# A Simple Network Analog Approach for the Quasi-Static Characteristics of General Lossy, Anisotropic, Layered Structures

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*Abstract* —A network analog method to compute the quasi-static parameters of multilayered planar structures consisting of lossy and/or anisotropic dielectric media is presented. The discrete network analog having complex (e.g., $RL, RC$) branches can be reduced and solved for the desired interface node voltages and currents by using known techniques leading to the solution of the quasi-static potential problems. All of the quasi-static transmission-line constants required for the evaluation of the propagation characteristics of general multilayered quasi-TEM planar structures are computed from the solution of the two-dimensional discrete analog network. These constants include the self- and mutual-resistances, inductances, conductances, and capacitances per unit length of the structure. The method is applied to compute the propagation constants, impedances, and field distribution for typical single and coupled strip structures on lossy, anisotropic, and layered substrates.

## I. Introduction

OF ALL THE METHODS that have evolved over the years for the computation of the propagation characteristics and other properties of planar structures, perhaps the most direct approach is the use of the finite-difference equations (e.g., [1]–[3]). The corresponding resistive network analog for lossless planar structures, together with simple multiport network theory, enabled Lennartson [1] to formulate a simple, yet accurate, computational procedure for the capacitance matrix elements of coupled microstrips. The method has also been extended to planar lossless microstrip problems without the top cover [4] and three-dimensional lossless problems, and has been applied to microstrip rectangular disk and microstrip gap discontinuity problems [5]. More recently, the remarkably efficient and versatile method of lines has also evolved from the finite-difference equations for the frequency-dependent parameters of planar structures, as well as the solution of three-dimensional problems [6]–[8]. In this paper, Lennartson's method is extended to apply to general lossy, anisotropic multilayered structures. In addition, it is shown that planar structures with strips at different levels, as well as the effect of strip thickness, can also be included in the analysis and computations. Also, for a given structure, the charge distribution on the strips, the potential and, hence, the electric-field variation everywhere can also be evaluated by using this network analog approach. The knowledge of the charge distribution is also used to estimate the conductor losses in strips where thickness is large as compared to the skin depth. This conceptually simple, direct, yet accurate approach is intended to complement other techniques with varying degrees of complexity, accuracy, and sophistication that have evolved over the years (e.g., [5]–[16]) for the study of single and multilayered structures.

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## II. The Network Analog

The quasi-static fields are the solutions to the following equations subject to all the boundary conditions of the structure:

$$\nabla \times \bar{E} = 0 \quad \text{or} \quad \bar{E} = -\nabla\phi \tag{1a}$$

$$\nabla \times \bar{H} = \bar{J} + j\omega\bar{D}. \tag{1b}$$

For the general lossy, anisotropic case, the potential $\phi$ in each region then is a solution of

$$\nabla\cdot[\sigma\nabla\phi + j\omega\overleftrightarrow{\epsilon}\cdot\nabla\phi] = 0 \tag{2}$$

where $\overleftrightarrow{\epsilon}$ is the permittivity dyadic. The boundary conditions at the interface of any two media 1 and 2 are given by

$$\hat{n}\times(\vec{E}_1 - \vec{E}_2) = 0 \tag{3a}$$

$$\hat{n}\cdot[(\sigma_1\vec{E}_1 + j\omega\vec{D}_1) - (\sigma_2\vec{E}_2 + j\omega\vec{D}_2)] = 0 \tag{3d}$$

where $\vec{E}_{1,2} = -\nabla\phi_{1,2}$, $\vec{D}_{1,2} = \overleftrightarrow{\epsilon}_{1,2}\cdot\vec{E}_{1,2}$, $\sigma$ is the conductivity of the medium, and $\omega$ is the frequency. Equation (2) can be expressed in a finite-difference form which, together with the boundary conditions as given by (3), leads to a three-dimensional discrete network analog having, in general, complex branches. In this paper, we consider the two-dimensional boundary-value problem associated with the evaluation of the quasi-TEM propagation characteristics of planar structures having, in general, lossy and/or anisotropic (uniaxial or biaxial) layers with a diagonal permittivity tensor. For such structures (Fig. 1(a)), the two-dimensional boundary-value problem is expressed as

$$(\sigma + j\omega\epsilon_x)\frac{\partial^2\phi}{\partial x^2} + (\sigma + j\omega\epsilon_y)\frac{\partial^2\phi}{\partial y^2} = 0 \tag{4a}$$

$$\frac{\partial\phi}{\partial x} \text{ is continuous at the boundaries} \tag{4b}$$

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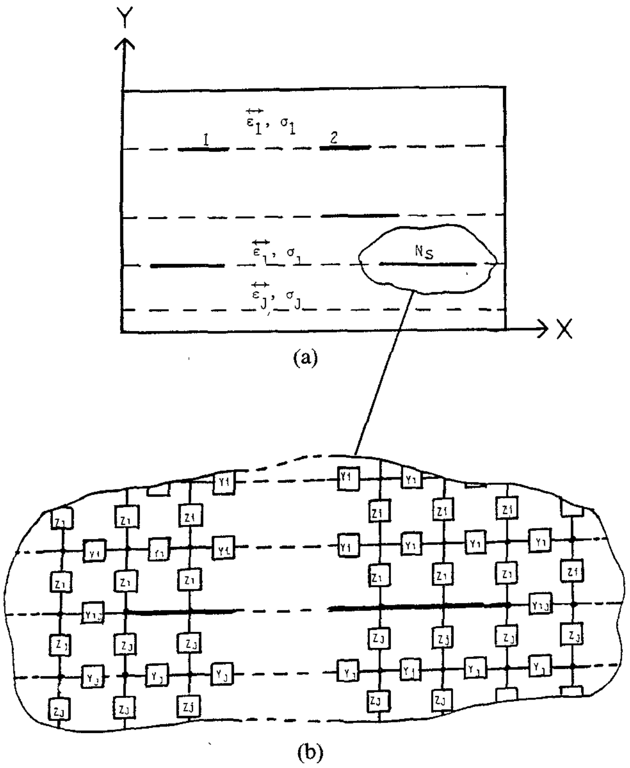



Fig. 1. (a) A generic layered structure with $N_s$ strips. (b) The network analog for a representative region. $Y$'s and $Z$'s depend on the structure, e.g., for lossy isotropic medium

$$Y_i = \sigma_i + j\omega\epsilon_i \quad Z_i = 1/Y_i \quad Y_{ij} = \tfrac{1}{2}(Y_i + Y_j)$$

and for lossless anisotropic medium

$$Y_i = j\omega\epsilon_{xi} \quad Z_i = 1/j\omega\epsilon_{yi} \quad Y_{ij} = \tfrac{1}{2}(Y_i + Y_j).$$

$$(\sigma - j\omega\epsilon_y)\frac{\partial\phi}{\partial y} \text{ is continuous at the boundaries and excluding the strips} \tag{4c}$$

and

$$\phi = V_i, \qquad i = 1, 2, \cdots, N \text{ on the strips.} \tag{4d}$$

Expressing the above equations in a finite-difference form [2], [3] leads to

$$(\sigma + j\omega\epsilon_x)\frac{\phi(x+\Delta x, y) + \phi(x-\Delta x, y) - 2\phi(x, y)}{\Delta x^2} + (\sigma + j\omega\epsilon_y)\frac{\phi(x, y+\Delta y) + \phi(x, y-\Delta y) - 2\phi(x, y)}{\Delta y^2} \cong 0 \tag{5}$$

which, together with the boundary conditions as given by

$$(\sigma + j\omega\epsilon_y)\frac{\phi(x, y+\Delta y) - \phi(x, y)}{\Delta y}$$

and

$$\frac{\phi(x+\Delta x, y) - \phi(x, y)}{\Delta x}$$

are continuous, and define an electrical network analog having complex branches as shown in Fig. 1(b). The right-hand side of (5) will be equal to $(-\rho)$ if we were writing the Poisson's equation, in which case the node current will correspond to the charge density at the point of interest. It should be noted that $\Delta x$ need not be equal to $\Delta y$, which enables us to conveniently scale the problem independently in the two transverse directions in each layer of the structure. For the case of $\Delta x$ equal to $\Delta y$, the immittance values for the branches are given in Fig. 1(b) for the lossy isotropic, as well as the lossless uniaxial medium case.

The next problem is to solve for the currents at a set of nodes where the voltages are specified. The solution for the sum of currents at the nodes on the conductor strip when all the node voltages are known at a given frequency gives the total equivalent admittance per unit length of the strip. The same solution in the absence of the dielectric medium is used to find the inductance matrix of the structure. The conductor loss can also be computed by this method in terms of the fields at the surface of the conductor or the charge distribution on the conducting strips [3]. As an example, for a structure composed of a single strip of width $W$ and thickness $T$, we discretize the strip surface into $N$ sections and solve for the currents ($\mathrm{I}_{\text{node}}$) at each strip node when the voltage at all the strip nodes is 1 V at frequency $\omega$ rad/s. Then the transmission-line constants per unit length for this case are

$$C = \mathrm{Im}\left[\sum_1^N \mathrm{I}_{\text{node}}\right] \Big/ \omega, \qquad \text{F/m} \tag{6a}$$

$$G = \mathrm{Re}\left[\sum_1^N \mathrm{I}_{\text{node}}\right], \qquad \Omega/\text{m} \tag{6b}$$

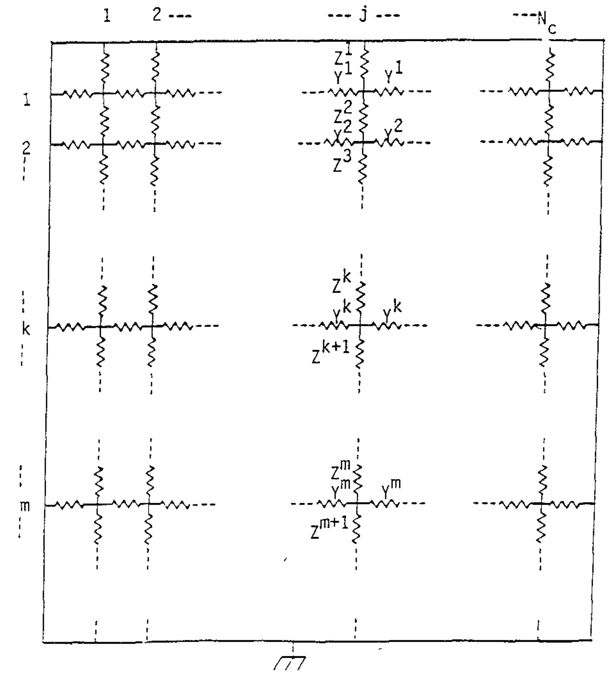
$$L = \omega\mu_0\epsilon_0 \Big/ \sum_1^N \mathrm{Im}[\mathrm{I}_{\text{node}}], \qquad \text{H/m, with all the dielectric layers removed} \tag{6c}$$

$$R = \frac{R_s N}{2(W+T)} \frac{\sum_1^N (\mathrm{Im}[\mathrm{I}_{\text{node}}])^2}{\left(\sum_1^N \mathrm{Im}[\mathrm{I}_{\text{node}}]\right)^2}, \quad \Omega/\text{m}; \quad R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}. \tag{6d}$$

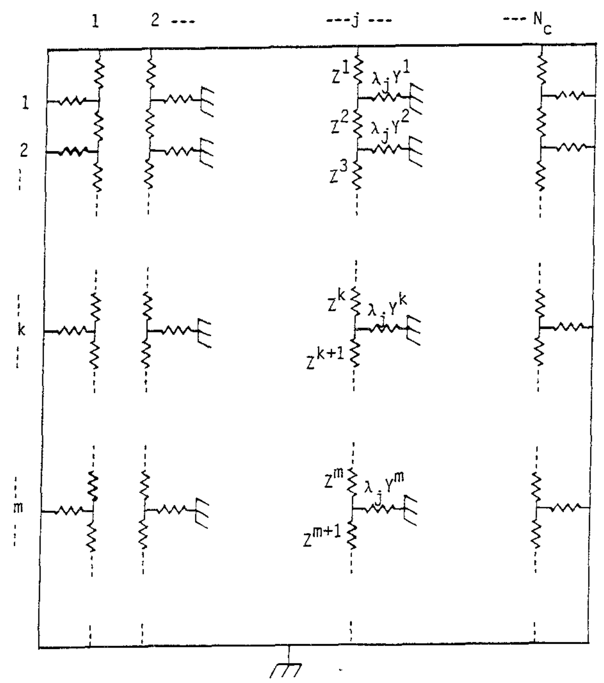
The above expressions are readily generalized to a multiple strip situation.

## III. The Solution Method

For the case of infinitesimally thin strips on layered lossless media, Lennartson solved for the charge on each strip by first deriving the total resistance matrix representing the relationship between the node voltages and currents at the interface utilizing some basic transformations and properties of the electrical network. He then found the current in each strip which corresponds to the total charge on the strip by adding the currents on each node of the strip when a given potential is applied on all the strips. The procedure given in [1] provides a simple computational algorithm for obtaining the impedance ma-



(a)



(b)

Fig. 2. (a) The discrete network analog. (b) The algebraically equivalent transformed network.

trix associated with the node voltages and currents at any interface. This procedure is readily modified to apply to the case of lossy, anisotropic layered structures with thin strips on one interface and to the case of thick strips at different boundaries as shown below.

The $N_c$ voltages at a given boundary, where $N_c$ represents the number of columns in the discretization scheme, are expressed in terms of the corresponding node currents in the form of an $N_c \times N_c$ total impedance matrix as given by (see Fig. 2)

$$[V]=[Z][I]. \tag{7}$$

We should note that, in relation to the boundary-value problem, the elements of $[Z]$ are essentially a discrete representation of the boundary Green's function in real space. The elements of $[Z]$ are obtained as in [1] in an algebraically equivalent transformed domain in terms of a diagonal matrix $[\hat{Z}]$ as given by

$$[\hat{Z}]=[A][Z][A] \tag{8}$$

where $[A]$ is an $N_c \times N_c$ involuntary matrix consisting of the eigenvectors of the tridiagonal connection matrix at each level as given by [1]

$$\{a_{ij}\} = \sqrt{\frac{2}{N_c+1}}\,\sin\left(\frac{ij\pi}{N_c+1}\right). \tag{9}$$

The diagonal matrix elements at the boundary level $L$

$$\hat{Z}_j^L = \frac{1}{\dfrac{1}{(\alpha_u^L)_j} + \dfrac{1}{(\alpha_l^L)_j} + \lambda_j y^L}, \qquad j=1,2,\cdots,N_c \tag{10}$$

are computed from the recurrence relation

$$(\alpha_{u,l}^{k+1})_j = \frac{1}{\dfrac{1}{(\alpha_{u,l}^{k})_j} + \lambda_j y^k} + z^{k+1} \tag{11a}$$

with

$$\alpha_{u,l}^1 = z_{u,l}^1. \tag{11b}$$

$z_{u,l}^1$ is the impedance of the series element corresponding to the first level from the upper ($u$) and the lower ($l$) side, respectively. $\lambda_j$'s are the eigenvalues of the connection matrix and are given by [1]

$$\lambda_j = 4\sin^2\left[\frac{j\pi}{2(N_c+1)}\right], \qquad j=1,2,\cdots,N_c. \tag{12}$$

In addition to the above straightforward modification to the method given in [1], we should note that for structures without a top or a bottom cover (grounded plane), an asymptotic expression can be derived for $\alpha_u$ or $\alpha_l$ by requiring that

$$(\alpha_{u,l}^{k+1})_j = (\alpha_{u,l}^{k})_j \triangleq (\alpha_{u,l})_j, \qquad j=1,2,\cdots,N_c. \tag{13}$$

This simplifies the computations for open structures and structures without a ground plane. Equation (13), for an open structure, leads to

$$(\alpha_{u,l})_j = \frac{\lambda_j yz + \left[\lambda_j^2 y^2 z^2 + 4\lambda_j yz\right]^{1/2}}{2\lambda_j y} \tag{14}$$

where $z$ and $y$ are the appropriate impedance and the admittance elements of the upper or lower unbounded homogeneous material. For isotropic materials, the above expression simplifies to

$$(\alpha_{u,l})_j = \frac{z}{2}\left(1+\sqrt{1+\frac{4}{\lambda_j}}\right). \qquad (15)$$

For normalized $z=1$, the above equation (15) reduces to the one obtained in [4] for unshielded lossless microstrip case.

## IV. Thick and Multilevel Strip Case

For structures with strips at more than one level or structures with thick strips, the above procedure is generalized in terms of impedance matrix elements relating the voltages at the nodes of all the interfaces where the strips are located to the corresponding node currents. That is, the total impedance matrix is now of the order $nN_c$, where $n$ is the number of different levels where the strips are located. In this case, the elements of the total impedance matrix corresponding to self-impedance terms are evaluated in exactly the same manner as for the previous case, that is, the elements corresponding to transfer impedance terms are derived in the transformed diagonalized domain. The transfer impedance terms in this diagonalized domain relating the voltage on a given interface node at level $k$ to the current on another interface node at level $m$ in the same column $j$ are found to be (Fig. 2(b)):

$$\hat{Z}_{km} = \left[\frac{1}{\frac{1}{(\alpha_u^k)_j}+\lambda_j y^k} \cdot \frac{\frac{1}{(\alpha_u^m)_j}}{\frac{1}{(\alpha_u^m)_j}+\frac{1}{(\alpha_l^m)_j}+\lambda_j y^m}\right] \prod_{q=m+\operatorname{sgn}(k-m)}^{q=k-\operatorname{sgn}(k-m)} \frac{\frac{1}{(\alpha_u^q)_j}}{\frac{1}{(\alpha_u^q)_j}+\lambda_j y^q},$$

$$j=1,2,3,\cdots,N_c. \qquad (16)$$

The expression on the right side of (16) can be observed to be the fraction of the current on the level $m$ node which reaches the level $k$ node, multiplied by the impedance to the upper ground at level $k$, including the admittance $\lambda_j y^k$. Because the impedance matrix is symmetric for a passive network, the transfer impedance element relating the voltage at a level $m$ node to the current at a level $k$ node in the same column $j$ is obtained directly as

$$\hat{Z}_{mk} = \hat{Z}_{km}. \qquad (17)$$

The transfer impedance matrix in real space relating voltages at level $k$ and currents at level $m$ is given by

$$V]_k = [A][\hat{Z}]_{km}[A]I]_m \triangleq [Z]_{km} I]_m. \qquad (18)$$

The total impedance matrix for the general case with conducting strips at several levels can be constructed using the self-impedance submatrices as given by [1] and the transfer impedance submatrices as presented above

$$\begin{bmatrix} V]_1 \\ V]_2 \\ \vdots \\ V]_P \end{bmatrix} = \begin{bmatrix} [Z]_{11} & [Z]_{12} & & [Z]_{1p} \\ [Z]_{12} & [Z]_{22} & & \vdots \\ \vdots & & \ddots & \vdots \\ [Z]_{1p} & & & [Z]_{pp} \end{bmatrix} = \begin{bmatrix} I]_1 \\ I]_2 \\ \vdots \\ I]_P \end{bmatrix} \qquad (19)$$

Equation (19) can be used to extend Lennartson's [1] method for multiple strips (zero thickness) at the same interface level to handle multiple zero thickness strips at different levels and also multiple finite thickness strips at different levels.

For a given set of potentials on different strips, the solution of (19) for currents on the strips is found in the same manner as for the single interface infinitesimally thin strip case discussed earlier. These node currents are then used to find all the line constants and quasi-TEM normal mode parameters of the structure.

TABLE I
Resistance and Capacitance Per Unit Length Between Two Coplanar Strips on Silicon ($\sigma = 0.1\ \Omega/\text{m}$)

| W:S:W | COMPUTED | | | | | | EXACT | |
|---|---|---|---|---|---|---|---|---|
| | R,Ω/m | | | C,pf/m | | | R,Ω/m | C,pf/m |
| | N=20 | N=40 | Extrap. | N=20 | N=40 | Extrap. | | |
| 2:1.2 | 5.0075 | 5.1282 | 5.2489 | 112.24 | 109.6 | 106 96 | 5.2604 | 106 86 |
| 1:1:1 | 6.1387 | 6.2578 | 6.3769 | 91.55 | 89.81 | 88.07 | 6.3938 | 87 9 |
| .5:1:.5 | 7.5757 | 7.6746 | 7 7734 | 74.16 | 73.23 | 72 3 | 7.8186 | 71.93 |

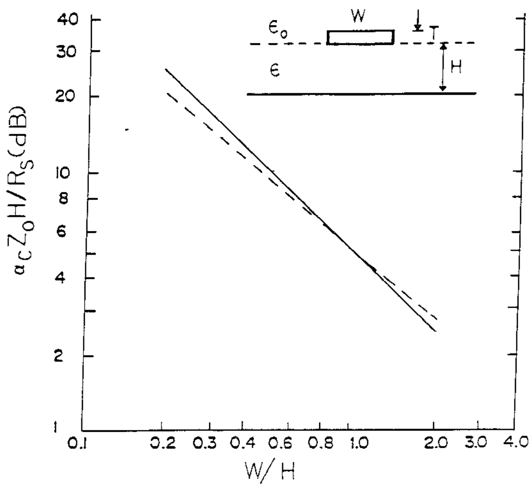
## V. Results and Discussion

The propagation characteristics of several structures consisting of single and coupled lines on lossy, anisotropic, and layered structures have been computed by utilizing the above techniques, and some typical results are presented here. In order to check the accuracy of our calculations, we have computed the propagation characteristics of some uniaxial and lossy structures for which either exact or reliable numerical results are available. In addition, propagation characteristics of other layered, multilevel structures are included to demonstrate the versatility of this technique.

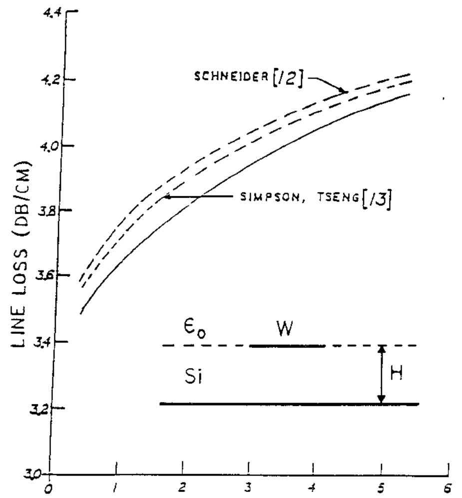
Table I shows the capacitance and resistance per unit length between two coplanar strips (width $W$ separated by a distance $S$) deposited on doped silicon with $\sigma = 0.1/\text{m}$, $\epsilon = 11.7\,\epsilon_0$. The computed values for two sets of discretizations corresponding to 10 and 20 nodes on each strip are given in the table together with the exactly calculated values for this simple case obtained by conformal mapping as given by

$$C = \frac{\epsilon_{si}+\epsilon_0}{2}\frac{K'(k)}{K(k)} \quad R = \frac{2K(k)}{\sigma K'(k)} \qquad (20)$$

where $K(k)$ is the complete elliptic integral of the first




(a)




(b)

Fig. 3. (a) Attenuation constant due to finite conductivity of the strip. ——— computed values, ---- from [11]. (b) Dielectric loss for microstrip on Silicon ($\sigma = 1.0$ Ω/m).

kind and

$$k = S/(S+2W)$$
$$K'(k) = K(k')$$
$$k' = \sqrt{1-k^2}.$$

It is seen that the error in the computed capacitance and resistance values with $N = 40$ is around 2 percent and that the accuracy can be further improved by using larger number of nodes on the strips or by using a simple extrapolation scheme such as

$$C_{\text{extrap}} = C_{2N} + (C_{2N} - C_N). \tag{21}$$

The results obtained for the attenuation constant of a microstrip due to conductor and dielectric losses are shown in Fig. 3(a) and (b), respectively, together with the corresponding results obtained by Pucel *et al.* [11] and Simpson and Tseng [13]. Other results obtained for MIS lines are also found to be in good agreement with those in [10] and [15] for the range of conductivities in the lossy dielectric propagation region. Fig. 4 shows the effect of the line thickness on the propagation characteristics of microstrips on lossy substrates. The even- and odd-mode velocities calculated for some coupled microstrips on uniaxial substrates are given in Table II, together with the same values computed by Alexopoulos and Maas [17, table I]. Fig. 5 shows the microstrip parameters for an inverted microstrip studied by Spielman [14], together with his results.

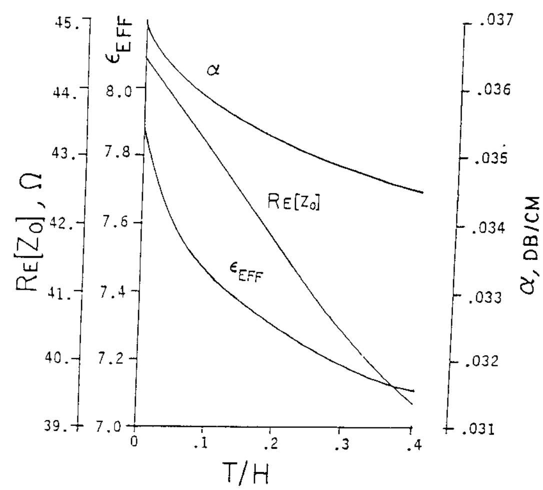



Fig. 4. Propagation characteristics as a function of microstrip thickness. Substrate silicon, $\sigma = 0.01$ Ω/m, $W = H$.

TABLE II
NORMAL-MODE PHASE VELOCITIES OF COUPLED MICROSTRIPS ON UNIAXIAL MEDIA

| | W/H | S/H | B/H | Calculated Velocities $\times 10^8$ m/s $v_{oe}$ | $v_{oo}$ | From [17] $\times 10^8$ m/s $v_{oe}$ | $v_{oo}$ |
|---|---|---|---|---|---|---|---|
| Epsilam Shielded | 0.700 | 0.260 | 2.55 | 1.187 | 1.193 | 1.207 | 1.210 |
| Epsilam Unshielded | 0.800 | 0.280 | > 6 | 1.107 | 1.192 | 1.138 | 1.204 |
| Alumina Unshielded | 0.875 | 0.260 | > 6 | 1.16 | 1.273 | 1.15 | 1.286 |
| Boron Nitride Shielded | 1.60 | 0.095 | 2.80 | 1.879 | 1.862 | 1.876 | 1.875 |
| Saphire Shielded (90° offset) | 0.690 | 0.225 | 2.20 | 1.265 | 1.255 | 1.256 | 1.257 |
| Saphire Unshielded | 0.730 | 0.260 | > 6 | 1.093 | 1.231 | 1.086 | 1.227 |

Fig. 6 shows the even- and odd-mode propagation characteristics of a pair of coupled microstrips on a Si–$SiO_2$ substrate as a function of the thickness of the two layers. The propagation characteristics of a simple symmetrical three-line–two-level structure chosen to demonstrate the application of this method to multilevel problems are shown in Fig. 7. Here the phase velocities of the three normal modes A (odd), and B (even–even), and C (even–odd) [18] are plotted as a function of the ratio of the thickness of the two dielectric layers.

It should be mentioned that the computation time for these calculations is dominated primarily by the CPU time required in inverting the $N \times N$ matrix associated with the nodes on the strips only and that the complexity of the configuration, including the number of columns, is only limited by the storage and the speed of the computer. Also,

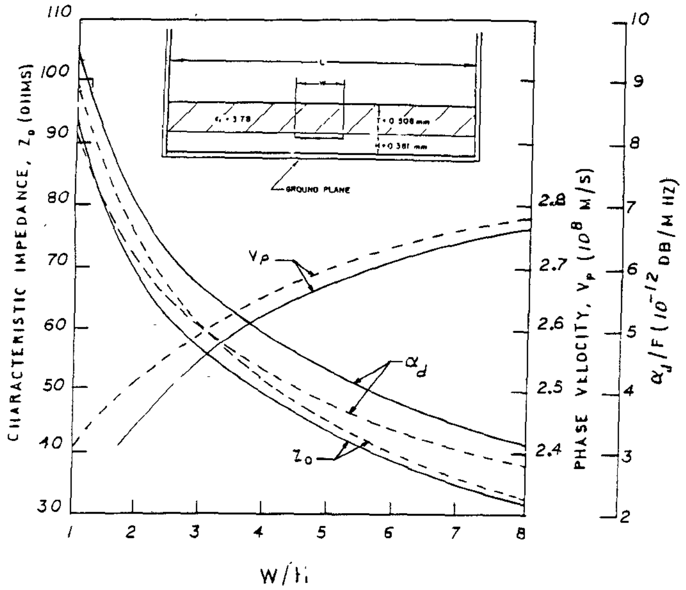



Fig. 5. Properties of inverted microstrip line.

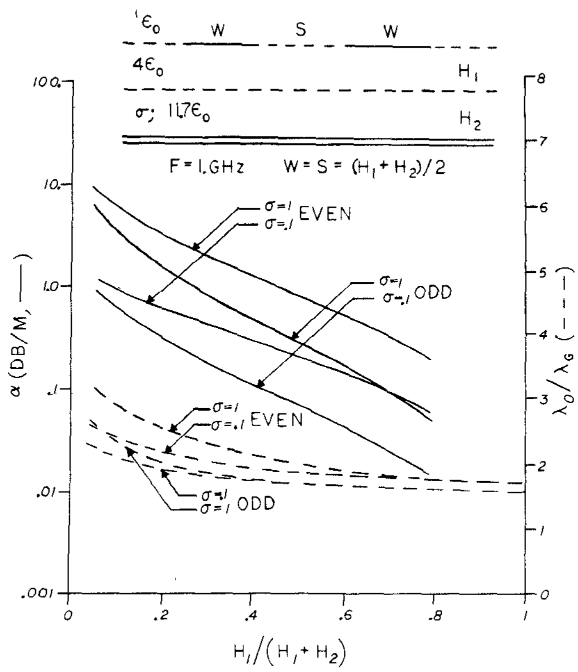



Fig. 6. Even- and odd-mode propagation constants for coupled microstrips on $Si-SiO_2$.

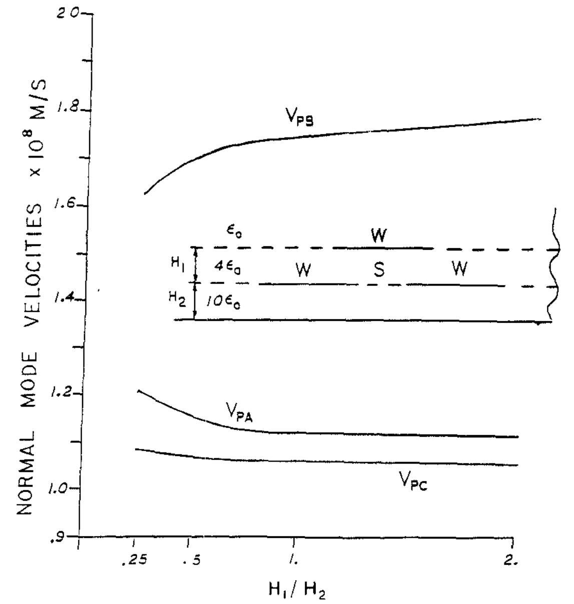



Fig. 7. Normal mode velocities of a two-level, symmetrical three-line structure $W = 2S = H_2$.

the method can be readily extended to three-dimensional quasi-static problems as shown by Chao [5] for lossless isotropic medium single-level structures.

## VI. Conclusion

In summary, a simple versatile method to compute all the parameters required for the computation of the quasi-TEM propagation characteristics of lossy layered structure with multilevel strips has been presented. The technique and results should be useful in the analysis of many structures where other more sophisticated techniques are either not available or become too cumbersome.

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