quad (13)$$

$(z \geqq z')$

$$h = -(2/\kappa a) \sin(\pi x/a)$$
$$\cdot \sin(\pi x'/a) \cos \kappa z \sin \kappa z' - G2 \quad (14)$$

TABLE I
FUNCTIONALS

z_{11}

$p = (2i/\kappa a)z_{11}$
$f = \sin(\pi x/a)\cos\kappa z$
$h = -(2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\cos\kappa z\sin\kappa z' - G2 \quad (z \geqq z')$
$= -(2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\sin\kappa z\cos\kappa z' - G2 \quad (z \leqq z')$

z_{22}

$p = -(2i/\kappa a)z_{22}$
$f = \sin(\pi x/a)\cos\kappa z$
$h = (2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\sin\kappa z\cos\kappa z' - G2 \quad (z \geqq z')$
$= (2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\cos\kappa z\sin\kappa z' - G2 \quad (z \leqq z')$

y_{11}

$p = -(2/\kappa a)y_{11}$
$f = \sin(\pi x/a)\sin\kappa z$
$h = i((2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\sin\kappa z\cos\kappa z' - G2) \quad (z \geqq z')$
$= i((2/\kappa a)\sin(\pi x/a)\sin(\pi x'/a)\cos\kappa z\sin\kappa z' - G2) \quad (z \leqq z')$

$G2(x, z; x', z')$
$= (i/a)\Sigma_{n=2}^{\infty}\sin(n\pi x/a)\sin(n\pi x'/a)e^{i\kappa_n|z-z'|}/\kappa_n$

$$(z \leqq z') \quad h = -(2/\kappa a)\sin(\pi x/a) \cdot \sin(\pi x'/a)\sin\kappa z\cos\kappa z' - G2 \quad (15)$$

where $G2$ is Green's function, with the first term discarded, as follows:

$$G2(x, z; x', z') = (i/a)\sum_{n=2}^{\infty}\sin(n\pi x/a) \cdot \sin(n\pi x'/a)e^{i\kappa_n|z-z'|}/\kappa_n \quad (16)$$

For z_{22} the same procedure has been used, and similar functions have been obtained.

In case of z_{12}, however, the function h obtained does not satisfy (1). This makes it impossible to treat the problem by the variational analysis. Comparison of the procedure for z_{11} with that for z_{12} implies that the function h for y_{11} might satisfy (1). Accordingly, we tried to find the functional for y_{11}, and the functional was successfully obtained. The matrix element z_{12} is, then, calculated by the equation, $z_{12}^2 = -z_{22} \cdot z_{11} + z_{22}/y_{11}$.

All the functions and functionals obtained are shown in Table I.

IV. Computational Procedure

It is well-known that the series in (16) converges slowly. In place of (16), for rapid convergence, the series shown in the reference [10] is used in the present paper. The summation of the series in the present paper is performed with n from 2 to 100.

The integration of $G2(r, r')K(r)$ which is involved in $h(r, r')K(r)K(r')$ in (4) is performed as the summation of $G2(r, r')K(r)\,\Delta S$ in the computer program. Although (16) shows that $G2(r, r')$ is infinite at $r = r'$, the integration of $G2(r, r') \cdot K(r)$ is finite, because this integration also appears in (3) and the value obtained by the integration is a physical quantity. Accordingly, it is expected that the summation of $G2(r, r') \cdot K \cdot \Delta S$ in the vicinity of $r = r'$ can be expressed by a converging series. In order to obtain the series the S-coordinate around the point at $r = r'$ was divided in such a way that the amount of each ΔS is selected as the half of the adjacent ΔS, as S approaches the point. By this selection the ratio of the $(n + 1)$th term of $G2(r, r') \cdot K(r) \cdot \Delta S$ to the nth term becomes less than one and decreases as n increases. It is well known that the series is convergent when this relation between two adjacent terms holds.

The summation of the series in the computer program was performed until the value of $G2(r, r')$ overflowed, twenty terms usually being summed. The amount of error is due to whether or not the series sufficiently converges before the overflow occurs.

The variational analysis is performed by Ritz's method. The function $K(r, r')$ is expanded in a Fourier series, with each coefficient being A_n, and the stationary condition is expressed by the derivative of p with respect to any of the coefficients A_n being zero [1]. In the present paper the expansion is performed with n from 1 to 7. The special form of (4) makes it possible to obtain the stationary value of p without obtaining the coefficients A_n.

When further precision is required, the techniques mentioned above and the others used in the computer programs should be improved.

V. Results

Our method is compared to Schwinger's method in the following examples. Examples from 1) to 2) treat a metallic post. Each example shows a good coincidence between two treatments. Examples from 3) to 4) treat two metallic posts. Example 5) treats a rectangular post.

1) A metallic post, the cross section of which is symmetrical, is treated by both methods.

As an example, 9.5 GHz microwave travelling in a WRJ-10 waveguide (Waveguide Rectangular Japanese industrial standard) is chosen. A circular metallic post is placed $0.4a$ from the waveguide side wall, where "a" is the inside width of the waveguide. The equivalent impedance matrices of four different radii are calculated.

Table II shows the comparison of the equivalent impedance matrix calculated by our method with that by Schwinger's method [11]. The result by our method shows that z_{11} is equal to z_{22} in their absolute values. This relation is due to the fact that the cross section of the post is symmetrical. In Schwinger's method, on the other hand, the relation has already been used in the theoretical process of obtaining the functional.

2) Equivalent parameters on the $z = 0$ plane of a circular post placed at $z = d$ as shown in Fig. 2 are calculated by both methods.

TABLE II
EQUIVALENT IMPEDANCE MATRIX ELEMENTS OF A CIRCULAR METALLIC POST IN A RECTANGULAR WAVEGUIDE CALCULATED BY BOTH METHODS

Radius	z_{11}	z_{22}	y_{11}	z_{12}
0.01a	0.7351i	−0.7351i	0.247 × $10^{+3}i$	−0.737i
0.02a	0.529i	−0.5291i	0.775 × $10^{+2}i$	−0.535i
0.035a	0.355i	−0.3551i	0.172 × $10^{+2}i$	−0.383i
0.06a	0.171i	−0.171i	0.727 × $10^{+1}i$	−0.229i

(a) Our method

Radius	z_{11}	z_{12}
0.01a	0.740i	−0.742i
0.02a	0.533i	−0.541i
0.035a	0.358i	−0.358i
0.06a	0.169i	−0.237i

(b) Schwinger's method

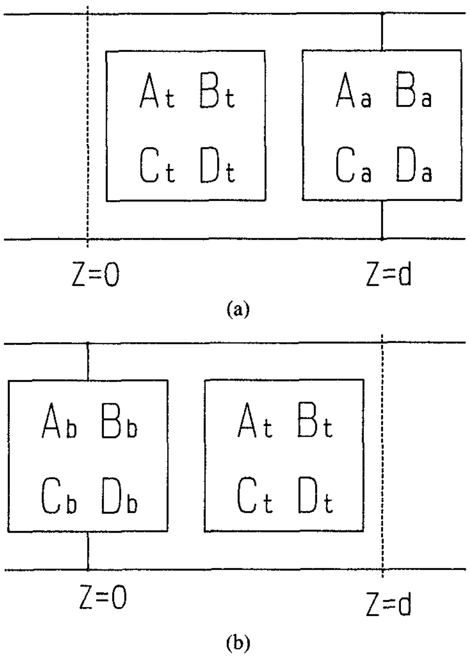


Fig. 2. Symmetrical and unsymmetrical treatments of a symmetrical post. (a) Symmetrical treatment (Schwinger's method). (b) Unsymmetrical treatment (Our method).

By Schwinger's method the four-terminal constants, A_a, B_a, C_a and D_a, of the equivalent circuit of the post are calculated at the $z = d$ plane, because the post is symmetrical about the plane, and then, they are converted to the four-terminal constants, A, B, C, and D, on the $z = 0$ plane by combining with the equivalent parameters, A_t, B_t, C_t and D_t, of the transmission line between $z = 0$ and $z = d$.

On the other hand, by our method, the four-terminal constants, A_b, B_b, C_b and D_b, of the post are calculated on the $z = 0$ plane. Since the circular post placed at $z = d$ is not symmetrical on the $z = 0$ plane, this treatment is possible only by our method. And then, the equivalent parameters, A_t, B_t, C_t and D_t, of the transmission line are combined.

TABLE III
EQUIVALENT FOUR-TERMINAL CONSTANTS AT $z = 0$

d/a	A	B	C	D
0.0	−0.9422	0.04255	2.637	−0.9422
	−0.9422	0.04255	2.637	−0.9422
0.4	−2.788	−0.9022	−0.2585	−0.2750
	−2.788	−0.9022	−0.2585	−0.2750
0.8	−0.4414	−0.4903	−2.765	0.8058
	−0.4414	−0.4903	−2.765	0.8058
1.2	2.5690	0.6589	−1.114	0.6749
	2.5690	0.6589	−1.114	0.6749
1.4	2.7123	0.9343	0.6954	0.1291
	2.7123	0.9343	0.6954	0.1291

Upper row indicates Schwinger's method.
Lower row indicates our method.

The four-terminal constants obtained for various d/a are shown as A, B, C, and D in Table III, the upper row being the result by Schwinger's method and the lower one being that by our method. Both results are of a good coincidence.

3) The case of two circular metallic posts placed unsymmetrically as shown in Fig. 3 are treated by both methods.

By Schwinger's method, each post is treated as a symmetrical case, and the parameters of two posts are combined together with the parameters of the transmission line between the posts.

On the other hand, our theory can treat two posts concurrently. The current density K along the S-axis in the integration of (4) is, however, usually discontinuous as shown in Fig. 4. Accordingly, the current density K is expanded into the series of orthogonal functions independently on each post, in order to obtain a more accurate result.

When two posts are placed far apart, the evanescent modes of each post do not interfere with each other, and Schwinger's method gives the correct result.

In this example the transmission line is terminated by the characteristic impedance of the line, and the reflection coefficient vs. frequency for various z_2 are calculated with $d_1 = d_2 = 0.07a$, $x_1 = 0.4a$, $x_2 = 0.2a$ as shown in Fig. 5. The two methods give almost the same results, since the distance between two posts is still large even when z_2 is zero. Then, it can be said that plural obstacles placed on the same z = constant plane can be treated independently when they are sufficiently separated in the x-direction.

4) The circular posts as used in the example 3) are placed with $x_2 = 0.365a$. In this case the evanescent modes of the posts interfere with each other when z_2 decreases, and they make it impossible to treat the posts as two independent symmetrical posts.

Fig. 6 shows that the result of Schwinger's method does not coincide with that of our method when z_2 is small.

5) The equivalent parameters of a rectangular post is calculated.

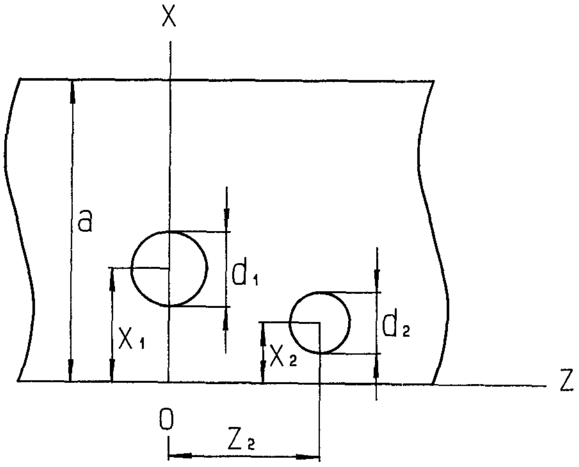


Fig. 3. Geometry of two posts.

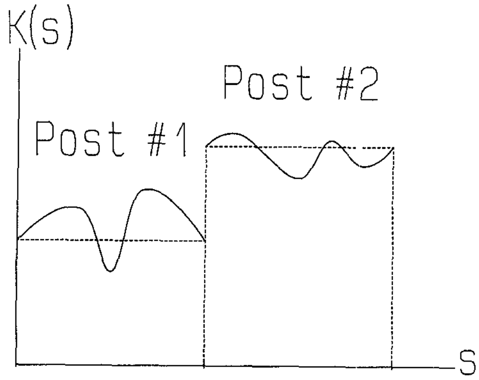


Fig. 4. Current density distribution on two posts.

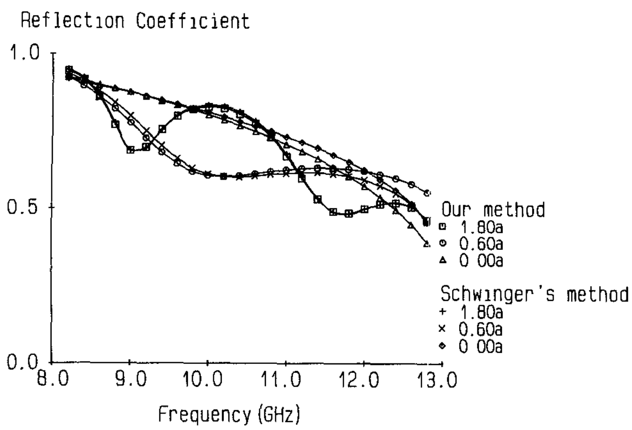


Fig. 5. Reflection coefficient of two metallic posts placed unsymmetrically ($x_2 = 0.2a$).

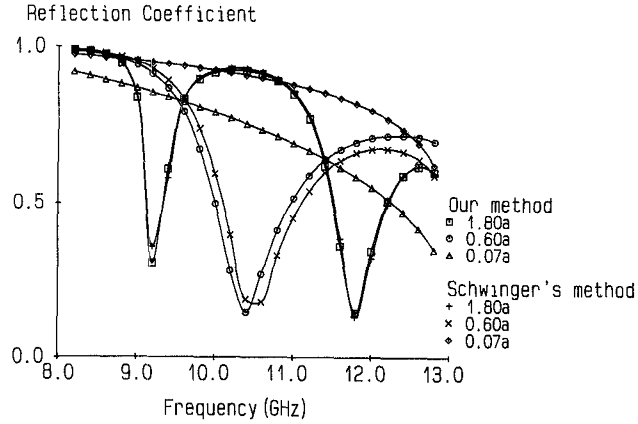


Fig. 6. Reflection coefficient of two metallic posts placed unsymmetrically ($x_2 = 0.365a$).

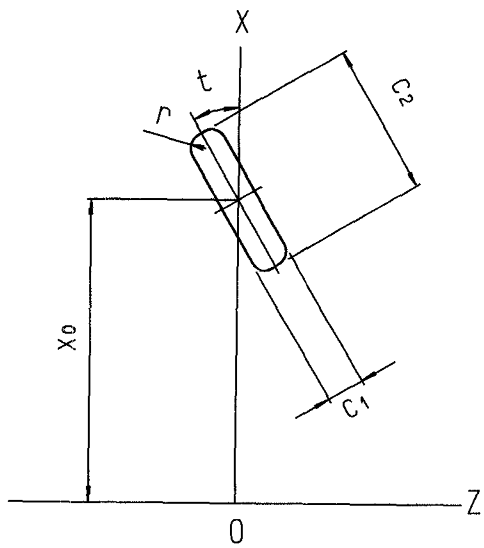


Fig. 7. Geometry of a rectangular post in a waveguide.

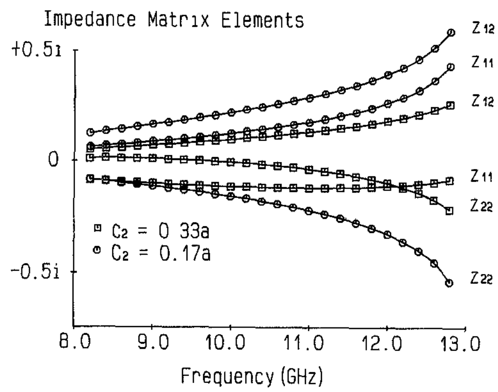


Fig. 8. Impedance matrix elements of a rectangular post.

The geometry of the post is shown in Fig. 7, where t is the angle of inclination. When t is not zero and x_0 is not $a/2$, the cross section of the post is unsymmetrical on the z = constant plane, and only our method can treat it.

The calculation is performed with $r = 0.035a$, $c_1 = 2r + 0.02a$, $t = \pi/6$ (radian), $x_0 = 0.4a$. The results for various c_2 are shown in Fig. 8.

A rectangular post with $c_1 = c_2 = 2r$ is nothing but a circular post, and it can be easily ascertained that the result obtained is coincident with that by Schwinger's method.

VI. Conclusion

Functionals for variational method, which are applicable to calculate the equivalent impedance matrix elements of metallic posts of arbitrary shape, number and position, have been presented. Each functional relates the current distribution on the metallic post to an impedance or admittance matrix element and the functional has the form which makes it possible to obtain the stationary value by Ritz's method without obtaining the stationary function. The results calculated by the presented functionals were compared with those by Schwinger's method and they are of good coincidence for the symmetrical cases.

Appendix

The field $\phi(x, z)$ in the waveguide with obstacles is given as follows:

$$\phi(x, z) = A \sin(\pi x/a) \cos \kappa z + B \sin(\pi x/a) \sin \kappa z + \int_{ob} G(x, z; x', z')\, K(x', z')\, dS' \quad \text{(A-1)}$$

where the sum of the first two terms is the incident field, $\kappa_n^2 = k^2 - (n\pi/a)^2$, $\kappa^2 = \kappa_1^2$, $k^2 = \omega^2 \epsilon\mu$, in the third term K is the induced current density which is constant along the y axis, the subscript ob stands for obstacle, and $G(x, z; x', z')$ is Green's function:

$$G(x, z; x', z') = (i/a) \sum_{n=1}^{\infty} \sin(n\pi x/a) \sin(n\pi x'/a) e^{i\kappa_n|z-z'|}/\kappa_n \quad \text{(A2)}$$

Applying the boundary condition on the surface of the metallic post to (A1),

$$0 = A \sin(\pi x_{ob}/a) \cos \kappa z_{ob} + B \sin(\pi x_{ob}/a) \sin \kappa z_{ob} + \int_{ob} G(x_{ob}, z_{ob}; x', z')\, K(x', z')\, dS' \quad \text{(A3)}$$

is obtained.

Under the condition that only the lowest mode ϕ_{Low} can travel, (A1) gives:

$$\phi_{\text{Low}}(x, z) = \sin(\pi x/a) \cdot V(z) \quad \text{(A4)}$$

where

$$V(z) = A \cos \kappa z + B \sin \kappa z + (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{i\kappa|z-z'|} K(x', z')\, dS'. \quad \text{(A5)}$$

Removing the influence of the evanescent modes in $V(z)$ by letting z be infinity, and then using the relation of $\partial V/\partial z = -i\kappa Z_0 I$, and finally letting z be zero, the left side voltage V_{10} and the current I_{10} adjacent to the discontinuity and also the right side voltage V_{20} and the current I_{20} are obtained as follows:

$$V_{10} = A + (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{+i\kappa z'} K(x', z')\, dS' \quad \text{(A6)}$$

$$V_{20} = A + (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{-i\kappa z'} K(x', z')\, dS' \quad \text{(A7)}$$

$$I_{10} = iB + (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{+i\kappa z'} K(x', z')\, dS' \quad \text{(A8)}$$

$$I_{20} = iB - (i/\kappa a) \int_{ob} \sin(\pi x'/a) e^{-i\kappa z'} K(x', z')\, dS' \quad \text{(A9)}$$

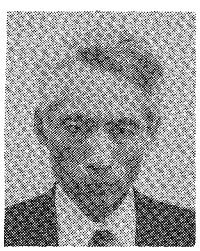
References

[1] J. Schwinger and D. S. Saxon, *Discontinuities in Waveguide.* New York: Gordon and Breach, 1968.
[2] R. E. Collin, *Field Theory of Guided Waves.* New York: McGraw-Hill, 1960.
[3] R. F. Harrington, *Field Computation by Moment Methods.* New York: Macmillan, 1968.
[4] R. Mittra, *Computer Techniques for Electromagnetics.* New York: Pergamon, 1973.
[5] L. Lewin, *Theory of Waveguide.* London: Newnes-Butterworths, 1975.
[6] Y. Leviatan, P. G. Li, A. T. Adams, and J. Perini, "Single-post inductive obstacle in rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 806–812, Oct. 1983.
[7] P. G. Li, A. T. Adams, Y. Leviatan, and J. Perini, "Multi-Post Inductive Obstacles in Rectangular Waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. 32, pp. 365–373, Apr. 1984.
[8] H. Auda and R. F. Harrington, "Inductive posts and diaphragms of arbitrary shape and number in a rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 606–613, June 1984.
[9] Y. Leviatan, D. Shau and A. T. Adams, "Numerical study of the current distribution on a post in a rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1411–1415, 1984.
[10] Y. Leviatan and G. S. Sheaffer, "Analysis of inductive dielectric posts in rectangular waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 48–59, Oct. 1987.
[11] N. Marcuvitz, *Waveguide Handbook.* New York: McGraw-Hill, 1951.

Takashi Toyama was born in Kobe, Japan, on December 7, 1941. He graduated from the Department of Applied Physics, University of Tokyo, Tokyo, Japan.

From 1965 to 1984 he was with Corporate Research and Development, Toyo Seikan Group, Yokohama, where he was engaged in research and development work on high-speed container manufacturing. Since 1984 he has been a principal of three vocational schools of information processing, accounting and design, and is simultaneously involved in post graduate research at Tokyo Metropolitan University.

Mr. Toyama is a member of the Institute of Electronics, Information and Communications Engineers of Japan.



Eikichi Sawado received B.S. and M.S. degrees from Tokyo Metropolitan University, Tokyo, Japan, in 1959 and 1961, respectively, and the Ph.D. degree from Tohoku University, Sendai, Japan in 1980.

In 1961, he joined the Department of Electrical Engineering at Tokyo Metropolitan University, where he is now a Professor. His research has dealt mainly with the loss mechanism of ferrites for microwaves.

Dr. Sawado is a member of the Society of Physics of Japan and the Institute of Electronics, Information and Communications Engineers of Japan.