An Approximate Variational Solution to the Step Discontinuity in Finline

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Abstract —The step in finline is the basic building block of filters, transformers, and matching elements. We present a simplified, yet fairly accurate, treatment based on solving by variational methods the step in symmetric finned waveguide for the E and H formulations. Experiment is in good agreement with theoretical predictions for not too large steps and fairly good even for large steps. An "optimized" equivalent circuit with constant (lumped) components for commonly encountered steps is presented in a form directly usable by the designer.

I. Introduction

A. Objectives

ALTHOUGH experimental data may be readily available, the characterization of finline discontinuities from a theoretical viewpoint is important for two reasons. First, an insight into the physical mechanisms of the discontinuity allows appropriate equivalent circuits to be developed, which can then be applied to the broad-band modeling of measured discontinuities. Second, armed with accurate analysis techniques, circuit design can proceed directly, by using the equivalent circuit models in commercially available programs. The objectives are, therefore, to develop 1) a basic understanding of finline discontinuity problems, and 2) an accurate and efficient analytical technique which will lead to simple circuit models.

B. Review of Analytical Methods

Early theoretical treatments of the finline step discontinuity were given in [1]–[3]. Realizing the difficulties encountered in obtaining a sufficient number of finline modes, in [4] the problem was converted into one of determining resonator eigenvalues. The method is versatile, but does require large amounts of computer time. Using the singular integral equation (SIE) technique, in [5] higher order modes were obtained with greater ease, including modes of complex propagation [6].

A highly efficient method of determining the finline mode spectrum using the transverse resonance diffraction (TRD) technique was developed in [7]. The modes determined in this method may be easily incorporated into a variational formulation for most discontinuity problems. Such a formulation is readily amenable to approximate techniques, thereby enhancing numerical efficiency and allowing the results to be easily incorporated into CAD programs.

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II. Discussion of the Finline Step Discontinuity Problem

The similarity between finlines and ridge waveguides has been observed by numerous workers. Much of the field is concentrated under the ridge, with very little field outside. Because of this, a step in a ridge waveguide can be compared to a step in height within a parallel-plate guide (see Fig. 1), and this may be rigorously solved from the quasi-static solution employing the conformal mapping technique [8].

From these solutions two distinct edge effects can be identified. The first is associated with the 90° bend, A (see Fig. 2). This causes a localized concentration of electric field in the $x-z$ plane, while in accordance with the behavior of the wall currents, all magnetic fields must vanish at this point. The second edge effect, on the 270° bend, B, operates in the opposite manner, intensifying the y-directed magnetic field and causing all electric fields to vanish.

In the limiting case of ridge waveguides, when the ridge is considered to be infinitesimally thin (finned waveguide), the discontinuity is located only in the $x-z$ plane, so that distortions to the y variation of fields are minimal. The discontinuity will therefore excite modes with a similar y variation to that of the incident wave. These include the other fundamental mode and the first few members of higher order slot mode families. However, particularly in the case of large steps, the excitation of other high-order modes will also occur. Moreover, since the ridge is now extremely thin, an additional effect must be considered; the step in finned waveguide affects the $y-z$ electric and magnetic fields as a current concentration builds on the metallization edge, C.

The scattering mechanisms of a step discontinuity in a finline, including the addition of a substrate layer, are therefore highly complex and involve all field components. With exact knowledge of the high-order modes this may be reduced to a two-dimensional problem and solved rigor-

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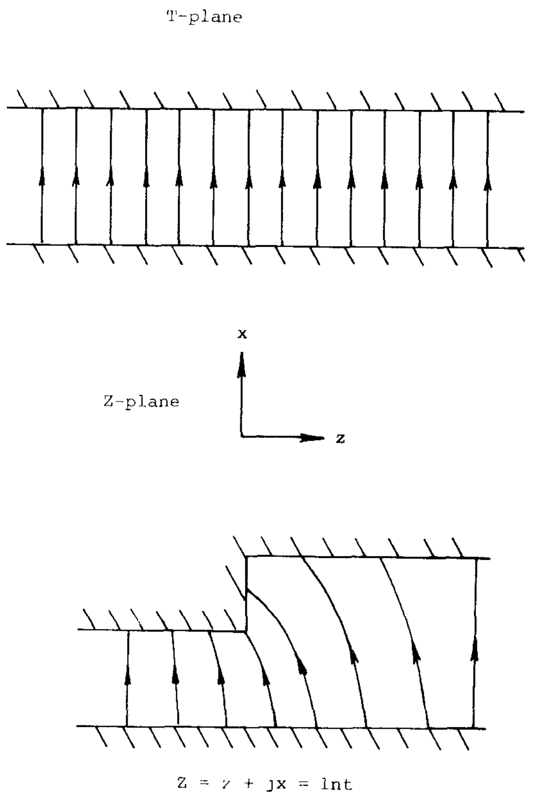

Fig. 1. Step discontinuity in parallel-plate waveguide.

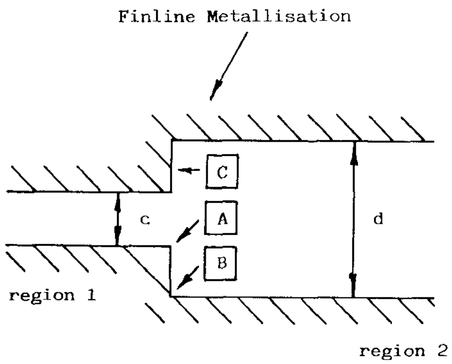

Fig 2. Finline step discontinuity.

ously by imposing continuity of transverse fields over the waveguide cross section. However, the relationship between transverse electric and magnetic fields is not straightforward, necessitating the use of dyadic wave impedances within the dielectric region. Several simplifications of the problem will therefore be made, as follows:

1) Since there is no discontinuity of dielectric in a finline step, the effect of the dielectric on the field shape may be neglected. This simplification does not allow for a fully rigorous solution, especially in the case of thick substrates of high permittivity. This situation, however, is not commonly found in practice.
2) From previous work [7], it was demonstrated that for symmetrical finned waveguides, modal solutions reduce to transverse electric (TE) and transverse magnetic (TM) waves. Important also is that the coupling between these modes, which gives rise to hybrid and complex propagation [6], [7], [9], vanishes.

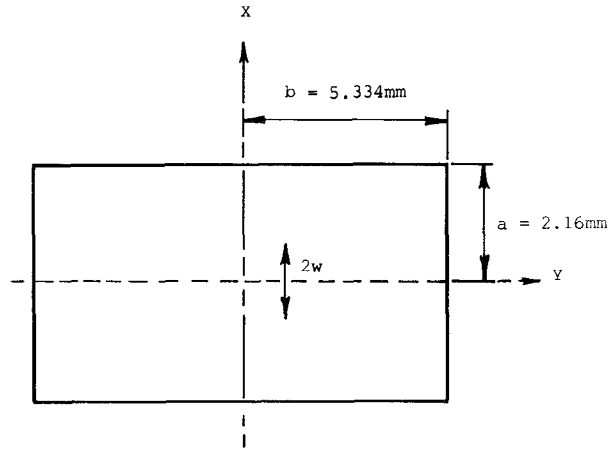

Fig. 3. Symmetrical finned waveguide: $a = 2.16$ mm, $b = 5.334$ mm.

III. Modes of the Symmetrical Finned Waveguides

Consider the guiding structure shown in Fig. 3. Assume a z dependence of $\exp(-j\beta z)$. TE modes are given by a z-directed potential as

$$\begin{bmatrix} E_x(x,y) \\ E_y(x,y) \\ E_z(x,y) \end{bmatrix} = \boldsymbol{E}(x,y) = \begin{bmatrix} +\dfrac{\partial}{\partial y} \\ -\dfrac{\partial}{\partial x} \\ 0 \end{bmatrix} \sigma_{te}(x,y) \qquad (1)$$

$$\boldsymbol{H}(x,y) = (1/j\omega\epsilon) \begin{bmatrix} -j\beta\dfrac{\partial}{\partial x} \\ +j\beta\dfrac{\partial}{\partial y} \\ K_0^2 - \beta^2 \end{bmatrix} \sigma_{te}(x,y) \qquad (2)$$

where

$$\sigma_{te}(x,y) = \sum_{n=0}^{\infty} U_{en}(\delta_n/a)^{1/2} \cdot \cos(n\pi x/a)\cosh K_{ny}(h-y)/\cosh K_{ny}h,$$

$$\delta_n = \begin{cases} 2 & \text{for } n > 0 \\ 1 & \text{for } n = 0 \end{cases}$$

$$K_{ny} = \left\{(n\pi/a)^2 + \beta^2 - K_0^2\right\}^{1/2}.$$

K_0 is the free-space wavenumber and U_{en} are as yet unknown coefficients. Similarly, for TM modes,

$$E(x,y)=\frac{1}{j\omega\mu}\begin{bmatrix}+j\beta\frac{\partial}{\partial x}\\ -j\beta\frac{\partial}{\partial y}\\ K_0^2-\beta^2\end{bmatrix}\sigma_{tm}(x,y) \tag{3}$$

$$H(x,y)=\begin{bmatrix}\frac{\partial}{\partial y}\\ -\frac{\partial}{\partial x}\\ 0\end{bmatrix}\sigma_{tm}(x,y) \tag{4}$$

where

$$\sigma_{tm}(x,y)=\sum_{n=1}^{\infty}U_{hn}(2/a)^{1/2}\cdot\sin(n\pi x/a)\sinh K_{ny}(h-y)/\sinh K_{ny}h.$$

Here U_{hn} are as yet unknown coefficients. Solutions for TE and TM modes, and hence the coefficients U_{en} and U_{hn}, are obtained by imposing the continuity of fields (implicit in this the symmetrical case), subject to the boundary conditions of the fins. For instance, for TE modes at $y=0$,

$$E_x(x)=-\sum_{n=0}^{\infty}U_{hn}(\delta_n/a)^{1/2}\cdot\cos(n\pi x/a)K_{ny}\tanh K_{ny}h \tag{5a}$$

$$E_y(x)=\sum_{n=1}^{\infty}U_{hn}(2/a)^{1/2}(n\pi/a)\sin(n\pi x/a) \tag{5b}$$

$$H_x(x)=(\beta/\omega\epsilon)\sum_{n=1}^{\infty}U_{hn}(2/a)^{1/2}\cdot(n\pi/a)\sin(n\pi x/a) \tag{5c}$$

$$H_y(x)=-(\beta/\omega\epsilon)\sum_{n=0}^{\infty}U_{hn}(\delta_n/a)^{1/2}\cdot\cos(n\pi x/a)K_{ny}\tanh K_{ny}h. \tag{5d}$$

(Note the occurrence of a scalar wave impedance linking the fields E_x and H_y and E_y and H_x, which is a property of pure TE and TM modes. This does not hold in general finline structures.)

By matching a transverse electric and a transverse magnetic field component, say $E_x(x)$ and $H_x(x)$, the problem is solved, and to this end it is convenient to adopt the modified field quantity

$$H_x^I(x)=-\int H_x(x)\,dx=(\beta/\omega\epsilon)\sum_{n=0}^{\infty}U_{hn}\varphi_{hn}(x) \tag{6}$$

where

$$\varphi_{hn}(x)=(\delta_n/a)^{1/2}\cos(n\pi x/a).$$

This unifies the boundary conditions in x, so that an integral equation linking the two fields at the plane of the fins is readily obtained as

$$U_{h0}\varphi_{h0}(x)Y_0+\int Y(x;x')E_x(x')\,dx'=0 \tag{7}$$

where the kernel (known as the Green's admittance in this case) is given by

$$Y(x;x')=\sum_{n=1}^{\infty}(\beta/\omega\epsilon)\varphi_{hn}(x)\varphi_{hn}(x')\coth K_{ny}h/K_{ny}$$

and

$$Y_0=(\beta/\omega\epsilon)\cot\left[(K_0^2-\beta^2)^{1/2}h\right]/(K_0^2-\beta^2)^{1/2}.$$

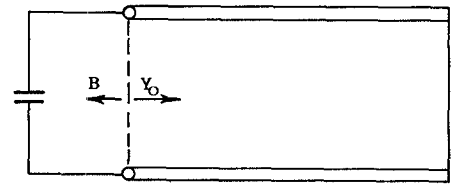

Fig. 4. Transverse resonance model.

The integral equation is now expanded in terms of a set of functions $f_m(x)$ which exist only over the fin aperature. By applying the Ritz–Galerkin procedure, (7) is converted into

$$Y_0+\left(P_0^T\cdot Y^{-1}\cdot P_0\right)^{-1}=0. \tag{8}$$

P_0^T and P_0 are row and column vectors respectively of elements P_{0m}. The coefficients P_{nm} link the nth eigenfunction $\varphi_{hn}(x)$ to the mth expansion function $f_m(x)$ in the Ritz–Galerkin procedure. Y is a matrix resulting from the expansion of the Green's admittance $Y(x:x')$ and Y_0 is the (scalar) admittance linking fields of the fundamental transverse mode at the plane of the fins.

Solutions to (8) can be interpreted as resonances of the transverse network given in Fig. 4. The resonance condition is

$$Y_0+B=0 \tag{9}$$

where B is the combined admittance of all higher order transverse modes coupled by the fin, that is,

$$B=\left(P_0^T Y^{-1}\cdot P_0\right)^{-1}.$$

The efficiency of the solution is vastly enhanced by employing a set of basis functions $\{f_m(x)\}$ which are obtained from the conformal mapping of the electric field into an iris. These are the Schwinger functions, which approximate the exact slot field so well that it is often only necessary to employ one expansion function. For instance, the zeroth Schwinger function $(f_0(x))$ gives rise to solutions, known as the TE_0 family, from

$$P_{00}^2Y_0+\sum_{n=1}^{\infty}P_{n0}^2Y_n=0.$$

But since

$$P_{n0}^2Y_n\to\left(P_{n0}^2/n\right)\quad\text{as}\quad n\to\infty$$

a special property of Schwinger functions allows the infi-

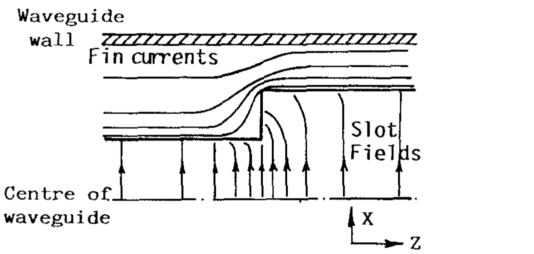

Fig. 5. Illustration of slot fields and fin currents around the finline step.

nite sum to be evaluated analytically as

$$\sum_{n=1}^{\infty} P_{n0}^2/n = \left(P_{00}^2/2\right)\ln|\csc^2(\pi w/a)|$$

where w is the fin gap. This gives the result

$$Y_0 + \tfrac{1}{2}\ln|\csc(\pi w/a)| + \sum_{n=1} (P_{n0}/P_{00})^2 (Y_n - 1/n) = 0. \quad (10)$$

Here the infinite sum has been reduced to a correction series which converges rapidly (after two or three terms) and so further improves numerical efficiency. Moreover, the nearly exact description afforded by the Schwinger functions to the eigenmodes of the fin implies that high-order TE_m mode families follow directly from the solution of

$$\sum_{n=0}^{\infty} P_{nm}^2 Y_n = 0.$$

A similar procedure is followed for TM modes. Here, however, the TM_0 family is physically impossible.

IV. Simplified Dispersion

Since the modes of the symmetric finned guide are pure TE or TM, their dispersion may be simply described by an expression of the form

$$\beta = \sqrt{K_0^2 - K_c^2} \quad (11)$$

where K_0 is the free-space wavenumber, and K_c is the cutoff wavenumber.

Thus the previous analysis need be performed only once for a particular fin gap, by imposing $\beta = 0$, so that the complete mode spectrum of finned waveguide is obtained via the determination of the cutoff frequencies.

V. Variational Formulation for the Step Discontinuity in Finned Waveguide

Having obtained the complete mode spectrum of finned waveguide, a solution to the step discontinuity problem can now be formulated. From the physical considerations given in Section II the likely behavior of the slot field and fin currents is as shown in Fig. 5. The distortion to the slot field will excite only TM modes via the required E_z field, introducing a shunt capacitive reactance, whereas the distortion of the current will excite only TE modes via the required H_z field, introducing a series inductive reactance. Furthermore, the difference between the y variation of the field on either side of the step will most significantly excite higher order TE_0 modes, introducing additional inductive reactance. An equivalent circuit for the step discontinuity will therefore be chosen as shown in Fig. 6. The elements of the equivalent circuit may be obtained from *separate* admittance and impedance matrix formulations. These are

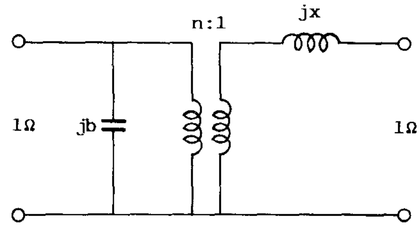

Fig. 6. Equivalent circuit model for finline step discontinuity.

$$n = \sqrt{(Z_{11}/Z_{22})} = \sqrt{(Y_{22}/Y_{11})} \quad (12a)$$

$$b = 1/Z_{11} \quad (12b)$$

and

$$x = 1/Y_{22}. \quad (12c)$$

Variational expressions for the elements of the normalized impedance matrix are given by [10]

$$Z_{11} = \boldsymbol{C}^T \cdot \boldsymbol{Y}^{-1} \cdot \boldsymbol{C}$$
$$Z_{12} = Z_{21} = \boldsymbol{C}^T \cdot \boldsymbol{Y}^{-1} \cdot \boldsymbol{D}$$
$$Z_{22} = \boldsymbol{D}^T \cdot \boldsymbol{Y}^{-1} \cdot \boldsymbol{D} \quad (13)$$

where $\boldsymbol{C}^T$ is a column vector of elements given by

$$C_i = \int \psi_0(x, y) e_i(x, y)\, dx\, dy. \quad (14)$$

Here $\psi_0(x, y)$ is the fundamental modal field function in region 1 (see Fig. 2), and $e_i(x, y)$ is the ith basis function for the discontinuity electric field on the discontinuity. Similarly,

$$D_i = \int \chi_0(x, y) e_i(x, y)\, dx\, dy \quad (15)$$

where $\chi_0(x, y)$ is the modal function in region 2. The matrix $\boldsymbol{Y}$ is the Green's admittance which links magnetic and electric fields over the discontinuity plane, expanded onto the basis $e_i(x, y)$, that is,

$$Y_{ij} = \int\int Y(\boldsymbol{r}; \boldsymbol{r}') e_i(\boldsymbol{r}) e_j(\boldsymbol{r}')\, d\boldsymbol{r}\, d\boldsymbol{r}'$$

where $\boldsymbol{r}$ denotes (x, y) and $\boldsymbol{r}'$ denotes (x', y').

The Green's admittance itself is given by

$$Y(\boldsymbol{r}; \boldsymbol{r}') = \sum_{k=1}^{\infty} (j\omega\epsilon/\gamma_k)\psi_k(\boldsymbol{r})\psi_k(\boldsymbol{r}') + \sum_{m=1}^{\infty} (j\omega\epsilon/\gamma_m)\chi_m(\boldsymbol{r})\chi_m(\boldsymbol{r}') \quad (16)$$

where $\psi_k(\boldsymbol{r})$ is the modal field function for the kth TM mode in region 1 and γ_k is its propagation coefficient. $\chi_m(\boldsymbol{r})$ is similarly the modal field function in region 2 and γ_m its propagation coefficient.

It is noted that, once an appropriate choice for the electric field on the discontinuity is assumed, we obtain an expression for b and an expression for n. We shall now proceed to obtain an expression for x and a second one for n, given an appropriate discontinuity magnetic field.

Variational expressions for the normalized admittance matrix are similarly given by

$$Y_{11} = \overline{C}^T \cdot Z^{-1} \cdot \overline{C}$$
$$Y_{12} = \overline{C}^T \cdot Z^{-1} \cdot \overline{D}$$
$$Y_{22} = \overline{D}^T \cdot Z^{-1} \cdot \overline{D} \tag{17}$$

where now

$$\overline{C}_i = \int \overline{\psi}_0(\mathbf{r}) h_i(\mathbf{r})\, d\mathbf{r} \tag{18a}$$

$$\overline{D}_i = \int \overline{\chi}_0(\mathbf{r}) h_i(\mathbf{r})\, d\mathbf{r} \tag{18b}$$

where $h_i(\mathbf{r})$ is the ith basis function for the magnetic field at the discontinuity,

$$Z_{ij} = \int\int Z(\mathbf{r};\mathbf{r}') h_i(\mathbf{r}) h_j(\mathbf{r}')\, d\mathbf{r} d\mathbf{r}'. \tag{19}$$

The Green's impedance is given by

$$Z(\mathbf{r};\mathbf{r}) = \sum_{k=1}^{\infty} (j\omega\mu/\overline{\gamma}_k)\overline{\psi}_k(\mathbf{r})\overline{\psi}_k(\mathbf{r}') + \sum_{m=1}^{\infty} (j\omega\mu/\overline{\gamma}_m)\overline{\chi}_m(\mathbf{r})\overline{\chi}_m(\mathbf{r}'). \tag{20}$$

Here $\overline{\psi}_k(\mathbf{r})$ is the modal field function for the kth TE mode in region 1, and $\overline{\chi}_m(\mathbf{r})$ is the modal field function in region 2.

Regarding now the modal functions, these are defined in (5) as infinite series. Their use in the Green's functions (16) and (20) requires them to be orthonormalized over the guide cross section, as follows. In the impedance matrix formulation, where an electric field expansion is employed, the modal functions are given by

$$\psi_i(\mathbf{r}) = E_{ci}(\mathbf{r}) \Big/ \left\{ \int E_{ci}^2(\mathbf{r})\, d\mathbf{r} \right\}^{1/2} \tag{21a}$$

$$\chi_i(\mathbf{r}) = E_{di}(\mathbf{r}) \Big/ \left\{ \int E_{di}^2(\mathbf{r})\, d\mathbf{r} \right\}^{1/2} \tag{21b}$$

where $E_{ci}(\mathbf{r})$ and $E_{di}(\mathbf{r})$ are appropriate truncations of the infinite series (5) representing the transverse electric fields of the ith mode in regions 1 and 2 respectively. Thus

$$\int \psi_i^2(\mathbf{r})\, d\mathbf{r} = 1 \qquad \int \chi_i^2(\mathbf{r})\, d\mathbf{r} = 1$$

and similarly in the admittance matrix formulation where a magnetic field expansion is employed.

For narrow fin gaps the denominator terms in the above normalizations are in fact proportional to the z-directed power flow for each mode, and for small steps in narrow finlines the equivalent circuit reduces to a simple transformer, whose ratio is given by the two fundamental mode powers. In general, however, the full variational formulation is required to model properly the reactive effects associated with a step discontinuity.

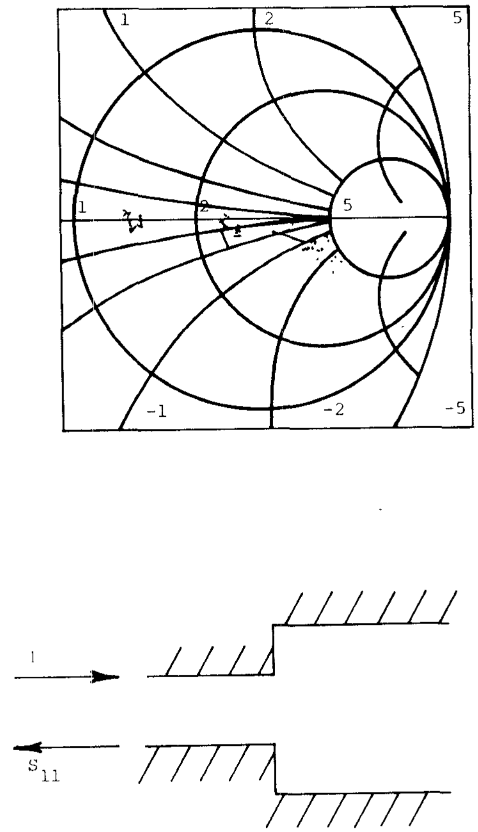

Fig. 7. Comparison of experimental and calculated data for S_{11}

Finally, we shall now discuss the choice of expression functions for the transverse electric ($e_i(\mathbf{r})$) and magnetic $h_i(\mathbf{r})$) fields to be used in the variational expressions. Although the formulation so far is fairly general, we will now seek to employ a single function in each formulation, by making use of the redundancy still present in the definition of the transformer ratio (12), which is common to both formulations. As to the choice of this function, we noted in the introduction that whereas the edge singularity and the quasi-static fields near the gap in the infinite finline are known, those for the step of Fig. 2 are not. In each formulation we shall employ here the fundamental quasi-static field of a fin gap of dimensions g intermediate between c and d. The precise value of g is fixed, in fact, by the condition that the value of n be consistent in both formulations.

VI. Equivalent Circuit Models for Unilateral Finline Step Discontinuities

Theoretical results for the three finline step discontinuities are compared in Figs. 7 and 8 with experiment. The experiment was carried out at K-band (18–26, 5 GHz) in an automated vector measuring system. First, waveguide-to-finline tapered transitions were tested and their characteristics stored on disk. Subsequently, the scattering parameters of the step itself could be "de-embedded" from

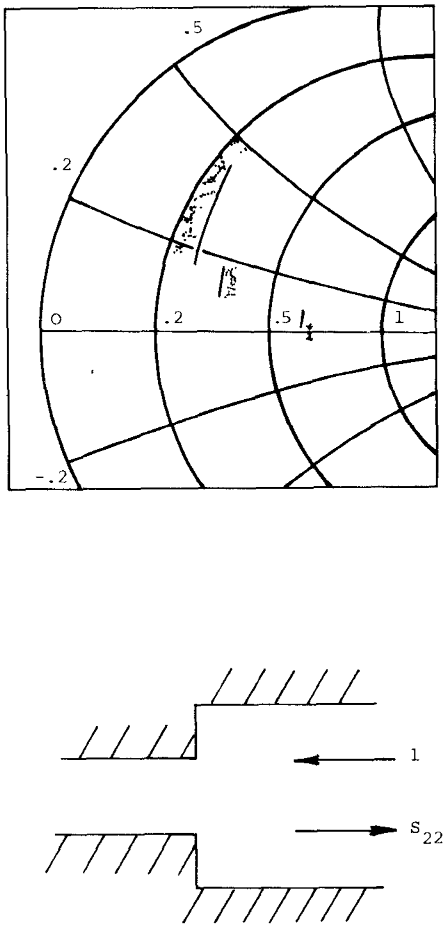

Fig. 8. Comparison of experimental and calculated data for S_{22}.

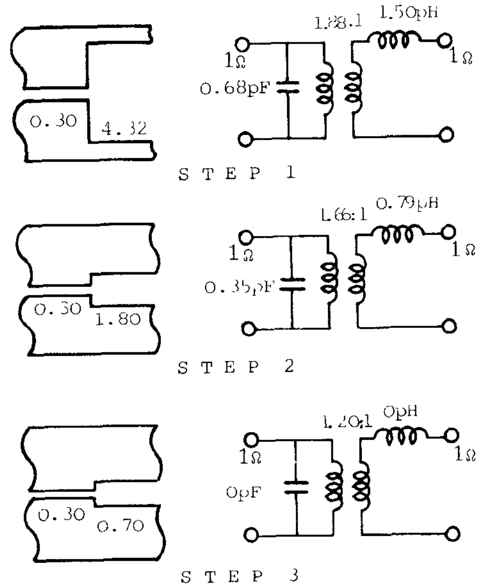

Fig. 9. Equivalent circuit models for the three finline step discontinuities (dimensions in mm).

the measurement of a second set of identical test jigs, now containing the discontinuity. Overall attenuation loss was in the region of 0.1 dB, mainly occurring in the transitions. Return loss of the transition was in the region of 20 dB, indicating a good match. Consequently, transmission characteristics can be deduced from the reflection. The dots in Figs. 7 and 8 indicate a scatter of experimental points to be compared with the calculated data continuous lines. Calculations employed only one expansion function, that of an intermediate finline gap, with ten higher order TE and TM slot modes and three higher order TE_0 modes.

It was previously reported [7] that the higher order slot mode cutoff frequencies rapidly approach asymptotic values (corresponding to box resonances) as the fin gap is reduced. Indeed this effect was found to cause several modes to vanish from the calculations. Moreover, it was found that since a step between narrow finlines causes little disturbance to the variation of field, such a step had very little associated reactance. However, as the step was widened, higher order TE and TM slot modes became excited, introducing a shunt susceptance and series reactance. Since these modes are found to be well cut off, these reactances did not vary much with frequency. The y perturbation, on the other hand, excites the less cut off TE_0 modes, introducing an additional series reactance. This can vary rapidly with frequency, in fact faster than the reactance of a lumped inductor, so that an improved circuit model may be required to account for this effect. From Figs. 7 and 8 it can be seen that the theoretical and experimental results agree very well concerning the basic behavior of the step discontinuity.

In terms of numerical efficiency, the solution is excellent. After an initial calculation for cutoff frequencies has been performed (typically 10 seconds on a minicomputer for 20 modes) the various integrals are quickly evaluated (resolved into simple sums because of the orthogonality of $\varphi_{hn}(x)$). This information is then used to evaluate the elements of the equivalent network at any particular frequency. Since the frequency dependence of the Green's admittances is simple, this is also straightforward.

However, discrepancies remain, indicating that the solution has not yet converged, not because of a lack of higher order modes, but because only a single basis function was used. In order to improve accuracy, future work will be aimed at developing a more sophisticated set of basis functions which incorporate the physical effects outlined in Section II.

Finally, the equivalent circuit models for the three unilateral finline step discontinuities with circuit element values obtained from theory are presented in Fig. 9. It is noted that 0.3 mm, corresponding in absolute terms to 155–145 Ω in the range 18–26 GHz, is the gap width commonly used in mounting beam-lead diodes. Figs. 10 and 11 compare their response with the experiment (see also Figs. 7 and 8). These models may be used directly in CAD design procedures for finline components.

VII. Conclusions

We have applied the variational method to a step discontinuity in unilateral finline on the basis of a simplified description of the finline modes, as modes of a symmetrical finned waveguide. A prudent choice of the "trial field"

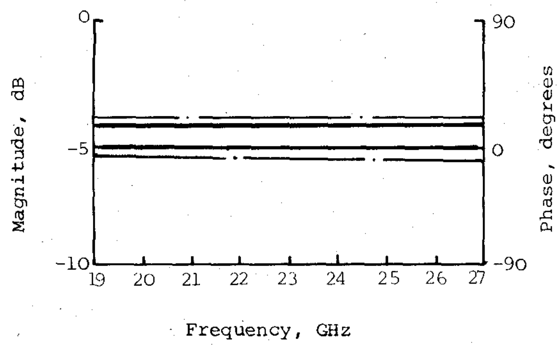

Fig. 10. Measured and computed data relating to the first finline step discontinuity: ——— · ——— · ——— best fit from experiment; ——— computed.

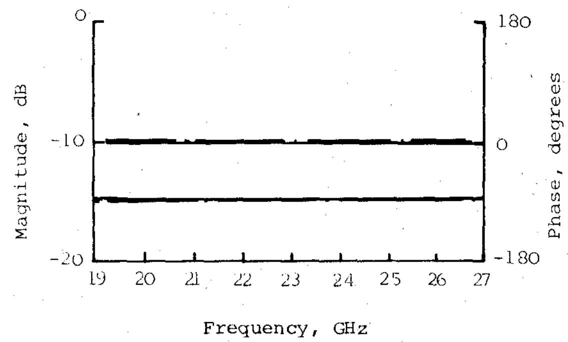

Fig. 11. Measured and computed data relating to the third finline step discontinuity: ——— · ——— · ——— best fit from experiment; ——— computed.

in the electric and the magnetic formulations allows us to derive, very economically, simple equivalent circuits with frequency-independent elements over a full waveguide band for a broad range of practical step ratios. This information is directly usable for CAD purposes.

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