Spectral-Domain Computation of Characteristic Impedances and Multiport Parameters of Multiple Coupled Microstrip Lines

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Abstract —**The numerical procedure based on the spectral-domain techniques is formulated to compute all the frequency-dependent normal-mode parameters of general multiple coupled line structures in an inhomogeneous medium. In addition to the phase and attenuation constants for all the normal modes, these parameters include the line-mode and decoupled line modal impedances and the current and equivalent voltage eigenvector matrices of the coupled system. The multiport admittance (and impedance) matrices and coupled line equivalent circuit model parameters are evaluated in terms of these normal-mode parameters. Numerical results for these normal-mode parameters for typical asymmetric two-, three-, and four-line microstrip structures are included to demonstrate the procedure and the frequency dependence of these parameters.**

I. Introduction

A CONSIDERABLE amount of work has been done in recent years on the computation of the propagation characteristics of multiple coupled strips on a single substrate as well as in a layered medium including lossy and anisotropic medium (e.g., [1]–[12]). The propagation constants for these structures have been computed in the past by using the rigorous full-wave analysis [2]–[7]. However, works reporting on other design parameters such as characteristic impedance eigenvector matrices and the multiport network functions and equivalent circuit models have been confined primarily to the quasi-TEM analysis [1], [8]–[12].

Quasi-TEM structures are completely characterized for their properties in terms of all the self and mutual line constants (equivalent series impedance and shunt admittances per unit length) of the structure. For the lossless case consisting of N lines, these are the $N \mathrm{x} N$ inductance and the capacitance matrices. For the general lossy case, the $N \times N$ equivalent impedance and admittance matrices are symmetrical for passive systems and consist of $N(N+1)/2$ independent entries which depend on the structure configuration and geometry. That is, for a general N-line distributed parameter structure, $N(N+1)$ independent variables are needed to completely characterize the system. The general coupled line analysis leads to $N(N+1)$ independent normal-mode parameters which are required to study the circuit properties of the system. This number is reduced for special situations encountered for various structures such as physical symmetry or medium homogeneity. For example, the number is reduced by $2(N-1)$ for structures having physical symmetry and by $N-1$ for homogeneous systems where all the eigenvalues are degenerate.

The evaluation of the frequency- and time-domain response is facilitated by the derivation of the network functions (e.g., impedance, admittance, or scattering parameters) or the exact equivalent circuit models based on the properties of the structures. These network functions and equivalent circuit models have been derived in terms of the normal-mode parameters of the coupled line structure [8]–[15] for the quasi-TEM case and can be evaluated for the dynamic case based on the results obtained by the spectral domain or other full-wave techniques.

In this paper, starting from the known spectral-domain Green's function interrelating the strip currents and resulting electric fields [16]–[18], the procedure to compute all the frequency-dependent normal-mode parameters of a general multiple coupled strip structure in a layered medium is presented. Propagation constants (including attenuation constants), current and equivalent-voltage eigenvector components, line-mode impedances, and decoupled characteristic modal impedances are computed for typical multiple coupled line structures. These frequency-dependent normal-mode parameters are used to compute the $2N$ port network functions and equivalent circuit models used in the frequency and time-domain analysis and design of multiple coupled line circuits such as filters, couplers, and VLSI single and multilevel interconnections.

II. Theoretical Formulation

The numerical technique used to compute the phase constants for the dominant hybrid modes is well known and documented as the spectral-domain technique (e.g., [16]–[18]) and is not repeated here. The propagation constants are evaluated by applying the Galerkin method to the transformed Green's function matrix relating the cur-

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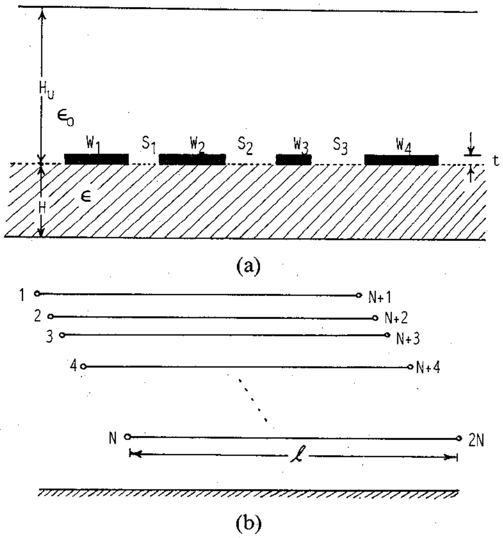

Fig. 1. (a) Cross section of multiple coupled microstrips. (b) Schematic of the multiple N coupled line $2N$ port.

rents and electric fields at various boundaries of the structure and solving for the roots of the determinant (e.g., [16]–[18]). For example, for a single-layer multiple strip structure (Fig. 1), the tangential components of the electric field at the interface are related to the surface currents by the Green's dyadic called the impedance matrix [18]. Expansion of surface currents in a set of basis functions and imposition of the condition that the tangential electric fields must be zero on the strips leads to a determinantal equation for unknown eigenvalues β. We have used Chebychev functions of first and second kind with edge terms for the basis functions to expand the longitudinal and transverse components of strip currents. That is, at a given interface the two components of surface currents are expanded as

$$J_z = \sum_{n=0}^{\infty} A_n J_{nz}$$

and

$$J_x = \sum_{m=1}^{\infty} B_m J_{mx} \tag{1}$$

$$J_{nz}(x) = \sum_{i=0}^{i=N} A_{nl} \frac{T_n(X_i)}{\sqrt{1-X_i^2}}, \qquad n = 0,1,2\cdots \tag{2}$$

$$J_{mx}(x) = \sum_{i=0}^{i=N} B_{mi} U_{m-1}(X_i) \cdot \sqrt{(1-X_i^2)}, \qquad m = 1,2,3\cdots \tag{3}$$

where

$$X_i = \frac{2}{W_i}\{x - x_i\}$$

with W_i being the width of the ith strip and x_i is the distance from origin to the center of the strip. In the transformed domain these currents are the well-behaved cylindrical Bessel functions which are readily calculated.

For each orthogonal normal mode the current distribution, the total strip current for each strip, and the resulting normalized electric and magnetic fields are computed in terms of the corresponding eigenvalue or the phase constant. These are used to compute the attenuation constant due to conductor and dielectric losses in a manner similar to the one used for single and symmetrical coupled lines [17]. The attenuation constant for each mode due to conductor and dielectric losses is computed from

$$\alpha_c = \frac{R_s \int |H_t|^2 \, dl}{2\,\mathrm{Re} \iint (E_x H_y^* - E_x H_y^*)\, dS}, \qquad \beta = \beta_m \text{ for mode } m \tag{4a}$$

$$\alpha_d = \frac{\sum_i \omega \epsilon_i \tan\delta_i \iint (|E_x|^2 + |E_y|^2 + |E_z|^2)\, dS_i}{2\,\mathrm{Re} \iint (E_x H_y^* - E_x H_y^*)\, dS} \tag{4b}$$

where R_s is the surface resistance, H_t is the tangential magnetic field at the conductor surface, and subscript i represents the ith dielectric layer having a dielectric constant ϵ_i and loss tangent $\tan\delta_i$.

A. The Current Eigenvector Matrix and the Characteristic Impedances

The normalized current eigenvector matrix $[M_I]$ and the characteristic impedances of the multiple coupled structure are also computed by using the solutions for the currents and field distribution associated with each mode.

The normalized current on each line for each mode represents the component of the current eigenvector, m_{lm}, for that mode and is calculated by integrating the current distribution for each strip. That is,

$$m_{lm} = \int_{W_l} J_z \, dx \quad \text{for } \beta = \beta_m, \qquad l, m = 1,2,\cdots N \tag{5}$$

with

$$(m_{1m}^2 + m_{2m}^2 + m_{3m}^2 + \cdots m_{Nm}^2) = 1, \qquad m = 1,2,\cdots N. \tag{6}$$

An equivalent voltage eigenvector matrix can also be defined by utilizing the orthogonality between the current and the voltage eigenvectors [9], [11] and is given by

$$[M_V] = \left[[M_I]^T\right]^{-1} \tag{7}$$

The elements of the equivalent voltage eigenvector corresponds to an equivalent line voltage associated with a given mode defined such that

$$P_{lm} = 1/2[\mathrm{Re}\{V_{lm} I_{lm}^*\}]. \tag{8}$$

V_{lm} is the normalized voltage on line l for mode m at low

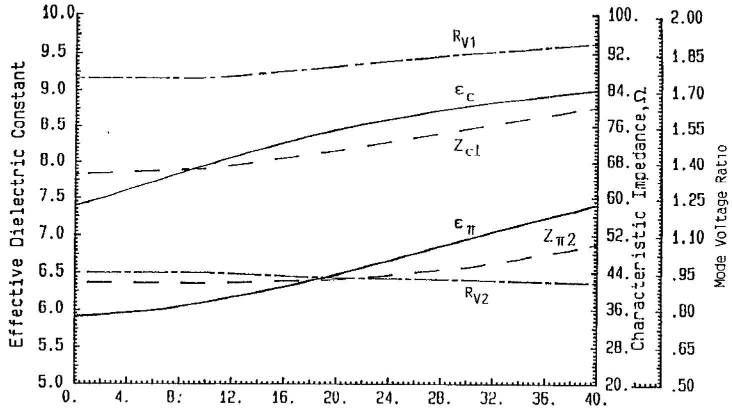

Fig. 2. Frequency-dependent normal-mode parameters of an asymmetric two-line structure. $H = 0.635$ mm, $H_u = 20$ mm, $W_1 = 0.6$ mm, $W_2 = 1.2$ mm, $S = 0.3$ mm, $\epsilon_r = 9.80$.

frequencies when quasi-TEM approximation is valid and a unique line voltage can be defined. Otherwise it may be considered as an equivalent voltage which leads to the same value for the power associated with line l for mode m as obtained by the integration of the associated Poynting vector.

Both line-mode and decoupled normal-mode impedances have been used in the past to calculate the frequency- and time-domain characteristics of the multiports [8], [9], [11], [13], [14]. The elements of line-mode impedance matrix z_{lm} are the characteristic impedances of line l for mode m. The lines must be terminated in these impedances in order to match all the lines when the given mode m is excited. These impedances have been used to evaluate the multiport impedances (admittances) and other parameters as demonstrated for asymmetric two- and symmetrical three-line structures in [19] and [20] in a closed form. In general, the multiport functions are computed by using the general solutions in a matrix form in terms of all the normal-mode parameters as shown in [8], [9], [11], and [12] for the quasi-TEM case. The decoupled modal impedance matrix $[Z]_c$ is diagonal and has been used in equivalent circuit representation of the coupled line system [8], [14].

It is seen that the line-mode impedance can be evaluated for all the hybrid modes in a straightforward manner by calculating the power associated with a given line for a given mode and the corresponding line current. We have formulated these impedances in terms of the now accepted power–current definition of the characteristic impedance of microstrip-like structures in an inhomogeneous medium, e.g., the line-mode impedances are given by

$$z_{lm} = \frac{\text{power associated with line } l \text{ for mode } m\,(=P_{lm})}{(\text{normalized current in line } l \text{ for mode } m)^2\,(=I_{lm}^2)} \tag{9}$$

where P_{lm} is calculated by integrating the Poynting vector over the total cross section when the current distribution on line l corresponds to the solution for currents when $\beta = \beta_m$ and all the other line currents are zero. The total power associated with mode m is then the sum of power

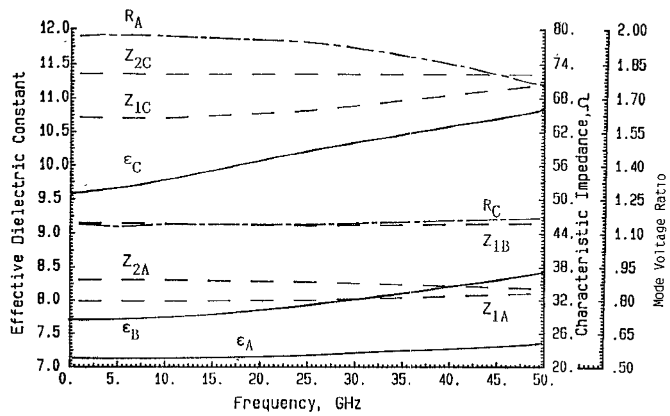

Fig. 3. Normal-mode parameters of a symmetrical three-line structure. $H = 200$ μm, $W_1 = W_2 = W_3 = 150$ μm, $S_1 = S_2 = 150$ μm, $\epsilon_r = 12.9$.

associated with each line for that mode. That is,

$$P_{\text{total},\,m} = P_{1m} + P_{2m} + P_{3m} + \cdots P_{Nm}, \qquad l, m = 1,2,3,\cdots N \tag{10}$$

$$= \text{Re} \iint \left(E_x H_j^* - E_y H_x^* \right) dS. \tag{11}$$

B. The Multiport Parameters and the Equivalent Multiple Coupled Line System

The coupled line multiport can now be analyzed for its frequency- and time-domain characteristics by using either the complex network functions or the equivalent circuit consisting of uncoupled lines and decoupling and coupling transformer banks for the dependent sources [8], [11].

The admittance, impedance, and scattering parameters can be computed for the structure by utilizing the expressions for these parameters in terms of the normal-mode parameters. For example, the admittance matrix for the $2N$ port is given by [13], [14]

$$[Y] = \begin{bmatrix} [Y_a] & [Y_b] \\ [Y_b] & [Y_a] \end{bmatrix} \tag{12}$$

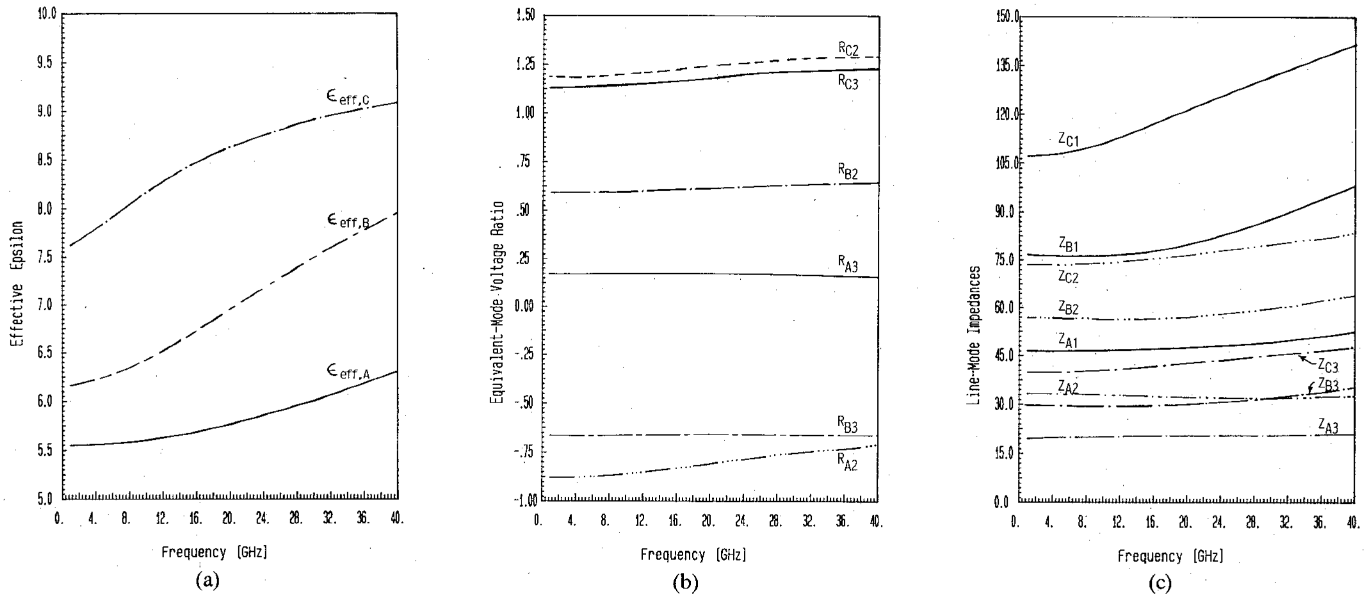

Fig. 4. Frequency-dependent normal-mode parameters of a general three-line structure. $H = 0.635$ mm, $H_u = 20$ mm, $W_1 = 0.3$ mm, $S_1 = 0.2$ mm, $W_2 = 0.6$ mm, $S_2 = 0.4$ mm, $W_3 = 1.2$ mm, $\epsilon_r = 9.8$. (a) Effective dielectric constants for the three modes. (b) Equivalent voltage eigenvector matrix elements. The three eigenvectors ae $[1, R_{A2}, R_{A3}]$, $[1, R_{B2}, R_{B3}]$, and $[1, R_{C2}, R_{C3}]$. (c) Line-mode impedances Z_{ij} with $i = A, B, C$ and $j = 1,2,3$.

with

$$[Y_a] = [Y_{lm}] * [M_V][\coth(\gamma_i l)]_{\text{diag}}[M_I]^T$$

and

$$[Y_b] = [Y_{lm}] * [M_V][\text{csch}(\gamma_i l)]_{\text{diag}}[M_I]^T.$$

In the above equations a product matrix has been defined [14] in accordance with the definition that for $[C] = [A]*[B]$ the elements of matrix $[C]$ are the product of the corresponding terms of the two matrices $[A]$ and $[B]$. That is, $c_{ij} = a_{ij}b_{ij}$. The above submatrices $[Y_a]$ and $[Y_b]$ have also been expressed in terms of the diagonal modal admittance (impedance) matrix [11], [12] and are given by

$$[Y_a] = [M_V]^T[Y_c]_{\text{diag}}[\coth(\gamma_i l)]_{\text{diag}}[M_I]^T$$

and (13)

$$[Y_b] = [M_V]^T[Y_c]_{\text{diag}}[\text{csch}(\gamma_i l)]_{\text{diag}}[M_I]^T.$$

It should be noted that an equivalent multiple coupled transmission-line system having distributed self and mutual series impedances and shunt admittances can also be defined in order to model the coupled lossy dispersive system and the resulting multiport circuit. For the lossless N line case (Fig. 1(b)) the system is defined in general by two $N \times N$ frequency-dependent equivalent capacitance and inductance matrices which are symmetrical. The conductor and dielectric losses are represented by frequency-dependent series resistance and shunt conductance, respectively, of this equivalent transmission line system. For example, for the lossless case the $N \times N$ equivalent inductance and capacitance matrices are found by expressing the eigenvalues, eigenvectors, and line-mode impedances derived in terms of the $[L]$ and $[C]$ matrices [8], [9], [11] and solving for the $[L]$ and $[C]$ matrices. The solution for the equivalent $[L]$ and $[C]$ matrices is found to be

$$[L]_{\text{equivalent}} = [M_I]*[Z_{lm}][\beta_m]_{\text{diag}}[M_I]^{-1}$$

and (14)

$$[C]_{\text{equivalent}} = [M_V]*[Y_{lm}][\beta_m]_{\text{diag}}[M_V]^{-1}.$$

The above expressions have been verified by comparing the matrix elements with those obtained directly from a quasi-TEM program at low frequencies for a three- and a four-line system [21], [22]. At low frequencies the values obtained are the same as the ones obtained by using the quasi-TEM techniques.

III. Numerical Results

A computer program has been written to evaluate all the normal-mode parameters and the multiport network functions of general coupled microstrips in accordance with the procedure outlined in the previous section.

The accuracy of the computer program was checked by comparing the results obtained by this program with known frequency-dependent results for single and symmetrical coupled strips [17] and quasi-TEM results for general multiple strip cases at low frequencies [21], [22]. The computer program has been used on personal computers including IBM AT's as well as larger machines including VAX 780. It is seen that the choice of Chebychev polynomials for basis functions results in rapid convergence and only two terms for J_z and one term for J_x result in reasonably accurate results unless the lines are very tightly coupled, in which case more terms are required. The CPU time depends on the structure configuration including the

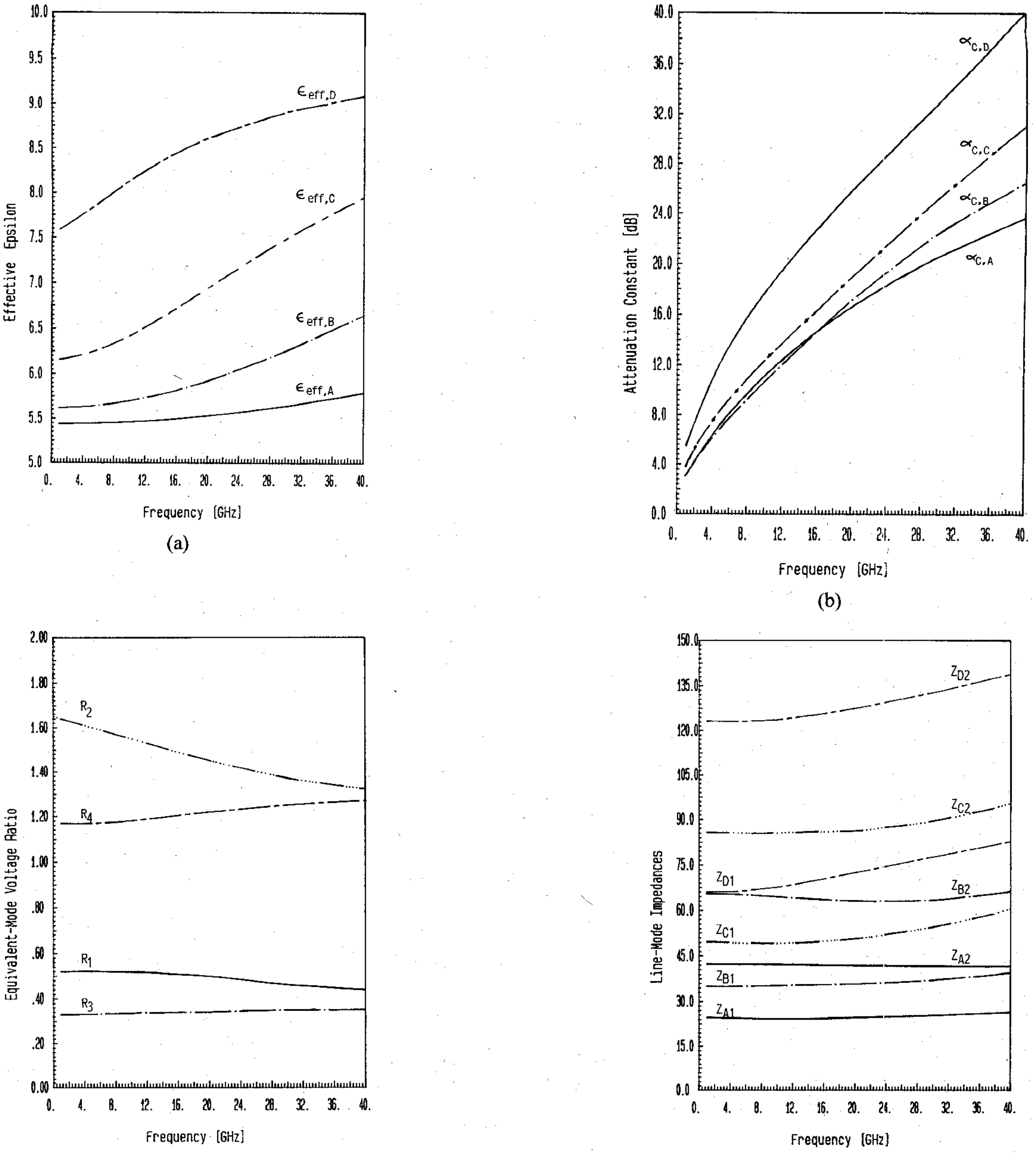

Fig. 5. Frequency-dependent normal-mode parameters of a symmetrical four-line structure. $H = 0.635$ mm, $H_u = 50$ mm, $W_1 = 0.6$ mm, $S_1 = 0.3$ mm, $W_2 = 0.3$ mm, $S_2 = 0.2$ mm, $W_3 = 0.3$ mm, $S_3 = 0.3$ mm, $W_4 = 0.6$ mm, $\epsilon_r = 9.8$. (a) Effective dielectric constants for the four normal modes. (b) Attenuation constants due to conductor loss for the four modes. (c) Equivalent mode voltage ratios. The four eigenvectors for this case are defined in the text. (d) Line-mode impedances. $Z_1 = Z_4$ and $Z_2 = Z_3$ for all modes due to symmetry.

number of lines and the machine used for computations and may range from a few seconds to a few minutes.

Figs. 2 and 3 show the effective dielectric constants, impedances, and equivalent mode voltage ratios for typical asymmetric two-line and symmetric three-line structures. For these two cases, closed-form expressions for the four- and six-port admittances (impedances), respectively, have been derived in terms of normal-mode parameters and the equivalent self and mutual line constants of the system [19], [20]. For the asymmetric two-line case, c and π refer to the two normal modes, and R_{V1} and R_{V2} are the mode voltage ratios. Their definitions and the expressions for the four-port impedance and admittance matrix in terms of these parameters are given in [19]. For the symmetrical three-line structure A, B, and C refer to the three normal modes and the equivalent voltage eigenvectors are $[1, R_A, 1]$, $[1, 0, -1]$, and $[1, R_C, 1]$. The expressions for the six-port impedance or admittance matrix in terms of these normal-mode parameters are given in [20].

Results for a general three-line and a symmetric four-line structure are shown in Figs. 4 and 5 to demonstrate the behavior of all the normal-mode parameters as a function of frequency. For the three-line structure, even though three eigenvalues, six mode voltage ratios representing the eigenvector matrix, and nine impedances are plotted as a function of frequency, only three-line mode impedances are independent (e.g., Z_{A1}, Z_{B1}, and Z_{C1} for line 1 for the three modes) and the others can be derived from these by using the orthogonality between the voltage and the current eigenvector for a given mode. The general three-line system has 12 independent normal-mode parameters required for the analysis and design of the six port.

The symmetrical four-line structure with $W_1 = W_4$, $W_2 = W_3$, and $S_1 = S_3$ results in $Z_{m1} = Z_{m4}$ and $Z_{m2} = Z_{m3}$ and an equivalent voltage eigenvector matrix as given by

$$[M_V] = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -R_1 & -R_2 & R_3 & R_4 \\ R_1 & -R_2 & -R_3 & R_4 \\ -1 & 1 & -1 & 1 \end{bmatrix}.$$

Note that for this case the number of independent equivalent line constants or normal-mode parameters is 14 because of symmetry. This number would be 20 for a general four-line structure without symmetry.

IV. Concluding Remarks

In conclusion, the full-wave spectral-domain technique for the computation of all the frequency-dependent normal-mode parameters and the resulting multiport network functions for general multiple coupled inhomogeneous transmission lines has been presented. Even though the paper deals primarily with coupled microstrips, the procedure presented is a general one and can be applied to other coupled propagation structures such as coupled slots, fin lines, and dielectric waveguides. The results for all the frequency-dependent propagation characteristics including multiport terminal parameters should be quite useful in the analysis and design of multiple coupled line structures such as couplers, filters, and transformers at higher frequencies where the effects of losses and dispersion become significant.

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