Solution of the Finline Step-Discontinuity Problem Using the Generalized Variational Technique

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Abstract **—The finline step discontinuity is an essential component in millimeter-wave integrated circuits. The discontinuity problem is formulated using an unknown magnetic current in the transverse junction plane. A numerical solution is obtained by a method termed the Generalized Variational Method, and illustrative examples of scattering parameter calculations are given.**

I. Introduction

FINLINE TECHNOLOGY has gained popularity for the realization of millimeter-wave integrated circuits. Considerable theoretical material has been published concerning the analysis of uniform finline [1]–[5]. However, only a relatively few papers have been published on the characterization of finline discontinuities [6]–[9].

The solution of the general finline discontinuity problem is fundamental to designing many millimeter-wave integrated-circuit components, such as filters and matching structures. The traditional mode-matching approach has been applied to the discontinuity problem with some success [6]–[9]. A novel approach for solving this problem using unknowns in the transverse junction plane is presented here. The method is called the Generalized Variational Technique (GVT), which is analogous to the Conjugate Gradient Method [10]. The Generalized Variational method is an extension of the classical variational method, which represents the unknown in terms of one function [11]. Techniques presented here allow an improved solution by representing the unknown in terms of a number of characteristic functions, which are generated by means of prescribed routines. The method of formulation and numerical solution together with examples of computed results are given.

II. Formulation of the Discontinuity Problem Using Unknowns in the Junction Plane

The unilateral finline structure shown in Fig. 1 is considered specifically. A finline discontinuity consisting of a step change in the slot width is shown in Fig. 2. This

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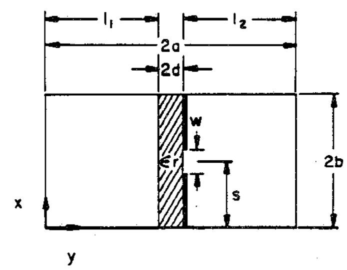

Fig. 1. Unilateral finline structure.

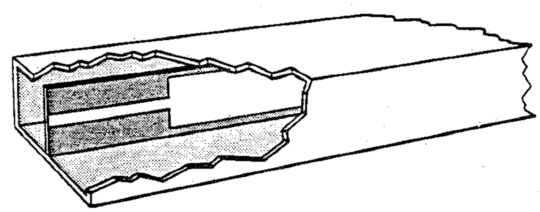

Fig. 2. Single step discontinuity in finline.

problem can be formulated using mode functions on either side of the discontinuity [12]. Consider the junction of two waveguides, with waveguide A for $z<0$ and waveguide B for $z>0$. The transverse field for $z<0$ and $z>0$ can be expressed in terms of the mode functions in waveguides A and B. Consider that I modes are used in this representation. A representation for the junction can employ equivalent magnetic currents over the transverse junction plane backed by perfect electric conductors, which radiate into both waveguides. For the discontinuity of Fig. 2, the equivalent magnetic currents exist over the complete cross section of the finline shielding enclosure. An integral operator equation can be derived using the Green's function for each waveguide.

With I modes, the transverse fields are

$$\boldsymbol{E}_t = \begin{cases} \boldsymbol{e}_{a1} e^{-\gamma_{a1} z} + \sum_{i=1}^{I} a_i \boldsymbol{e}_{ai} e^{\gamma_{ai} z}, & z<0 \\ \sum_{i=1}^{I} b_i \boldsymbol{h}_{bi} e^{-\gamma_{bi} z}, & z>0 \end{cases} \tag{1a}$$

$$\boldsymbol{H}_t = \begin{cases} \boldsymbol{h}_{a1} e^{-\gamma_{a1} z} - \sum_{i=1}^{I} a_i \boldsymbol{h}_{ai} e^{\gamma_{ai} z}, & z<0 \\ \sum_{i=1}^{I} b_i \boldsymbol{h}_{bi} e^{-\gamma_{bi} z}, & z>0. \end{cases} \tag{1b}$$

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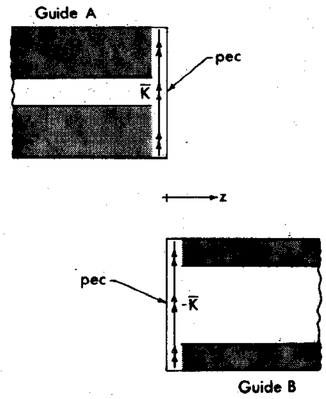

Fig. 3. Equivalent waveguide junction problem.

Rather than pursuing the regular mode-matching formulation, consider an alternate approach as follows. Fig. 3 shows a representation for the junction employing equivalent magnetic currents over the apertures. The total transverse field for the equivalent problem is

$$\boldsymbol{E}_t = \begin{cases} \boldsymbol{e}_{a1}e^{-\gamma_{a1}z} - \boldsymbol{e}_{a1}e^{\gamma_{a1}z} + \sum_{i=1}^{I} d_i \boldsymbol{e}_{ai}e^{\gamma_{ai}z}, & z<0 \\ \sum_{i=1}^{I} b_i \boldsymbol{e}_{bi}e^{-\gamma_{bi}z}, & z>0 \end{cases} \tag{2a}$$

$$\boldsymbol{H}_t = \begin{cases} \boldsymbol{h}_{a1}e^{-\gamma_{a1}z} + \boldsymbol{h}_{a1}e^{\gamma_{a1}z} - \sum_{i=1}^{I} d_i \boldsymbol{h}_{ai}e^{\gamma_{ai}z}, & z<0 \\ \sum_{i=1}^{I} b_i \boldsymbol{h}_{bi}e^{-\gamma_{bi}z}, & z>0 \end{cases} \tag{2b}$$

The fields produced in guide A by $\boldsymbol{K}$ are $\boldsymbol{E}_a(\boldsymbol{K}), \boldsymbol{H}_a(\boldsymbol{K})$, and in guide B by $-\boldsymbol{K}$ are $\boldsymbol{E}_b(-\boldsymbol{K}), \boldsymbol{H}_b(-\boldsymbol{K})$. For continuity of $\boldsymbol{E}_t$

$$\boldsymbol{K} = \hat{z}\times \boldsymbol{E}_a(\boldsymbol{K})|_{z=0} = \sum_{i=1}^{I} d_i \hat{z}\times \boldsymbol{e}_{ai} \tag{3a}$$

$$\boldsymbol{K} = \hat{z}\times \boldsymbol{E}_b(-\boldsymbol{K})|_{z=0} = \sum_{i=1}^{I} b_i \hat{z}\times \boldsymbol{e}_{bi}. \tag{3b}$$

Continuity of $\boldsymbol{H}_t$ requires

$$2\boldsymbol{h}_{a1} = \sum_{i=1}^{I} d_i \boldsymbol{h}_{ai} + \sum_{i=1}^{I} b_i \boldsymbol{h}_{bi}. \tag{4}$$

The solution for the unknown quantity $\boldsymbol{K}$ could be obtained via several numerical approaches, for example, the mode-matching method. The solution for $\boldsymbol{K}$ via certain iterative techniques is of interest in this paper.

Taking the inner products of (3), and using the orthogonality property of the modes with normalized mode functions, we have

$$\iint_s \boldsymbol{h}_{ak}\cdot \boldsymbol{K}\, ds = \sum_{i=1}^{I} d_i \iint_s \boldsymbol{h}_{ak}\cdot \hat{z}\times \boldsymbol{e}_{ai}\, ds = d_k \tag{5a}$$

$$\iint_s \boldsymbol{h}_{bk}\cdot \boldsymbol{K}\, ds = \sum_{i=1}^{I} b_i \iint_s \boldsymbol{h}_{bk}\cdot \hat{z}\times \boldsymbol{e}_{bi}\, ds = b_k. \tag{5b}$$

Substitution for the d's and b's in (4) results in the following integral equation, which may be used to solve for the unknown magnetic current $\boldsymbol{K}$:

$$2\boldsymbol{h}_{a1}(x,y) = \sum_{i=1}^{I} \boldsymbol{h}_{ai}(x,y) \iint_s \boldsymbol{h}_{ai}(x',y')\cdot \boldsymbol{K}(x',y')\, dx'\, dy' + \sum_{i=1}^{I} \boldsymbol{h}_{bi}(x,y) \iint_s \boldsymbol{h}_{bi}(x',y') \cdot \boldsymbol{K}(x',y')\, dx'\, dy'. \tag{6}$$

This equation may be interpreted in terms of the Green's function for each guide as follows. The dyadic Green's function can be found simply from the mode functions using a procedure outlined in Collin and Zucker [13]. Equation (6) can be written as

$$2\boldsymbol{h}_{a1} = \iint_s [\bar{\bar{G}}_a + \bar{\bar{G}}_b][\boldsymbol{K}]\, ds' \tag{7}$$

where

$$\boldsymbol{h}_{a1} = \begin{bmatrix} h_{a1x} & (x,y) \\ h_{a1y} & (x,y) \end{bmatrix}$$

$$\boldsymbol{K} = \begin{bmatrix} K_x & (x',y') \\ K_y & (x',y') \end{bmatrix}$$

$$\bar{\bar{G}}_q = \begin{bmatrix} \sum_{i=1}^{I} h_{qix}(x,y) h_{qix}(x',y') & \sum_{i=1}^{I} h_{qix}(x,y) h_{qiy}(x',y') \\ \sum_{i=1}^{I} h_{qiy}(x,y) h_{qix}(x',y') & \sum_{i=1}^{I} h_{qiy}(x,y) h_{qiy}(x',y') \end{bmatrix}, \quad q\in\{a,b\}.$$

The modal solutions can be determined by firstly employing a spectral-domain formulation in the plane of the fin, and then solving for the slot electric field. The electric field is expressed in terms of a set of basis functions in the context of the Galerkin method [1]–[5]. The resulting equation is first solved for the phase constants. The relative weights of the basis functions, and, hence, the slot electric field, are determined next. The knowledge of the modal slot electric field can then be used to derive the modal fields over the entire waveguide cross section by using a transverse resonance technique [3]. The number of modes I derived from this procedure is usually limited to a small number owing to the numerical difficulty of finding a large number of orthogonal modes.

Following the solution for $\boldsymbol{K}$, the mode coefficients can be found using (5). The scattering parameters can then be determined from these mode coefficients following a renormalization for unit modal power. Assuming that the modes have been normalized for $\int_s \int \boldsymbol{e}_n \times \boldsymbol{h}_n \, ds = 1$, the scattering parameters for the single propagating mode are given by [14]

$$S_{n1} = \iint_s \boldsymbol{h}_{q1} \cdot \boldsymbol{K} \, ds \frac{\left[\iint_s \boldsymbol{e}_{a1} \times \boldsymbol{h}^*_{a1} \, ds \right]^{1/2}}{\left[\iint_s \boldsymbol{e}_{q1} \times \boldsymbol{h}^*_{q1} \, ds \right]^{1/2}}, \quad q \in \{a, b\}, n \in \{1, 2\}. \tag{8}$$

III. Solution Using the Generalized Variational Technique

The approach for solving the discontinuity problem presented here considers the fields at the plane of the junction, $z = 0$, as the unknowns. Again, consider (7), which is of the form $Lf = g$, where L is an integral operator, f is the unknown (corresponding to $\boldsymbol{K}$), and g is the known incident field (corresponding to $\boldsymbol{h}_{a1}$).

The unknown quantity f may be expressed as a superposition of characteristic functions f_n, which are recursively generated by using a procedure given as follows. The unknown f can be expressed as

$$f = \sum_{n=0}^{N} c_n f_n. \tag{9}$$

Consider an inner product defined by

$$\langle \boldsymbol{F}, \boldsymbol{G} \rangle = \iint_s \boldsymbol{F}^* \cdot \boldsymbol{G} \, ds. \tag{10}$$

The characteristic functions f_n are L-orthogonal, and satisfy

$$\langle f_n, Lf_m \rangle = \eta_n \delta_{nm} \tag{11}$$

where δ_{mm} is the Kronecker delta function. A suitable set of characteristic functions can be generated by

$$f_n = \frac{u_n}{\|u_n\|^2} + f_{n-1} \tag{12}$$

where u_n is an auxiliary function which satisfies the orthogonality property

$$\langle u_n, u_m \rangle = \xi_n \delta_{nm}. \tag{13}$$

The auxiliary function can be found by

$$u_n = u_{n-1} - \zeta_{n-1} Lf_{n-1} \tag{14}$$

where

$$\zeta_{n-1} = \frac{1}{\eta_{n-1}}.$$

Substituting (9) into LF_g, and using the orthogonality relationship (11) gives

$$c_n = \frac{1}{\eta_n} \langle f_n, g \rangle. \tag{15}$$

The routine for generating the characteristic functions and their coefficients can be summarized as

$$\boxed{n = 0} \qquad f_0 = \frac{u_0}{\|u_0\|^2}$$

$$\boxed{n = n+1} \longrightarrow \eta_n = \langle f_n, Lf_n \rangle$$

$$c_n = \frac{\langle f_n, g \rangle}{\eta_n}$$

$$u_{n+1} = u_n - \frac{1}{\eta_n} Lf_n$$

$$f_{n+1} = \frac{u_{n+1}}{\|u_{n+1}\|^2} + f_n. \tag{16}$$

The Generalized Variational Technique may also be applied to the equation $L^A Lf = L^A g$, where L^A is the adjoint integral operator. It should be pointed out that $L^A L$ is positive definite; hence, the convergence of this procedure is guaranteed to be monotonic. Now the generation routine becomes

$$\boxed{n = 0} \qquad f_0 = \frac{u_0}{\|u_0\|^2}$$

$$\boxed{n = n+1} \longrightarrow \eta_n = \langle f_n, L^A Lf_n \rangle$$

$$c_n = \frac{\langle f_n, L^A g \rangle}{\eta_n}$$

$$u_{n+1} = u_n - \frac{1}{\eta_n} L^A Lf_n$$

$$f_{n+1} = \frac{u_{n+1}}{\|u_{n+1}\|^2} + f_n. \tag{17}$$

These routines can be used to solve for the unknown magnetic current in the junction plane of the finline discontinuity. A good choice for u_0 is $\hat{z} \times \boldsymbol{e}_{a1}$, where $\boldsymbol{e}_{a1}$ is the incident transverse E-field mode function, with a possible alternative being $\hat{z} \times (\boldsymbol{e}_{a1} + \boldsymbol{e}_{b1})$. The coefficients c_n, and successive characteristic functions f_n, are generated by (16) or (17).

IV. Numerical Results

The results given here were generated using three waveguide modes for construction of the Green's function. These modes were generated in turn by using two basis functions for E_x and E_z in the plane of the fin. The basis functions given in the Appendix were used with $p = 0$, 1 and $q = 2$, 4. Let us now turn to the characteristic function solution. Referring to (16) and (17), the initial auxiliary function u_0 was chosen as $\hat{z} \times \boldsymbol{e}_{a1}$. This results in the first characteristic function f_0. Subsequent characteristic functions f_n, and coefficients c_n, can then be generated according to (16) and (17). The fields over the waveguide cross section were represented discretely at (m, n) points. That is, the magnetic currents, characteristic functions, and waveguide modes were represented by a matrix of points over the shielded enclosure cross section. The mode coefficients and scattering parameters can then be found by using (5) and (8).

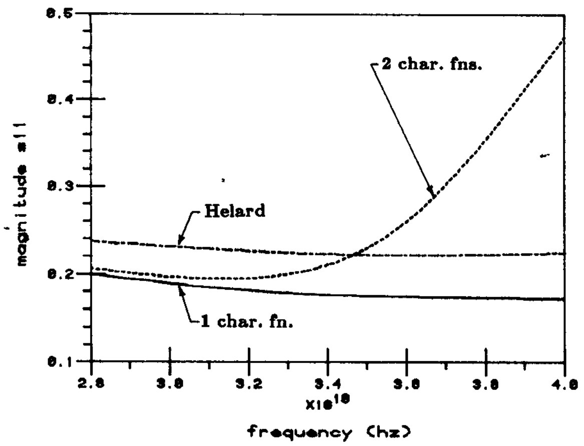

Fig. 4. $|S_{11}|$ for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

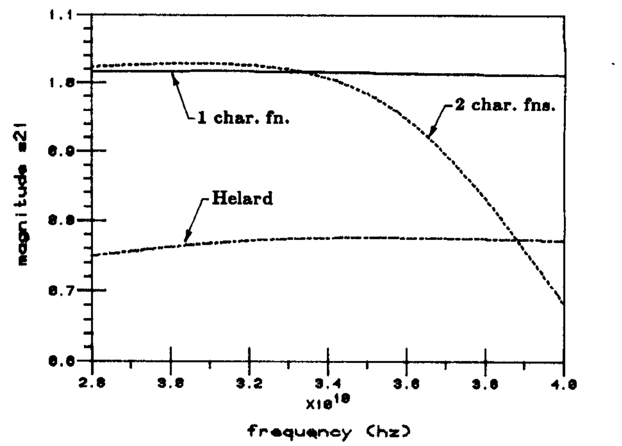

Fig. 6. $|S_{21}|$ for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

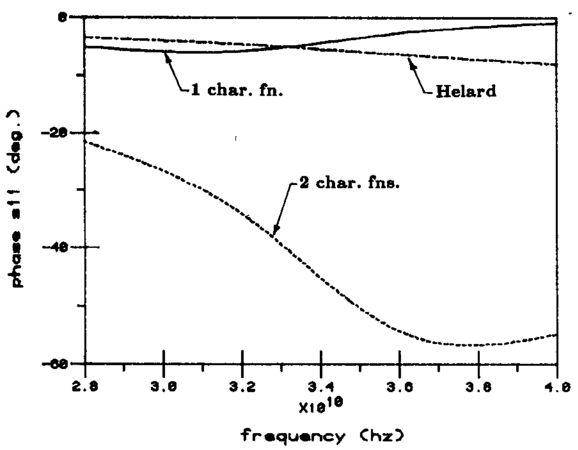

Fig. 5. Phase (S_{11}) for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

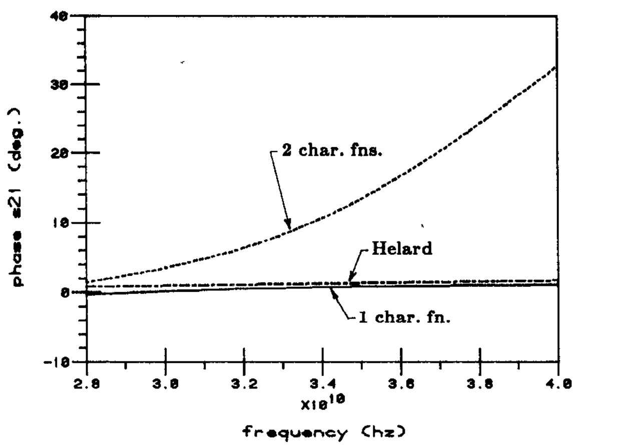

Fig. 7. Phase (S_{21}) for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

There is a shortage of data in the literature for comparative purposes. Consider as an example finline in a WR-28 shield, for which mode-matching data is given in the paper by Helard *et al.* [9]. The finline cross section shown in Fig. 1 gives the dimensional parameters. Figs. 4–7 show the computed scattering parameters for a step discontinuity in finline with a WR-28 shield. The equation $Lf = g$ is used here with one and two characteristic functions. As the operator L is not positive definite, a monotonically convergent solution as a function of the number of characteristic functions is not guaranteed. It is important to verify that for the single propagating mode, the numerical results satisfy

$$|S_{11}|^2 + |S_{21}|^2 = 1. \tag{18}$$

In drawing a comparison with the mode-matching data, it should be pointed out that (18) is not satisfied well in [9]. Quite good agreement for S_{11} using one characteristic function was achieved. There is a significant change in the results for one and two characteristic functions. This change can be attributed to the small number of modes available for constructing the Green's function and the fact that the

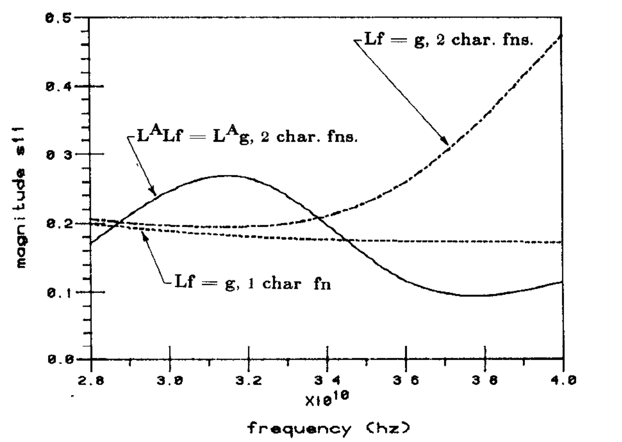

Fig. 8. $|S_{11}|$ for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

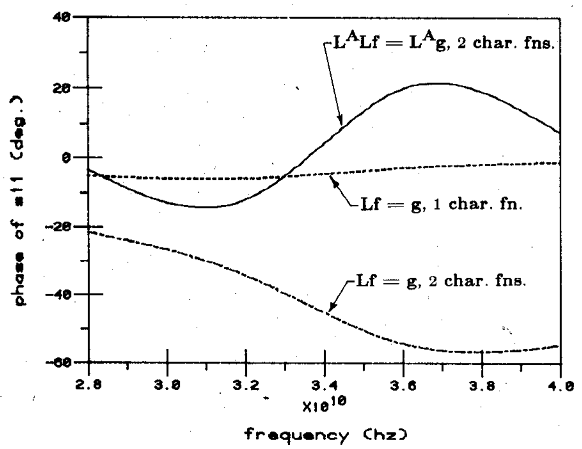

Fig. 9. Phase (S_{11}) for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

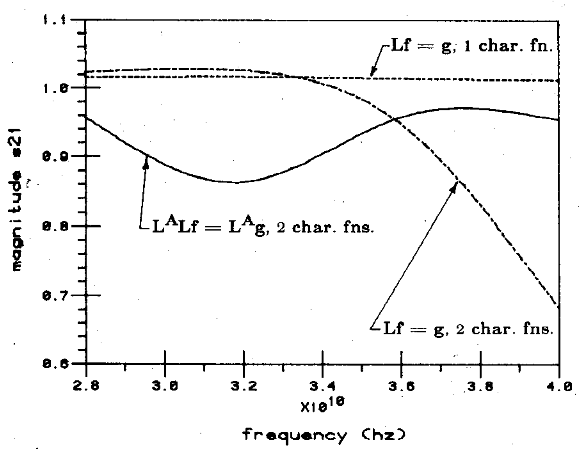

Fig. 10. $|S_{21}|$ for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

solution does not converge monotonically with an increasing number of characteristic functions.

A comparison between the equation $Lf = g$ with one and two characteristic functions, and the equation $L^A Lf = L^A g$ with two characteristic functions, is given in Figs. 8–11. Use of the positive definite operator improves the behavior of the solution, but a larger number of waveguide modes are required to improve the accuracy significantly.

The computed scattering parameters for a step discontinuity in finline with a WR-62 shield, using the equation $Lf = g$, are shown in Figs. 12–15. Equivalent circuits for this problem using S_{11} have been generated by El Hennawy and Schunemann using a mode-matching technique [8]. A comparison with these results shows some variation. Notice that the Generalized Variational Technique results with one characteristic function satisfy (18) well. By increasing the number of characteristic functions to two, the magnitude of S_{11} approaches the results in [8], but due to the small number of modes in the Green's function, the phase of S_{11} and the magnitude of S_{21} show some deterioration in behavior. An indication of the accuracy of the mode solutions and the satisfaction of (18)

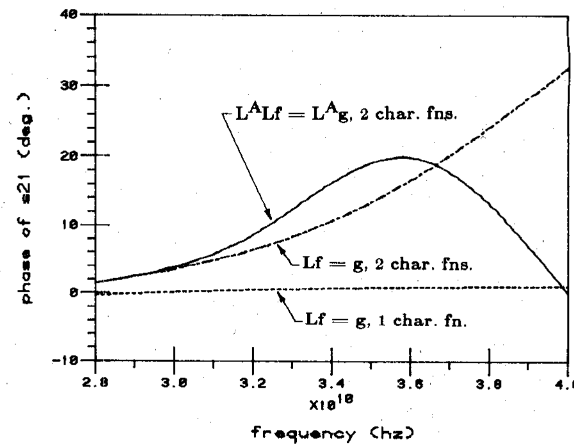

Fig. 11. Phase (S_{21}) for a discontinuity in finline with a WR-28 shield. $l_1 = l_2 = 3.429$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.22$, $2b = 2.556$ mm, $w_1 = 1$ mm, $w_2 = 2$ mm, $m = 17$, $n = 33$.

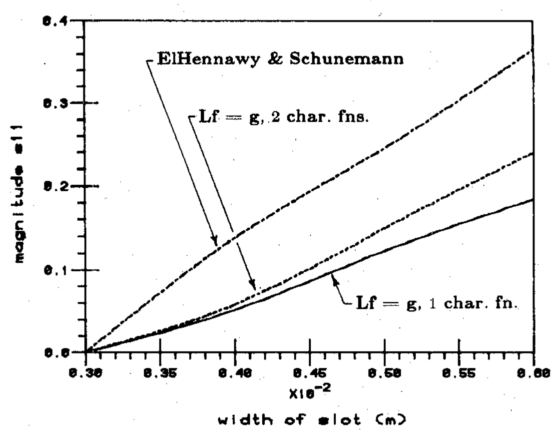

Fig. 12. $|S_{11}|$ for a discontinuity in finline with a WR-62 shield. $l_1 = l_2 = 7.773$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.2$, $2b = 3.95$ mm, $w_1 = 3$ mm, $m = 17$, $n = 33$.

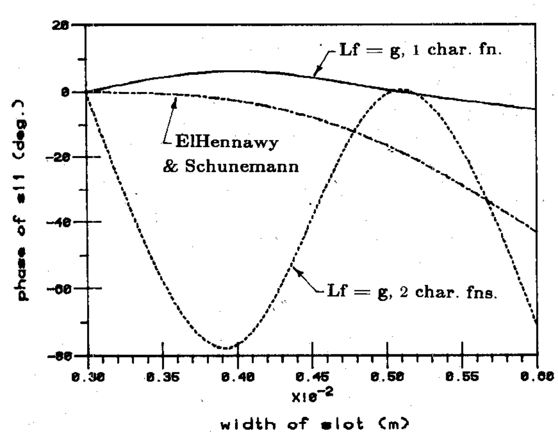

Fig. 13. Phase (S_{11}) for a discontinuity in finline with a WR-62 shield. $l_1 = l_2 = 7.773$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.2$, $2b = 3.95$ mm, $w_1 = 3$ mm, $m = 17$, $n = 33$.

cannot be determined from this mode-matching work [6], [8].

It should be pointed out that the maximum number of characteristic functions, and, hence, the accuracy of the procedure, is limited by the number of waveguide modes that have been used to construct the Green's function. The

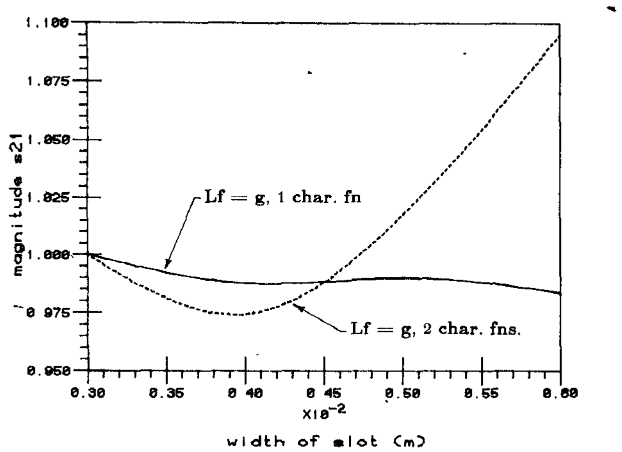

Fig. 14. $|S_{21}|$ for a discontinuity in finline with a WR-62 shield. $l_1 = l_2 = 7.773$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.2$, $2b = 3.95$ mm, $w_1 = 3$ mm, $m = 17$, $n = 33$.

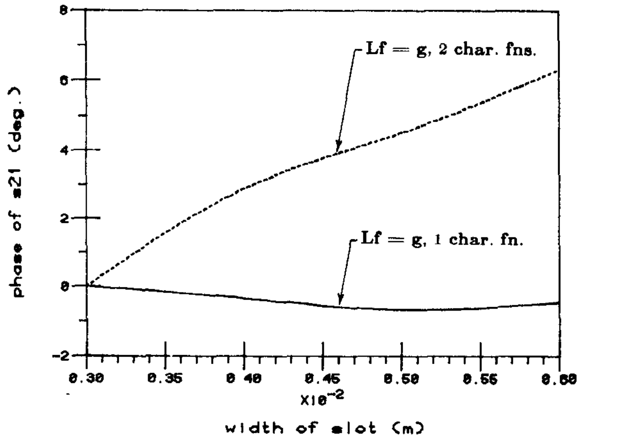

Fig. 15. Phase (S_{21}) for a discontinuity in finline with a WR-62 shield. $l_1 = l_2 = 7.773$ mm, $2d = 0.254$ mm, $\epsilon_r = 2.2$, $2b = 3.95$ mm, $w_1 = 3$ mm, $m = 17$, $n = 33$.

$$\left.\begin{aligned} \zeta_p(x) &= \frac{\cos\left[\frac{(p-1)\pi}{w}\left(x - s - \frac{w}{2}\right)\right]}{\sqrt{1 - \left[\frac{2(x-s)}{w}\right]^2}}, \quad p = 1,2,3,\cdots \\ \eta_q(x) &= \frac{\sin\left[\frac{q\pi}{w}\left(x - s - \frac{w}{2}\right)\right]}{\sqrt{1 - \left[\frac{2(x-s)}{w}\right]^2}}, \quad q = 1,2,3,\cdots \end{aligned}\right\} s - \frac{w}{2} < x < s + \frac{w}{2} \tag{A2}$$

$$\left.\begin{aligned} \zeta_p(x) &= 0 \\ \eta_q(x) &= 0 \end{aligned}\right\} \text{otherwise}$$

accuracy of the solution cannot be increased arbitrarily due to the lack of availability of a large number of satisfactory higher order modes. An approximate convergence criterion for the maximum number of characteristic functions p, with q modes in the Green's function, is $p \leqslant q - 1$.

V. Conclusion

The finline step-discontinuity problem has been formulated with an unknown magnetic current over the transverse junction plane. A solution for this magnetic current was obtained using an approach termed the Generalized Variational Technique. This resulted in the scattering parameters for the finline discontinuities. The computed scattering parameters for example discontinuities compared favorably with existing data. The approaches outlined can be applied to other metallized substrate waveguides. Further work remains to be done in order to improve the accuracy of the solution, and it is important to obtain experimental verification. If a larger number of good solutions for the finline modes are used to construct the Green's function, more characteristic functions can be used, resulting in a more accurate solution. It is, therefore, necessary to improve the accuracy of the higher order mode solutions. An investigation related to the discontinuity analysis of Sorrentino and Itoh [15], which was recently published, is currently being pursued.

Appendix

The expansion of the slot fields in terms of known basis functions is

$$E_x(x) = \sum_{p=1}^{P} a_p \zeta_p(x) \tag{A1a}$$

$$E_z(x) = \sum_{q=1}^{Q} b_q \eta_q(x). \tag{A1b}$$

A suitable set of basis functions is an orthogonal polynomial set, modified by the edge condition. The functions used are (A2)

and $\zeta_0(x) = P_x(s, w)$, where $P_x(s, w)$ is a pulse function of width w centered at $x = s$.

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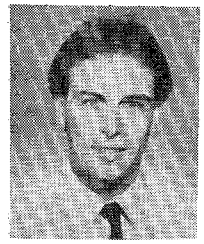

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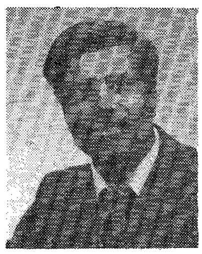

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