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Two-Layer Circuit Elements Suitable for Integration with Monolithic MICs

by

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Abstract

A general procedure for the analysis of multiple conductor coupled transmission line systems in an inhomogeneous dielectric medium is presented and used for the analysis and design of various two-layer circuit elements suitable for integration with monolithic microwave integrated circuits. The multiple conductor transmission line model used assumes quasi-TEM modes propagating on a lossless line. Quasi-static line parameters characterize normal modes of propagation on the multiple conductor transmission line. From normal mode parameters, a network representation in the form of an impedance matrix is found for a coupled line section. With the impedance matrix and a set of port terminating impedances, a scattering parameter representation is found and used to evaluate circuit performance.

Analysis procedures and algorithms are implemented in FORTRAN programs. Inputs to programs are the quasi-static capacitance and inductance coefficients of the transmission line and scattering parameters are output.

The two-layer circuit elements investigated include a two conductor 3 dB coupler or hybrid, a three conductor re-entrant mode coupler, and a planar balun.
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CHAPTER I
INTRODUCTION

1.1 Motivation

Most of the current monolithic microwave integrated circuit (MMIC) designs make use of a single layer topology for passive components. For example, transmission lines or coupled lines are fabricated using a metalization layer located at the top surface of a grounded substrate such as Gallium Arsenide (GaAs). Of course, metal insulator metal (MIM) capacitors and air bridges are exceptions.

Typically in MMIC's, a thin layer of silicon nitride ($\text{Si}_3\text{N}_4$) or polyamide is grown over the GaAs substrate in order to passivate the MMIC surface. If an additional metalization layer were added on top of this passivating layer, it could be used in the design of two-layer passive components. Such two-layer components could be used to increase the density and enhance the functionality of monolithic circuits.

One of the advantages of a two-layer topology over a single layer configuration is that tighter coupling in transmission line couplers can be achieved. Broadside coupled line designs permitted by a two-layer structure can
achieve tighter coupling than edge coupled microstrips at a single level. Limits on gap fabrication restrict single layer couplers to loose coupling. Use of a two-layer structure thus opens up a range of possibilities for designing wide-band 3-dB couplers without using interdigitated designs such as the Lange design [1],[2].

Another useful component possible with the tight coupling available in two layer structures is the broadband balun. Such unbalanced to balanced line transformers could be used in mixer designs or for the excitation of class B push-pull amplifiers.

1.2 Objectives

In this research, an analysis procedure for a general coupled transmission line has been developed. Starting with characteristic line parameters, a multi-port characterization in the form of scattering parameters is found. This scattering parameter representation has been used to evaluate the performance of several specific coupled transmission line systems.

Implementation of the coupled transmission line analysis procedure has been carried out in the form of FORTRAN programs. This analysis software is used for the analysis of various passive circuit elements. These include a two-line directional coupler of a two-layer topology, a monolithic re-entrant type coupler, and a
planar version of the Marchand balun.

1.3 Review of Related Work

Wave propagation in coupled transmission line systems has been a research topic of continued interest because of its importance in many engineering problems. The simplest coupled line system to analyze, and one of the earliest investigated, is that of two identical coupled lines in a homogeneous medium [3],[4].

With the advances in integrated circuit technology, the study of properties and applications of coupled lines in an inhomogeneous medium, such as coupled microstrip lines, has become important. The network parameters for inhomogeneous symmetrical coupled lines have also been derived [5].

The theory of non-symmetric coupled systems in an inhomogeneous medium has also been addressed. Procedures have been developed for studying systems of two asymmetric coupled lines [6] and three symmetrical coupled lines [7],[8] in terms of their characteristic line parameters. Recent research addresses the analysis of general N-conductor coupled transmission line systems in inhomogeneous media [9].

Design procedures for directional couplers in a homogeneous medium are well documented [3],[4]. Directional couplers in inhomogeneous media, such as
microstrip couplers, have also been investigated and various design data is available. Although many references are available for design of directional couplers, no design procedure for two-layer couplers is readily available.

A re-entrant type coupler which utilizes the two-layer configuration has been developed [10]. Similarly, a planar balun has been fabricated [11] using a two-layer topology. The analysis procedure given in this work can be helpful in the design of such two-layer elements.

1.4 Outline of Report

In Chapter II, a procedure for the analysis of coupled transmission line systems is described. Starting with characteristic line parameters, normal mode parameters and the impedance or admittance characterization of a general coupled line system are found. For the specific cases of two asymmetric, and three symmetric coupled line systems, closed form expressions for impedance matrix elements are given in terms of characteristic line parameters. A procedure for the analysis of general N-conductor coupled transmission line systems is then presented.

In Chapter III, the analysis procedures described in Chapter II are applied to the analysis of two-layer directional couplers. A two line 3-dB directional coupler in a two-layer configuration is analyzed and calculated coupler performance as well as intermediate results are
presented. Comparison of this coupler with a single level microstrip coupler is also given. A monolithic re-entrant type coupler is then analyzed and its performance results are presented. An "inverted" re-entrant type coupler is also analyzed and comparison is made between the two re-entrant couplers.

Chapter IV is devoted to the study of the planar Marchand balun. This balun consists of two coupled line sections which are analyzed using procedures given in Chapter II. These sections are then combined using an impedance matrix segmentation procedure and overall balun performance is investigated. An analysis example is presented and intermediate data and calculated balun performance are reported.
CHAPTER II

MODELING OF MULTIPLE CONDUCTOR TRANSMISSION LINES

2.1 General Formulation

The multiple conductor transmission line model used in this research begins with a quasi-static analysis of transmission line structures of a two level configuration to obtain characteristic line parameters (inductance, resistance, capacitance, and conductance coefficients) of the coupled line system. These line parameters characterize normal modes of propagation on the multiple conductor transmission line. The normal mode parameters can be used to find a multi-port characterization of a transmission line section as given by an impedance or admittance matrix. With this port characterization and a set of port termination impedances, a scattering parameter representation can be found and used to evaluate the performance of a multiple coupled line section.

For the inhomogeneous, lossless coupled transmission line systems under consideration, pure transverse electromagnetic (TEM) modes of propagation are not supported. It is reasonable, however, that at relatively low frequencies the transmission line would behave approximately according
to the line parameter values predicted by static calculations. The frequency range for which this assumption is valid is referred to as the quasi-static approximation range. The assumption is adequate for designing circuits at low enough frequencies where the strip widths and substrate thickness are much smaller than the wavelength in the dielectric material. A rule of thumb for the range of validity [12] is that it holds good within one percent, provided the substrate thickness is not greater than about three percent of the associated wavelength. For certain structures the quasi-static approximation can be valid up to fairly high frequencies (X-band).

Another approximation used in this formulation is that the transmission lines are considered to be lossless. For the typical applications investigated, losses are small and can be neglected. When losses are neglected a simplification can be made in the analysis of the coupled line system.

A coupled transmission line system is one in which the voltage and current on the conductor of one line depends on the voltages and currents on the conductors of all other lines. Consider the fundamental equations governing voltages and currents on a multiple conductor transmission line system:
\[
\frac{\partial}{\partial z} \mathbf{v}(z, t) = -[L] \frac{\partial}{\partial t} \mathbf{i}(z, t) - [R] \mathbf{i}(z, t) \tag{2.1a}
\]

\[
\frac{\partial}{\partial z} \mathbf{i}(z, t) = -[C] \frac{\partial}{\partial t} \mathbf{v}(z, t) - [G] \mathbf{v}(z, t) \tag{2.1b}
\]

Here, \( \mathbf{v} \) and \( \mathbf{i} \) are column vectors representing voltages and currents respectively on the lines. Characteristic line parameters are written in matrix form where \([L],[R],[C]\), and \([G]\) contain coefficients of inductance, resistance, capacitance, and conductance respectively. Losses are accounted for by resistance and conductance coefficients of the lines. When these are neglected (2.1) becomes:

\[
\frac{\partial}{\partial z} \mathbf{v}(z, t) = -[L] \frac{\partial}{\partial t} \mathbf{i}(z, t) \tag{2.2a}
\]

\[
\frac{\partial}{\partial z} \mathbf{i}(z, t) = -[C] \frac{\partial}{\partial t} \mathbf{v}(z, t) \tag{2.2b}
\]

Because we are considering time harmonic modes propagating along the line as \( e^{-j(\beta z - \omega t)} \), (2.2) can be written as

\[-j\beta \mathbf{v} = -j\omega [L] \mathbf{i} \tag{2.3a}\]

\[-j\beta \mathbf{i} = -j\omega [C] \mathbf{v} \tag{2.3b}\]

This is a system of coupled equations in \( \mathbf{v} \) and \( \mathbf{i} \) which can be decoupled to give relations containing voltages only or
currents only as

\[
[L] \{V\} = \frac{\beta^2}{\omega^2} \{V\} \tag{2.4a}
\]

\[
[C] \{I\} = \frac{\beta^2}{\omega^2} \{I\}. \tag{2.4b}
\]

It can be seen that finding the propagation constants and the normal modes of propagation for the voltages and currents of a multiple conductor transmission line is accomplished by solving these matrix eigenvalue and eigenvector problems. The solutions are in terms of the characteristic inductance and capacitance coefficients. One must find values of \([L]\) and \([C]\) for the configurations of interest in order to examine properties of the normal modes of propagation.

Definitions of line parameters \([L]\) and \([C]\) can be understood by considering the coupled line system depicted in Figure 2.1. Capacitance and inductance coefficients are written in the matrix form

\[
[C] = \begin{bmatrix}
C_{11} & C_{12} & \cdots & C_{1N} \\
C_{12} & C_{22} & \cdots & C_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
C_{1N} & C_{2N} & \cdots & C_{NN}
\end{bmatrix}
\]

\[
[L] = \begin{bmatrix}
L_{11} & L_{12} & \cdots & L_{1N} \\
L_{12} & L_{22} & \cdots & L_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
L_{1N} & L_{2N} & \cdots & L_{NN}
\end{bmatrix}
\]
Figure 2.1 Incremental Equivalent Circuit. a) Capacitive elements of N-line, b) Inductive elements of N-line.
where $C_{ij}$ is the capacitance per unit length between the $i^{th}$ and $j^{th}$ lines, defined negative. The self capacitance per unit length of the $i^{th}$ line is defined by

$$C_{ii} = C_{ig} - \sum_{j \neq i}^{N} C_{ij}$$

where $C_{ig}$ is the capacitance per unit length between the $i^{th}$ line and the ground line. The mutual inductance per unit length between the $i^{th}$ and $j^{th}$ lines is given by $L_{ij}$ and the self inductance per unit length of the $i^{th}$ line is given by $L_{ii}$.

Capacitance and inductance parameters of a given structure can be found by electrostatic and magnetostatic calculations for the structure. It can be noted that calculations of the line parameters can be reduced to an electrostatic calculation only. Consider a pure TEM transmission line system in a homogeneous medium of free space or air (denoted by the subscript 0). There exists only one phase velocity; that of electro-magnetic waves in free space or air. Using the relationship between phase velocity and propagation constant

$$v_{ph} = \frac{\omega}{\beta}$$

(2.5)

and noting that the phase velocity of an electro-magnetic wave in free space is given by
\[ v_{ph} = \frac{1}{\sqrt{\varepsilon \mu_0}} \]  

(2.6)

we find that the eigenvalues of (2.4), which are completely degenerate, can be written as:

\[ \frac{\beta^2}{\omega^2} = \frac{1}{v_{ph}^2} = \varepsilon \mu_0 \]

(2.7)

This is only possible when the matrices \([L_o]\) and \([C_o]\) have the relationship of congruence, namely

\[ [L_o] [C_o] = [C_o] [L_o] = \varepsilon \mu_0 \]

(2.8)

Because the materials of interest are non-magnetic, the inductance coefficients of the inhomogeneous dielectric structure and the equivalent homogeneous free space structure are the same. The inductance coefficients can thus be written in terms of the capacitance coefficients of the homogeneous free space structure as

\[ [L] = \varepsilon \mu_0 [C_o]^{-1} \]

(2.9)

Line parameters can be found by electrostatic calculations of capacitance coefficients for the given inhomogeneous dielectric structure and the equivalent structure in a homogeneous medium of free space.

The line parameters can be found by solving Laplace’s or Poisson’s equations for the capacitive coefficients of
coupling by utilizing various techniques [13]. These include numerical methods such as the finite difference method, the finite element method, and integral equation methods. In this research, methods for obtaining solutions for line parameters are not investigated. Line parameters are calculated by means of available software [14],[15].

The eigenvalues of equations (2.4) contain information about normal mode propagation constants, phase velocities, and effective dielectric constants. By using the relationship between propagation constants and phase velocities, the normal mode phase velocities can be found as

\[ v_{ph\,n} = \frac{\omega}{\beta_n} . \]  

(2.10)

Here \( n = 1,2,\ldots,N \) denotes the normal mode where \( N \) is the number of lines. Normal mode effective dielectric constants are defined by

\[ \epsilon_{\text{eff\,n}} = \frac{v_{ph\,n}^2}{v_{ph\,n}^2} = \frac{1}{\epsilon_0 \mu_0 \omega^2} . \]  

(2.11)

Information about voltages and currents on the lines is contained in the voltage and current eigenvectors which can be written
\[
\begin{align*}
V_{1n} & \quad I_{1n} \\
V_{2n} & \quad I_{2n} \\
V_n & \quad I_n \\
V_{Nn} & \quad I_{Nn}
\end{align*}
\]

Characteristic impedances or admittances of the normal modes on the lines can be defined in terms of voltages and currents as

\[
Z_{in} = \frac{1}{Y_{in}} = \frac{V_{in}}{I_{in}}.
\]

(2.12)

Here \(Z_{in}\) and \(Y_{in}\) are the characteristic impedance and admittance respectively on the \(i^{th}\) line for the \(n^{th}\) mode. Using equation (2.3b) the currents are given by

\[
I_{in} = v_{ph} n \sum_{k=1}^{N} C_{ik} V_{kn}.
\]

(2.13)

The normal mode characteristic impedances and admittances can be written in terms of phase velocities, capacitance coefficients, and voltages only as

\[
Z_{in} = \frac{1}{Y_{in}} = \frac{V_{in}}{v_{ph} n \sum_{k=1}^{N} C_{ik} V_{kn}}.
\]

(2.14)

For a given length of transmission line, an impedance or admittance matrix representation for the 2N ports can be found by solving port voltage-current relationships. This is demonstrated in the following sections. Once this
multi-port representation is found and port terminating impedances are given, a scattering parameter characterization of the 2N-port network can be found.

2.2 Two Asymmetric Coupled Lines

The coupling characteristics for two symmetric coupled lines in a homogeneous medium are well known [3],[4]. For this case of coupled TEM lines, coupled line parameters are obtained in terms of characteristic impedances or admittances for even and odd modes of excitation. These even and odd modes correspond to cases where the voltages and currents on the two lines are equal in magnitude and in phase for the even mode and out of phase for the odd mode.

For the case of two asymmetric coupled lines in an inhomogeneous medium (Figure 2.2),[6], the even and odd TEM modes are not supported on the lines. The two independent modes of excitation which correspond to even and odd modes become the common and pi modes (denoted c and pi). These modes correspond to a linear combination of voltages and currents on the two lines which are related in magnitude and phase through terms involving line constants.

Four-port circuit parameters are obtained by writing solutions for voltages and currents on the two lines in terms of the two independent modes and deriving port voltage and current relationships in a suitable form leading to impedance or admittance parameters.
Figure 2.2 Asymmetric coupled line 4-port.

The capacitance and inductance matrices for two asymmetric coupled lines are written as

$$
[c] = \begin{pmatrix} C_{11} & C_{12} \\ C_{12} & C_{22} \end{pmatrix}
$$

$$
[l] = \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

The characteristic product matrix in equation (2.4a) is of the form

$$
[a] = [l][c] = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}
$$

for which
\[ A_{11} = L_{11} C_{11} + L_{12} C_{12} \]
\[ A_{12} = L_{11} C_{12} + L_{12} C_{22} \]
\[ A_{21} = L_{12} C_{11} + L_{22} C_{12} \]
\[ A_{22} = L_{12} C_{12} + L_{22} C_{22} \]

The eigenvalues which are solutions of (2.4a) satisfy

\[ \det([A] - \frac{\beta^2}{\omega^2} [\mathcal{U}]) = 0 \]  \hspace{1cm} (2.15)

where \([\mathcal{U}]\) is the identity matrix. This equation can be solved for the eigenvalues of the two normal modes of propagation of the system as

\[ \left(\frac{\beta^2}{\omega^2}\right)_{c,\pi} = \frac{A_{11} + A_{22}}{2} \pm \sqrt{(A_{11} - A_{22})^2 + 4A_{12}A_{21}} \frac{1}{2} \]

Phase velocities of the common and pi modes are thus given by

\[ v_{ph\,c,\pi} = \left[ \frac{A_{11} + A_{22}}{2} \pm \sqrt{(A_{11} - A_{22})^2 + 4A_{12}A_{21}} \right]^{-\frac{1}{2}} \]

and corresponding mode effective dielectric constants follow from equation (2.11) as

\[ \varepsilon_{eff\,c,\pi} = \left( \frac{v_{ph\,c,\pi}}{v_{ph\,c,\pi}} \right)^2 \]

Voltage eigenvectors which are solutions to (2.4a), when normalized with respect to the first line, can be written

\[ v_c = \frac{1}{R_c} \quad , \quad v_\pi = \frac{1}{R_\pi} \]
where

\[ R_c = \frac{V_{2c}}{V_{1c}} \quad \text{and} \quad R_\pi = \frac{V_{2\pi}}{V_{1\pi}} \]

These voltage ratios are found to be

\[ R_{c,\pi} = \frac{A_{22} - A_{11}}{2A_{12}} \pm \sqrt{\frac{(A_{11} - A_{22})^2 + 4A_{12}A_{21}}{4A_{12}^2}} \]

Characteristic impedances and admittances follow from equation (2.14) as

\[ Z_{2c,\pi} = \frac{1}{Y_{2c,\pi}} = \frac{1}{V_{ph\,c,\pi} [C_{11} + R_{c,\pi}C_{12}]} \]

\[ Z_{2c,\pi} = \frac{1}{Y_{2c,\pi}} = \frac{R_{c,\pi}}{V_{ph\,c,\pi} [C_{12} + R_{c,\pi}C_{22}]} \]

The general solutions of equation (2.4a) for voltages on the two lines are

\[ V_1 = B_1 e^{-j\beta x} + B_2 e^{-j\beta_\pi x} + B_3 e^{+j\beta_\pi x} + B_4 e^{+j\beta x} \]

\[ V_2 = B_1 R_c e^{-j\beta x} + B_2 R_\pi e^{-j\beta_\pi x} + B_3 R_c e^{+j\beta_\pi x} + B_4 R_\pi e^{+j\beta x} \]

where \( B_i \) (i = 1, 2, 3, 4) are arbitrary amplitude coefficients. These solutions represent forward and backward traveling voltage waves for the two modes on the two lines. The solutions for currents can be found from the voltage solutions by using the relationship between mode voltages.
and currents given by equation (2.12)

\[ I_{in} = Y_{in}V_{in} \]

where \( i = 1,2 \) denotes the line and \( n = c,pi \) denotes the mode. With this, the general solutions for currents are written as

\[ I_1 = Y_{1c}B_1e^{-j\beta_cz} + Y_{1n}B_2e^{-j\beta_nz} - Y_{1c}B_3e^{+j\beta_cz} - Y_{1n}B_4e^{+j\beta_nz} \]

\[ I_2 = Y_{1c}R_cB_1e^{-j\beta_cz} + Y_{1n}R_nB_2e^{-j\beta_nz} - Y_{1c}R_cB_3e^{+j\beta_cz} - Y_{1n}R_nB_4e^{+j\beta_nz} \]

The impedance or admittance matrix for a four-port coupled line section (Figure 2.2) can now be found. For instance, the impedance matrix is found by solving for port voltages in terms of port currents. If we take ports 1 and 2 to be at \( z = 0 \) and ports 3 and 4 to be at \( z = 1 \), port voltages and currents become

\[
\begin{align*}
V_1 &= 1 & 1 & 1 & 1 & B_1 \\
V_2 &= R_c & R_n & R_c & R_n & B_2 \\
V_3 &= e^{-j\beta_{cl}} & e^{-j\beta_{nl}} & e^{+j\beta_{cl}} & e^{+j\beta_{nl}} & B_3 \\
V_4 &= R_c e^{-j\beta_{cl}} & R_n e^{-j\beta_{nl}} & R_c e^{+j\beta_{cl}} & R_n e^{+j\beta_{nl}} & B_4 \\
\end{align*}
\]

\[
\begin{align*}
I_1 &= Y_{1c} & Y_{1n} & -Y_{1c} & -Y_{1n} & B_1 \\
I_2 &= Y_{2c}R_c & Y_{2n}R_n & -Y_{2c}R_c & -Y_{2n}R_n & B_2 \\
I_3 &= -Y_{1c}e^{-j\beta_{cl}} & -Y_{1n}e^{-j\beta_{nl}} & Y_{1c}e^{+j\beta_{cl}} & Y_{1n}e^{+j\beta_{nl}} & B_3 \\
I_4 &= -Y_{2c}R_c e^{-j\beta_{cl}} & -Y_{2n}R_n e^{-j\beta_{nl}} & Y_{2c}R_c e^{+j\beta_{cl}} & Y_{2n}R_n e^{+j\beta_{nl}} & B_4 \\
\end{align*}
\]

Elimination of the arbitrary amplitude coefficients \( B_i \) leads to the four-port impedance matrix representation
\[ V = [Z] I \]

for which \( Z \)-matrix elements are given as

\[ Z_{11} = Z_{33} = -j \left( \frac{Z_{1c} \cot \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} \cot \beta_\pi l}{1 - R_\pi/R_c} \right) \]

\[ Z_{12} = Z_{21} = Z_{34} = Z_{43} = -j \left[ \frac{Z_{1c} R_c \cot \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} R_\pi \cot \beta_\pi l}{1 - R_\pi/R_c} \right] \]

\[ Z_{13} = Z_{31} = -j \left[ \frac{Z_{1c} \csc \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} \csc \beta_\pi l}{1 - R_\pi/R_c} \right] \]

\[ Z_{14} = Z_{41} = Z_{23} = Z_{32} = -j \left[ \frac{Z_{1c} R_c \csc \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} R_\pi \csc \beta_\pi l}{1 - R_\pi/R_c} \right] \]

\[ Z_{22} = Z_{44} = -j \left[ \frac{Z_{1c} R_c^2 \cot \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} R_\pi^2 \cot \beta_\pi l}{1 - R_\pi/R_c} \right] \]

\[ Z_{24} = Z_{42} = -j \left[ \frac{Z_{1c} R_c^2 \csc \beta_c l}{1 - R_c/R_\pi} + \frac{Z_{1\pi} R_\pi^2 \csc \beta_\pi l}{1 - R_\pi/R_c} \right] \]

2.3 Three Symmetric Coupled Lines

The case of three symmetric coupled lines in an inhomogeneous medium has been investigated [7]. Derivation of closed form expressions of normal mode parameters and impedance matrix elements of a resultant six-port follows
that of the previous section.

For the case of three symmetric coupled lines shown in Figure 2.3, the capacitance and inductance matrices can be written as

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} \\
C_{12} & C_{22} & C_{12} \\
C_{13} & C_{12} & C_{11}
\end{bmatrix} = [C]
\]

\[
\begin{bmatrix}
L_{11} & L_{12} & L_{13} \\
L_{12} & L_{22} & L_{12} \\
L_{13} & L_{12} & L_{11}
\end{bmatrix} = [L]
\]

The characteristic product matrices of equations (2.4) are

Figure 2.3 Symmetric coupled line 6-port.
\[ [A] = [L] [C] = A_4 A_5 A_4 = [[C] [L]]^{-1} \\
A_3 A_2 A_1 \]

where

\[ A_1 = L_{11} C_{11} + L_{12} C_{12} + L_{13} C_{13} \]
\[ A_2 = L_{11} C_{12} + L_{12} C_{22} + L_{13} C_{12} \]
\[ A_3 = L_{11} C_{13} + L_{12} C_{12} + L_{13} C_{11} \]
\[ A_4 = L_{12} C_{11} + L_{22} C_{12} + L_{12} C_{13} \]
\[ A_5 = 2 L_{12} C_{12} + L_{22} C_{22} \]

The eigenvalue solutions of equation (2.4) are found by solving equation (2.15) with the result

\[ \left( \frac{\beta^2}{\omega^2} \right)_a = A_1 - A_3 \]

\[ \left( \frac{\beta^2}{\omega^2} \right)_{b,c} = \frac{A_1 + A_2 + A_3}{2} \pm \frac{\sqrt{(A_1 + A_3 - A_5)^2 + 8 A_2 A_4}}{2} \]

The phase velocities for the three normal modes of propagation of the system are thus given by

\[ v_{ph,a} = \frac{1}{\sqrt{A_1 - A_3}} \]

\[ v_{ph,b,c} = \left[ \frac{2}{(A_1 + A_3 + A_5) \pm \sqrt{(A_1 + A_3 - A_5)^2 + 8 A_2 A_4}} \right]^{\frac{1}{2}} \]

and the corresponding effective dielectric constants are

The voltage and current eigenvectors which give the ratios
\[ \varepsilon_{\text{eff} \ a, b, c} = \left( \frac{V_{\text{ph} \ a}}{V_{\text{ph} \ a, b, c}} \right)^2 \]

of voltages and currents respectively on the three lines for the three normal modes of propagation can be written as columns in voltage and current eigenvector matrices. When eigenvectors are normalized with respect to the first line these matrices can be written as

\[
[M_v] = \begin{bmatrix}
1 & 1 & 1 \\
0 & R_{vb} & R_{vc} \\
-1 & 1 & 1
\end{bmatrix}
\]

\[
[M_i] = \begin{bmatrix}
1 & 1 & 1 \\
0 & R_{ib} & R_{ic} \\
-1 & 1 & 1
\end{bmatrix}
\]

where voltage and current ratios \( R \) are given by

\[
R_{vb, c} = -\frac{A_1 + A_3 - A_5}{2A_2} \pm \sqrt{\frac{(A_1 + A_3 - A_5)^2}{4A_2^2} + \frac{A_4}{A_2}}
\]

\[
R_{ib, c} = -\frac{2}{R_{vc, b}}
\]

The elements \( M_{v_{in}} \) of the voltage eigenvector matrix represent voltages on lines \( i = 1, 2, 3 \) for modes \( n = a, b, c \). Similarly \( M_{i_{in}} \) represent currents on lines \( i \) for modes \( n \). These eigenvector matrices can be used to determine the characteristic impedances and admittances of the three normal modes on the three lines. These can be found by using equation (2.14) to be
\[ Z_{1a} = Z_{3a} = \frac{1}{Y_{1a}} = \frac{1}{Y_{3a}} = \frac{1}{V_{ph\ a}(C_{11} - C_{13})} \]

\[ Z_{2a} = \frac{1}{Y_{2a}} = 0 \]

\[ Z_{1b} = Z_{3b} = \frac{1}{Y_{1b}} = \frac{1}{Y_{3b}} = \frac{1}{V_{ph\ b}(C_{11} + R_{vb}C_{12} + C_{13})} \]

\[ Z_{2b} = \frac{1}{Y_{2b}} = \frac{R_{vb}}{V_{ph\ b}(2C_{12} + R_{vb}C_{22})} \]

\[ Z_{1c} = Z_{3c} = \frac{1}{Y_{1c}} = \frac{1}{Y_{3c}} = \frac{1}{V_{ph\ c}(C_{11} + R_{vc}C_{12} + C_{13})} \]

\[ Z_{2c} = \frac{1}{Y_{2c}} = \frac{R_{vc}}{V_{ph\ c}(2C_{12} + R_{vc}C_{22})} \]

Equations for voltages and currents for the six-port structure can be found in terms of the normal mode parameters of the system. Solving these equations for voltages in terms of currents gives elements of the six-port impedance matrix as

\[ Z_{11} = Z_{33} = Z_{44} = Z_{66} = -\frac{j}{2} \left[ Z_{1a} \cot \beta_a I - \frac{R_{vc} Z_{1b} \cot \beta_b I - R_{vb} Z_{1c} \cot \beta_c I}{R_{vb} - R_{vc}} \right] \]

\[ Z_{12} = Z_{21} = Z_{23} = Z_{32} = Z_{45} = Z_{54} = Z_{65} = Z_{56} = Z_{65} = -\frac{j}{2} \left[ Z_{2b} \cot \beta_b I - \frac{Z_{2b} \cot \beta_b I - Z_{2c} \cot \beta_c I}{R_{vb} - R_{vc}} \right] \]
\[ Z_{13} = Z_{31} = Z_{46} = Z_{64} = \frac{j}{2} \left[ Z_{1a} \cot \beta_a l + \frac{R_{VC} Z_{1b} \cot \beta_b l - R_{VB} Z_{1c} \cot \beta_c l}{R_{vb} - R_{vc}} \right] \]

\[ Z_{14} = Z_{41} = Z_{36} = Z_{63} = - \frac{j}{2} \left[ Z_{1a} \csc \beta_a l - \frac{R_{VC} Z_{1b} \csc \beta_b l - R_{VB} Z_{1c} \csc \beta_c l}{R_{vb} - R_{vc}} \right] \]

\[ Z_{15} = Z_{51} = Z_{24} = Z_{42} = Z_{35} = Z_{53} = Z_{26} = Z_{62} = - j \frac{[Z_{2b} \csc \beta_b l - Z_{2c} \csc \beta_c l]}{R_{vb} - R_{vc}} \]

\[ Z_{16} = Z_{61} = Z_{34} = Z_{43} = \frac{j}{2} \left[ Z_{1a} \csc \beta_a l + \frac{R_{VC} Z_{1b} \csc \beta_b l - R_{VB} Z_{1c} \csc \beta_c l}{R_{vb} - R_{vc}} \right] \]

\[ Z_{22} = Z_{55} = - j \frac{R_{VB} Z_{2b} \cot \beta_b l - R_{VC} Z_{2c} \cot \beta_c l}{R_{vb} - R_{vc}} \]

\[ Z_{25} = Z_{52} = - j \frac{R_{VB} Z_{2b} \csc \beta_b l - R_{VC} Z_{2c} \csc \beta_c l}{R_{vb} - R_{vc}} \]

### 2.4 General N-Conductor Coupled Lines

In the case of multiple conductor asymmetric coupled line systems [9], derivations of closed form expressions for normal mode parameters and impedance or admittance matrix elements become more difficult. For a general N-conductor coupled transmission line system (Figure 2.4), numerical methods of solving equation (2.4) can be used to find normal mode phase velocity eigenvalues and the corresponding voltage eigenvectors. The voltage eigenvector matrix is written as
Figure 2.4 Schematic of a coupled line 2N-port.

$$[M_y] = \begin{bmatrix} 1 & 1 & \ldots & 1 \\ \alpha_2 & \chi_2 & \ldots & \zeta_2 \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_N & \chi_N & \ldots & \zeta_n \end{bmatrix}$$

where $M_{vin}$ represent voltages on lines $i$ for modes $n$. Characteristic admittances follow from equation (2.14) and are given by

$$Y_{in} = V_{ph} n \sum_{k=1}^{N} C_{ik} M_{vkn} \frac{M_{vin}}{M_{vin}}$$

The elements of the current eigenvector matrix are given by

$$M_{tin} = Y_{in} M_{vin}$$
thus

\[
[M_I] = \begin{bmatrix}
Y_{11} & Y_{21} & \cdots & Y_{N1} \\
Y_{12} & Y_{22} & \cdots & Y_{N2} \\
\vdots & \vdots & \ddots & \vdots \\
Y_{1N} & Y_{2N} & \cdots & Y_{NN}
\end{bmatrix}
\]

The general solutions for port voltages on this N-line 2N-port structure are

\[
\begin{align*}
V_1 & = [M_Y] [M_Y] \quad B_1 \\
\vdots & = \quad \vdots \\
V_{2N} & = [M_Y] [e^{-j\beta_{n1}}]_{\text{diag}} + [M_Y] [e^{+j\beta_{n1}}]_{\text{diag}} \quad B_{2N}
\end{align*}
\]

and the corresponding currents for the 2N-ports are determined to be

\[
\begin{align*}
I_1 & = [M_I] - [M_I] \quad B_1 \\
\vdots & = \quad \vdots \\
I_{2N} & = -[M_I] [e^{-j\beta_{n1}}]_{\text{diag}} + [M_I] [e^{+j\beta_{n1}}]_{\text{diag}} \quad B_{2N}
\end{align*}
\]

where, as before, the \( B_i \) are arbitrary amplitude constants. The components of the diagonal matrix \([e]\) are defined by

\[
[e]_{\text{diag}} = \begin{bmatrix}
e^{+j\beta_{11}} & 0 & \cdots & 0 \\
0 & e^{+j\beta_{21}} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & e^{+j\beta_{n1}}
\end{bmatrix}
\]

The amplitude coefficients can be eliminated by solving for
port current in terms of port voltages. The resultant admittance matrix can be written as

\[
[Y] = \begin{bmatrix} [M_I] & -[M_I] \\ -[M_I] [e^{-j\beta_n l}]_{\text{diag}} & [M_I] [e^{+j\beta_n l}]_{\text{diag}} \end{bmatrix} \begin{bmatrix} [M_V] \\ -[M_V] [e^{-j\beta_n l}]_{\text{diag}} & [M_V] [e^{+j\beta_n l}]_{\text{diag}} \end{bmatrix}^{-1}
\]

or

\[
[Y] = -j \begin{bmatrix} [M_I] [\cot\beta_n l]_{\text{diag}} [M_V]^{-1} & -[M_I] [\csc\beta_n l]_{\text{diag}} [M_V]^{-1} \\ -[M_I] [\csc\beta_n l]_{\text{diag}} [M_V]^{-1} & [M_I] [\cot\beta_n l]_{\text{diag}} [M_V]^{-1} \end{bmatrix}
\]

The 2N-port impedance matrix is given as the inverse of the admittance matrix. From these, and given port terminating impedances, a scattering matrix representation can be found.

This procedure has been implemented numerically in the FORTRAN program NLINE (see Appendix). The program evaluates port characteristics and circuit performance in terms of characteristic line parameters for a general N-conductor transmission line. The general eigenvalue /
eigenvector equation (2.4a) is solved for normal mode phase velocities and voltage eigenvector matrix by the IMSL subroutine GVCRG. Normal mode impedances are then calculated. Admittance and impedance matrices are subsequently calculated for the 2N-port network. Scattering parameters are calculated from Z-matrix elements and port terminating impedances by the subroutine ZTOS.
CHAPTER III
DIRECTIONAL COUPLERS

3.1 Two Line Couplers

The design of symmetric coupled transmission directional couplers in a homogeneous medium has been thoroughly investigated [3],[4]. A coupled line directional coupler can be realized by a quarter wave coupled line section terminated at the four ports by matching terminating impedances. The resultant four port circuit element has the property that power input to one port is divided between two other ports while the third port remains isolated (Figure 3.1). Because the modes of propagation in a homogeneous medium are TEM, and phase velocities of the even and odd modes are equal, the coupler can be designed for perfect isolation and match at any frequency. The coupler is also characterized completely in terms of the normal mode impedances. Many designs are specified in terms of even and odd impedances [16],[17]. Terminating impedance for match $Z_0$ and coupling factor $k$ can be written in terms of the even and odd mode impedances as

$$Z_0 = \sqrt{Z_{0e} Z_{0o}}$$

(3.1)
Figure 3.1 Coupled line directional coupler.

\[ k = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \]  \hspace{1cm} (3.2)

or equivalently

\[ Z_{0e} = \sqrt{\frac{1 + k}{1 - k}} Z_0 \]  \hspace{1cm} (3.3)

\[ Z_{0o} = \sqrt{\frac{1 - k}{1 + k}} Z_0 \]  \hspace{1cm} (3.4)

Stripline couplers, for example, can be designed by calculating even and odd mode impedances for desired coupling and terminating impedance. Various design tools are available for stripline directional couplers and are usually in the form of plots or graphs. Typical design
plots relate even and odd mode impedances to values of strip widths and spacings for a given substrate geometry.

Research has also been done on symmetric couplers in inhomogeneous media [5]. Design data similar to that for stripline couplers is available for various symmetric microstrip couplers. Design procedures for general coupled line directional couplers are not readily available. Coupling characteristics are specific to geometries and only a limited number of geometries have been investigated.

For the inhomogeneous case, normal modes of propagation are no longer TEM and phase velocities of the two modes are unequal. The even and odd modes thus become the common and pi modes. The result is that perfect match and isolation are lost. The quarter wave condition can be taken as

$$\theta = \frac{\pi}{2} = \frac{\beta_c + \beta_\pi}{2} l$$  \hspace{1cm} (3.5)$$

or equivalently

$$l = \frac{1}{2} \frac{\lambda_0}{\sqrt{\varepsilon_{eff} c} + \sqrt{\varepsilon_{eff} \pi}}.$$  \hspace{1cm} (3.6)$$

If the phase velocities of the two modes are not too different, fairly good isolation can be achieved. Similarly, a good match can be found by proper choice of port terminating impedances.

In the design of directional couplers in inhomogeneous
media, port termination impedances can not simply be taken as the homogeneous values of equation (3.1) [18]. Port terminating impedances can be found by an iterative procedure for minimizing of reflection at the ports ($S_{11} = 0$, $S_{22} = 0$), [9]. Starting with initial values of port terminating impedances given by equation (3.1), analysis of the coupler yields the values of scattering parameters. These values are used to improve terminating impedances as given by

$$
Z_{0,1,2} = Z_{0,1,2} \left( \frac{k_{1,2}}{2} - 1 \right) \sqrt{\frac{k_{1,2}}{2} + 1}
$$

(3.7)

where

$$
k_1 = \frac{S_{14}^2 - S_{11}^2 - 1}{S_{11}^2}
$$

(3.8)

$$
k_2 = \frac{S_{23}^2 - S_{22}^2 - 1}{S_{22}^2}
$$

(3.9)

The steps are repeated in an iterative manner until convergence of terminating impedances is achieved.

The analysis procedures developed in Chapter II and the above procedure for matching port impedances can be used in an analysis/design procedure. Evaluation of specific coupled line geometries leads to scattering
parameters. By adjusting dimensions in the physical geometry and evaluating the performance in an iterative procedure, design of couplers can be achieved.

The analysis for two coupled line directional couplers has been implemented in the FORTRAN program ASSYMCPL (see Appendix). The closed form expressions for two asymmetric coupled lines given in Chapter II are used. For this program, line parameters are input and normal mode parameters are calculated. Transmission line length can be input or length of a quarter wave section can be calculated. Impedance matrix is then calculated at a given frequency. Port terminating impedances may be input or those needed for a match may be calculated in an iterative manner. Scattering parameters are subsequently calculated from the Z-parameters by the subroutine ZTOS.

Coupling equations and design data for homogeneous and microstrip couplers are a useful starting point for the design of a two-layer coupler. For a 3-dB coupler with 50 ohm impedances in a homogeneous medium, the desired even and odd mode impedances are found from equations (3.1) through (3.4) as

\[ k = 0.7071 \]
\[ Z_{oe} = 120.71 \text{ ohm} \]
\[ Z_{oo} = 20.71 \text{ ohm} \]

These values for tight coupling can not actually be achieved for a microstrip coupler, but were used as a
starting point for design of a two-layer coupler.

3.1.1 Microstrip Coupler

A microstrip coupler was designed for 3-dB coupling at a frequency of 10 GHz. A GaAs substrate with a thickness of \( h = 0.10 \) millimeter and metal layer thickness \( t = 0.0005 \) mm was chosen to reflect typical MMIC applications. The dimensions (Figure 3.2) are found to be

\[
\begin{align*}
    w &= 0.02 \text{ mm} \\
    s &= 0.0001 \text{ mm} \\
    h &= 0.10 \text{ mm} \\
    t &= 0.0005 \text{ mm}.
\end{align*}
\]

Capacitance and inductance matrices for this coupled line system are calculated as

\[
[C] = \begin{bmatrix}
    260.7 & -183.6 \\
    -183.6 & 260.7
\end{bmatrix} \quad \text{(pF/m)}
\]

\[
[L] = \begin{bmatrix}
    652.9 & 495.0 \\
    495.0 & 652.9
\end{bmatrix} \quad \text{(nH/m)}.
\]

Normal mode parameters are found to be

\[
\begin{align*}
    v_{phc} &= 1.06297 \text{ E8} \\
    v_{phpi} &= 1.19391 \text{ E8} \quad \text{(m/s)} \\
    e_{effc} &= 7.9543 \\
    e_{effpi} &= 6.3052 \\
    R_c &= 1.0000 \\
    R_{pi} &= -1.0000 \\
    Z_{1c} = Z_{2c} &= 122.02 \\
    Z_{1pi} = Z_{2pi} &= 18.85 \quad \text{(ohm)}
\end{align*}
\]

The quarter wave length of the coupled line section is found from equation (3.6) as
Figure 3.2 Microstrip coupler.

\[ l = 2.8116 \text{ (mm)} \]

The impedance matrix at center frequency is found to be

\[
[Z] = \begin{bmatrix}
4.714 & 6.437 & -51.798 & -70.728 \\
6.437 & 4.714 & -70.728 & -51.798 \\
-51.798 & -70.728 & 4.714 & 6.437 \\
-70.728 & -51.798 & 6.437 & 4.714
\end{bmatrix} \text{ (ohm)}
\]

Terminating impedances are found using the iterative procedure described. Several iterations and impedance values are given in Table 3.1. Using these values for terminating impedances, \((Z_0 = 47.8155 \text{ ohm})\), the scattering matrix at center frequency is calculated to be
\[ \begin{bmatrix} 0 \end{bmatrix} = \begin{bmatrix} -26.86 & -2.74 & -27.45 & -3.34 \\ -2.74 & -26.86 & -3.34 & -27.45 \\ -27.45 & -3.34 & -26.86 & -2.74 \\ -3.34 & -27.45 & -2.74 & -26.86 \end{bmatrix} \text{ (dB)} \]

The frequency response for this microstrip coupler is shown in Figures 3.3 and 3.4.

**Table 3.1**

<table>
<thead>
<tr>
<th>iteration</th>
<th>( Z_0 ) (ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>47.9612</td>
</tr>
<tr>
<td>1</td>
<td>47.8688</td>
</tr>
<tr>
<td>2</td>
<td>47.8350</td>
</tr>
<tr>
<td>3</td>
<td>47.8226</td>
</tr>
<tr>
<td>4</td>
<td>47.8181</td>
</tr>
<tr>
<td>5</td>
<td>47.8164</td>
</tr>
<tr>
<td>6</td>
<td>47.8158</td>
</tr>
<tr>
<td>7</td>
<td>47.8156</td>
</tr>
<tr>
<td>8</td>
<td>47.8155</td>
</tr>
</tbody>
</table>

![Figure 3.3](image_url)  
*Figure 3.3 Coupling of microstrip coupler.*
3.1.2 Two-layer coupler

A two-layer coupled line directional coupler was designed for 3-dB coupling at a center frequency of 10 GHz. As in the microstrip example, circuit parameters were chosen to reflect typical GaAs applications. For the two layer case a thin passivating layer of Si$_3$N$_4$ deposited onto the GaAs surface is used. The dimensions of the coupler are found to be (Figure 3.5)

$$w_1 = 0.0190$$
$$w_2 = 0.0270 \text{ (mm)}$$
$$s = 0.018$$

The resulting capacitance and inductance matrices are
Figure 3.5 Two-layer coupler cross section.

given as

$$[C] = \begin{bmatrix} 259.6 & -177.8 \\ -177.8 & 254.8 \end{bmatrix} \text{ (\textit{PF/m})}$$

$$[L] = \begin{bmatrix} 656.4 & 476.1 \\ 476.1 & 626.9 \end{bmatrix} \text{ (\textit{nH/m})}$$

Normal mode parameters are found to be

$$v_{ph\_c} = 1.05645 \text{ E8} \quad v_{ph\_pi} = 1.18481 \text{ E8 (m/s)}$$

$$e_{eff\_c} = 8.0527 \quad e_{eff\_pi} = 6.4024$$

$$R_c = 0.8359 \quad R_{pi} = -3.1537$$

$$Z_{1c} = 85.29 \quad Z_{1pi} = 10.29$$

$$Z_{2c} = 224.85 \quad Z_{2pi} = 27.12 \text{ (ohm)}$$

and the length of the quarter wave section is given as

$$l = 2.7924 \text{ (mm)}$$
The impedance matrix at center frequency is calculated as

\[
\begin{bmatrix}
5.887 & 5.697 & -49.763 & -69.862 \\
5.697 & 2.316 & -68.830 & -49.763 \\
-49.763 & -68.830 & 2.316 & 5.697 \\
-69.862 & -49.763 & 5.697 & 5.887
\end{bmatrix}
\text{ (ohm)}
\]

Port terminating impedances for several optimization iterations are given in Table 3.2. Terminating impedances are taken to be \( Z_{01} = Z_{04} = 48.318 \text{ ohm}, Z_{02} = Z_{04} = 47.656 \text{ ohm} \) and the resulting scattering matrix at center frequency is

\[
\begin{bmatrix}
-27.726 & -2.911 & -27.960 & -3.142 \\
-2.911 & -27.732 & -3.142 & -27.45 \\
\end{bmatrix}
\text{ (dB)}
\]

The frequency response of this coupler is shown in Figures 3.6 and 3.7. Coupling is tight and isolation and match are both less than -20 dB over the frequency range shown. The calculated quadrature performance for this coupler is shown in Figure 3.8.

It can be seen that a two-layer directional coupler can be designed for 3-dB coupling whereas a similar microstrip coupler requires a very small gap between lines. Typically, microstrip couplers can not be designed for coupling greater than about 6-dB without use of interdigitated lines. The two-layer design provides an alternative to interdigitated couplers.


Table 3.2

<table>
<thead>
<tr>
<th>Conductor --&gt;</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iteration</td>
<td>$Z_{01} = Z_{04}$</td>
<td>$Z_{02} = Z_{03}$ (ohm)</td>
</tr>
<tr>
<td>0</td>
<td>29.624</td>
<td>78.095</td>
</tr>
<tr>
<td>1</td>
<td>56.744</td>
<td>40.680</td>
</tr>
<tr>
<td>2</td>
<td>45.751</td>
<td>50.369</td>
</tr>
<tr>
<td>3</td>
<td>49.258</td>
<td>46.762</td>
</tr>
<tr>
<td>4</td>
<td>48.002</td>
<td>47.974</td>
</tr>
<tr>
<td>5</td>
<td>48.431</td>
<td>47.547</td>
</tr>
<tr>
<td>6</td>
<td>48.280</td>
<td>47.693</td>
</tr>
<tr>
<td>7</td>
<td>48.332</td>
<td>47.642</td>
</tr>
<tr>
<td>8</td>
<td>48.314</td>
<td>47.660</td>
</tr>
<tr>
<td>9</td>
<td>48.320</td>
<td>47.653</td>
</tr>
</tbody>
</table>

Figure 3.6 Coupling for two layer coupler
Figure 3.7 Match and isolation for two-layer coupler.

Figure 3.8 Quadrature performance of two-layer coupler.
3.2 Three Line Couplers (Re-entrant Type)

Re-entrant type coupler designs can achieve tight coupling, thus have been a research topic of interest. Coaxial TEM re-entrant couplers [19], as well as stripline re-entrant couplers [20],[21] have been investigated. Recently, a monolithic version of a re-entrant coupler was designed and fabricated [10].

The coupling concept can be understood by considering the coaxial cross section of Figures 3.9. The re-entrant coupler consists of two coupled lines A,B, shielded from ground by a third floating line C. The shield C forms a single conductor transmission line of impedance $Z_{01}$ with reference to the ground conductor, while conductors A and

![Figure 3.9 Coaxial re-entrant coupler cross section.](image-url)
B form transmission lines of impedance $Z_{02}$ with the shield C. The conductor C extends over the length of the re-entrant section (quarter wave) only. The impedance $Z_{01}$ of the single transmission line is in series with the impedances $Z_{02}$ of the two coaxial lines thus forming a mutually coupling medium.

This re-entrant coupler can be analyzed in terms of even and odd mode characteristic impedances. For the even mode, consider a magnetic wall along the vertical line of symmetry (Figure 3.10). The even mode impedance can be given as

$$Z_{0e} = Z_{02} + 2Z_{01}$$

(3.10)

![Figure 3.10 Even and Odd Mode Half-sections of Coaxial Re-entrant Coupler.](image)
Similarly, considering an electric wall, the odd mode impedance can be written as

\[ Z_{oo} = Z_{o2} \quad . \] (3.11)

Terminating impedances and coupling factor follow from equations (3.3) and (3.4) as

\[ Z_0 = \sqrt{Z_{oe} Z_{oo}} \]

\[ k = \frac{Z_{o1}}{Z_{o1} + Z_{o2}} \quad . \]

A monolithic version of the re-entrant type coupler has also been investigated [10]. A typical cross section is shown in Figure 3.11. One major difference between the coaxial and planar version of this coupler is that in the planar version the two conductors are shielded from ground but not from each other. Generally, coupling between these two lines is small, and for the most part, the lines are coupled through the floating shield. The equations for the coaxial TEM re-entrant coupler may only hold approximately for this inhomogeneous planar case but may be helpful in the design of a monolithic re-entrant coupler.

An analysis procedure for a re-entrant coupler has been implemented in the FORTRAN program RENTCPL (see Appendix). The equations for three symmetric coupled lines given in Chapter II are used to calculate normal mode parameters and Z-matrix. In this program line parameters
Figure 3.11 Monolithic re-entrant coupler cross-section.

are input and normal mode parameters are calculated. The transmission line length can be input or calculated as quarter wave for a given frequency. For the three line case, quarter wave is taken as

\[
\theta = \frac{\pi}{2} = \frac{\beta_a + \beta_b + \beta_c}{3} l \tag{3.12}
\]

or

\[
l = \frac{3}{4} \left[ \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}a}} + \sqrt{\varepsilon_{\text{eff}b}} + \sqrt{\varepsilon_{\text{eff}c}}} \right] \tag{3.13}
\]

The program then calculates the six-port impedance matrix. This Z-matrix is then reduced to a four port Z-matrix by considering the open ends of the floating line to be ideal.
Terminating impedances for the resulting four-port can be input or a match may be found using the iterative procedure. S-matrix is again calculated by the subroutine ZTOS.

3.2.1 Re-entrant Coupler Analysis Example

Typical re-entrant mode coupler dimensions were taken [10] for an analysis example. A GaAs substrate of thickness 0.15 mm with a thin film of Si₃N₄ with thickness 0.005 mm was chosen for design of a 10 GHz re-entrant coupler. Coupler dimensions are taken as (see Figure 3.11)

\[ w_1 = 0.015 \]
\[ w_2 = 0.100 \]
\[ s = 0.005 \]

Capacitance and inductance matrices for this three line coupler are found to be

\[
[C] = \begin{bmatrix}
175.0 & -152.6 & -23.4 \\
-152.6 & 496.9 & -152.6 \\
-23.4 & -152.6 & 175.0 \\
\end{bmatrix}
\]

\[
[L] = \begin{bmatrix}
820.4 & 484.2 & 549.5 \\
484.2 & 492.8 & 484.2 \\
549.5 & 484.2 & 820.4 \\
\end{bmatrix}
\]

The characteristic parameters describing the three normal modes of propagation are calculated as
mode | a     | b      | c
---|-------|--------|---
v_{ph} | 1.3640 E8 | 1.0329 E8 | 1.2575 E8 (m/s)
\(e_{\text{eff}}\) | 4.8310 | 8.4238 | 5.6836
R_{v} | 1.0730 | 0.1067 |
R_{1} | -18.7439 | -1.8639 |

and the characteristic impedances for these modes on the three lines are

\[ Z_{1a} = Z_{3a} = 36.95 \]
\[ Z_{1b} = Z_{3b} = -795.95 \]
\[ Z_{2b} = 45.57 \text{ (ohm)} \]
\[ Z_{1c} = Z_{3c} = 58.78 \]
\[ Z_{2c} = -3.36 \]

From equation (3.13) the quarter wave length is taken as

\[ l = 3.004 \text{ mm} \]

At center frequency (10 GHz) the Z-matrix for the 6-port network (Figure 2.3) is calculated from normal mode parameters and is given as

\[
[Z]_6 = j
\]

\[
\begin{bmatrix}
5.76 & 12.13 & 12.75 & -96.95 & -52.24 & -59.34 \\
12.13 & 13.25 & 12.13 & -52.24 & -52.68 & -52.24 \\
12.75 & 12.13 & 5.76 & -59.34 & -52.24 & -96.95 \\
-96.95 & -52.24 & -59.34 & 5.76 & 12.13 & 12.75 \\
-52.24 & -52.68 & -52.24 & 12.13 & 13.25 & 12.13 \\
-59.34 & -52.24 & -96.95 & 12.75 & 12.13 & 5.76 \\
\end{bmatrix} \text{ (ohm)}
\]

This 6-port is reduced to the 4-port of figure 3.1 by considering ideal open circuits at ports 2 and 5 and re-numbering ports accordingly. The 4-port Z matrix is
\[
[z]_4 = j \\
\begin{bmatrix}
5.76 & 12.75 & -59.34 & -96.95 \\
12.75 & 5.76 & -96.95 & -59.34 \\
-59.34 & -96.95 & 5.76 & 12.75 \\
-96.95 & -59.34 & 12.75 & 5.76
\end{bmatrix} \text{ (ohm)}
\]

Matching port terminating impedances are calculated as 
\(z_0 = 75.62\) ohm and the S-matrix at 10 GHz is
\[
[S] = \begin{bmatrix}
-22.65 & -4.35 & -20.40 & -2.09 \\
-4.35 & -22.65 & -2.09 & -20.40 \\
-20.40 & -2.09 & -22.65 & -4.35 \\
-2.09 & -20.40 & -4.35 & -22.65
\end{bmatrix} \text{ (dB)}
\]

The coupling, match, isolation and quadrature are plotted versus frequency in Figures 3.12, 3.13, and 3.14 respectively.

![Figure 3.12 Coupling for monolithic re-entrant coupler.](image-url)
Figure 3.13  Reflection and isolation of re-entrant coupler.

Figure 3.14  Quadrature performance of re-entrant coupler.
3.2.2 "Inverted" Re-entrant Coupler Analysis Example

A similar three line coupler was also analyzed. The dimensions for the coupler are taken the same as for the re-entrant coupler but the strip configuration is inverted so that the floating line is on top (Figure 3.15).

Capacitance and inductance matrices are given by

\[
[C] = \begin{pmatrix}
258.8 & -165.9 & -75.6 \\
-165.9 & 471.5 & -165.9 \\
-75.6 & -165.9 & 258.8 \\
\end{pmatrix} \quad (pF/m)
\]

\[
[L] = \begin{pmatrix}
818.1 & 480.7 & 545.9 \\
480.7 & 498.1 & 480.7 \\
545.9 & 480.7 & 818.1 \\
\end{pmatrix} \quad (nH/m)
\]

Normal mode parameters for this case are found as

![Diagram of "Inverted" re-entrant coupler cross section.](image)
mode a b c
\(v_{ph}\) 1.0482 E8 1.0499 E8 1.1539 E8 (m/s)
\(e_{eff}\) 8.1800 8.1530 6.7497
\(R_v\) 0.7103 -42.3655
\(R_i\) 0.0472 -2.8159

and normal mode characteristic impedances for the modes on the lines are
\[
Z_{1a} = Z_{3a} = 28.53
\]
\[
Z_{1b} = Z_{3b} = 145.59 \quad Z_{2b} = 2190.19 \quad \text{(ohm)}
\]
\[
Z_{1c} = Z_{3c} = 1.20 \quad Z_{2c} = 18.08
\]
The quarter wave length (equation 3.13) is \(l = 2.7046\) mm.
Matching termination impedances are found to be \(Z_0 = 63.93\) ohm. Impedance and scattering matrices for the 4-port coupler at center frequency are

\[
[Z] = \begin{bmatrix}
4.14 & 2.70 & -57.40 & -85.97 \\
2.70 & 4.14 & -85.97 & -57.40 \\
-57.40 & -85.97 & 4.14 & 2.70 \\
-85.97 & -57.40 & 2.70 & 4.14 \\
\end{bmatrix} \quad \text{(ohm)}
\]

\[
[S] = \begin{bmatrix}
-63.61 & -3.51 & -62.66 & -2.56 \\
-3.51 & -63.61 & -2.56 & -62.66 \\
-62.66 & -2.56 & -63.61 & -3.51 \\
-2.56 & -62.66 & -3.51 & -63.61 \\
\end{bmatrix} \quad \text{(dB)}
\]

The coupler frequency response is shown in figures 3.16, 3.17, and 3.18.

By comparison of the two re-entrant type couplers, it can be seen that isolation, match and coupling are better for the inverted case. For the re-entrant coupler, the
Figure 3.16 Coupling of "inverted" re-entrant coupler.

Figure 3.17 Match and isolation for "inverted" re-entrant coupler.
Figure 3.18 Quadrature performance of "inverted" re-entrant coupler.

fields of the "odd" coupling mode (mode a) are contained mostly in the air dielectric region of the thin film. This mode thus has a higher phase velocity (and lower effective dielectric constant) than the "even" mode whose fields are contained mostly in the dielectric regions. For the inverted case the fields of the coupling modes are contained mostly in the dielectric regions. The difference between the mode phase velocities becomes small and very good match, isolation and quadrature performance can be achieved.

Given the calculated coupling at center frequency and matching terminating impedance, "even" and "odd" impedances
can be calculated using equations (3.3) and (3.4). Re-entrant mode impedances of equations (3.10) and (3.11) can also be calculated and a comparison made with the normal mode impedances.

For the re-entrant coupler, the coupling at center frequency is -4.35 dB ($k = 0.6062$) and port terminations are 75.62 ohm. The even and odd mode impedances are thus given as

\[
Z_{0e} = 152.71
\]
\[
Z_{0o} = 37.44 \text{ (ohm)}
\]

and re-entrant mode impedances are in turn found as

\[
Z_{01} = 57.64
\]
\[
Z_{02} = 37.44 \text{ (ohm)}
\]

By comparison of these values with the re-entrant coupler normal mode impedances it is seen that $Z_{1a}$ corresponds to the odd coupling mode impedance $Z_{0o} = Z_{02}$ and $Z_{1c}$ corresponds to the impedance $Z_{01}$.

The inverted coupler has coupling of -3.51 dB and terminations of 63.93 ohms which leads to the impedance values

\[
Z_{0e} = 143.11 \quad \quad Z_{01} = 57.28
\]
\[
Z_{0o} = 28.56 \quad \quad Z_{02} = 28.56 \text{ (ohm)}
\]

Again $Z_{1a}$ corresponds to the odd impedance while $Z_{1b}$ corresponds to the even impedance.

Comparisons such as these can be useful in the design of monolithic re-entrant type couplers. Desired coupling
and terminating impedances can be used to calculate impedances of equations (3.3), (3.4), (3.10), and (3.11). By adjusting the physical dimensions of the coupler to realize the normal mode impedance values desired, re-entrant couplers can be designed.

It is seen that tight coupling can be achieved in a re-entrant mode coupler. Because of the mutual coupling of the lines through the shield, small spacings between lines are not required. Thus re-entrant couplers with tight coupling can be designed without the problems encountered in fine line fabrication of single layer coupler designs.
CHAPTER IV

PLANAR BALUN

4.1 Marchand Balun

A balun is a device which transforms an unbalanced transmission line to a balanced transmission line. Baluns can be used in the design of microwave mixers or antennas, as well as for the excitation of class B amplifiers. Several different balun structures have been investigated in the literature [22],[23],[24]. A balun design which can be adapted to a two-layer planar geometry is the Marchand type balun [25],[26]. The Marchand balun is a coaxial coupled line balun consisting of two quarter wave coupled transmission line sections. The cross section of this balun and the equivalent transmission line model are shown in Figures 4.1 and 4.2 respectively.

A planar version of this balun [11],[27] which can be integrated into MMIC circuits, is shown in Figure 4.3. The network model used in the analysis of this balun is depicted in Figure 4.4. Each of the two coupled line sections (1 and 2) can be analyzed in terms of its 4-port impedance matrix. The two sections can then be reduced to 3-ports by considering their shorted ports to be ideal.
Figure 4.1 Sectional view of a coaxial Marchand balun.

Figure 4.2 Marchand balun transmission line model.
Figure 4.3 Planar balun circuit topology.

Figure 4.4 Planar balun network model.
Section 2 can further be reduced to a 2-port by considering in ideal open circuit for its open port. An impedance matrix segmentation technique can be used to combine the Z-matrices of the two sections to obtain a 3-port Z-matrix characterization of the balun. Scattering parameters can then be calculated from this impedance matrix and a set of port terminating impedances.

An analysis procedure for this planar balun was implemented in the FORTRAN program MBALUN (see Appendix). Inputs to this program are the characteristic line parameters for each of the coupled line sections. Normal mode parameters and Z-matrices of the two sections are calculated by the methods of Chapter II. The two sections are then combined using the Z-matrix segmentation subroutine SEGMENT. Scattering parameters for the resulting 3-port network are found using the subroutine ZTOS.

Dimensions of a planar balun fabricated at Texas Instruments [11] are taken for an analysis example. The balun dimensions (Figures 4.5 and 4.6) are:

<table>
<thead>
<tr>
<th></th>
<th>Section 1</th>
<th>Section 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w_1 )</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>( w_2 )</td>
<td>0.010</td>
<td>0.127</td>
</tr>
<tr>
<td>( s )</td>
<td>0.070</td>
<td>0.012</td>
</tr>
<tr>
<td>( l )</td>
<td>0.914</td>
<td>0.889</td>
</tr>
</tbody>
</table>

The capacitance and inductance matrices for the two
Figure 4.5 Layout of a monolithic two-layer balun (courtesy Texas Instruments, Inc., Dallas, Texas).

Figure 4.6 Cross section of planar balun coupled line sections.
sections are found as

\[
\begin{align*}
[C]_1 &= \begin{bmatrix} 344.8 & -117.8 \\ -117.8 & 118.6 \end{bmatrix} \quad \text{\(pF/m\)} \\
[L]_1 &= \begin{bmatrix} 421.2 & 414.4 \\ 414.4 & 959.4 \end{bmatrix} \quad \text{\(nH/m\)} \\
[C]_2 &= \begin{bmatrix} 1455.6 & -1228.5 \\ -1228.5 & 1229.1 \end{bmatrix} \quad \text{\(pF/m\)} \\
[L]_2 &= \begin{bmatrix} 421.5 & 415.2 \\ 415.2 & 466.6 \end{bmatrix} \quad \text{\(nH/m\)}
\end{align*}
\]

Normal mode parameters for the two sections are calculated as:

**Section 1**

\[
\begin{align*}
\nu_{ph\; c} &= 1.0214 \text{ E8} \\
\varepsilon_{\text{eff}\; c} &= 8.6147 \\
R_c &= 0.9660 \\
Z_{1c} &= 42.46 \\
Z_{2c} &= -2875.42
\end{align*}
\]

\[
\begin{align*}
\nu_{ph\; pi} &= 1.2286 \text{ E8 (m/s)} \\
\varepsilon_{\text{eff}\; pi} &= 5.9537 \\
R_{pi} &= 70.0976 \\
Z_{1pi} &= -1.01 \\
Z_{2pi} &= 68.54 \quad \text{\(\text{ohm}\)}
\end{align*}
\]

**Section 2**

\[
\begin{align*}
\nu_{ph\; c} &= 1.0191 \text{ E8} \\
\varepsilon_{\text{eff}\; c} &= 8.6541 \\
R_c &= 0.9492 \\
Z_{1c} &= 32.54 \\
Z_{2c} &= -125.58
\end{align*}
\]

\[
\begin{align*}
\nu_{ph\; pi} &= 1.1887 \text{ E8 (m/s)} \\
\varepsilon_{\text{eff}\; pi} &= 6.3608 \\
R_{pi} &= 4.0655 \\
Z_{1pi} &= -1.97 \\
Z_{2pi} &= 7.59 \quad \text{\(\text{ohm}\)}
\end{align*}
\]

Using equation (3.6) and the above data, the frequency for which the sections are quarter wave can be found to be
approximately 30 GHz. Port terminating impedances are taken as \( Z_{o1} = 83 \) ohms and \( Z_{o2} = Z_{o3} = 26 \) ohms and the calculated S-parameter performance of this balun is shown in Figures 4.7, 4.8, and 4.9. The analysis results show the balun to be very broadband with good output amplitude balance and near 180 degree output phase difference over the 20 to 40 GHz frequency range. Input reflection over this range is below -15 dB.

As can be seen in Figure 4.3 that a co-planar coupled line section can be used for a connection to the output. The balun under consideration (Figure 4.5) has such a co-planar coupled line section. This symmetric coupled line section can be analyzed in terms of even and odd mode

![Figure 4.7 Planar balun amplitude balance.](image-url)
Figure 4.8 Differential phase at output for planar balun.

Figure 4.9 Input reflection of planar balun.
impedances. To match the balun output, the section can be designed to have its odd mode impedance equal to the terminating impedances taken at ports 2 and 3. For example, analysis results of the output co-planar section (section 3) of the TI balun \((w = 0.150 \text{ mm}, \ s = 0.025 \text{ mm}, \ l = 0.150 \text{ mm})\) are:

\[
[C]_3 = \begin{bmatrix} 258.6 & -76.4 \\ -76.4 & 258.6 \end{bmatrix} \quad \text{(pF/m)}
\]

\[
[L]_3 = \begin{bmatrix} 401.5 & 161.4 \\ 161.4 & 401.5 \end{bmatrix} \quad \text{(nH/m)}
\]

\[v_{ph \_c} = 9.8721 \times 10^7 \quad v_{ph \_pi} = 1.1145 \times 10^8 \quad \text{(m/s)}\]

\[e_{eff \_c} = 9.2219 \quad e_{eff \_pi} = 7.2351\]

\[R_c = 1.0000 \quad R_{pi} = -1.0000\]

\[Z_{1c} = Z_{2c} = 55.60 \quad Z_{1pi} = Z_{2pi} = 26.79 \quad \text{(ohm)}\]

Analysis results for this balun which includes the output section are shown in Figures 4.10, 4.11, 4.12. The port impedances are taken as \(Z_{01} = 83 \text{ ohm}\) and \(Z_{02} = Z_{03} = 26.79 \text{ ohm}\). The results are similar to those obtained by considering only the two coupled line sections.

To compare with measured results from TI the effects of via-hole inductances as well as bond wire inductances and bond pad capacitances were taken into account (Figure 4.5). Via-hole inductances are taken as 0.03 nH and bond wire inductances are taken as 0.035 nH. Capacitances of bonding pads at input and outputs are calculated to be 0.0292 pF and 0.0927 pF respectively. Terminating
Figure 4.10  Coupling of balun with output section included.

Figure 4.11  Phase difference of balun with output section included.
impedances are all taken as 50 ohm. Analysis results for this case are shown in Figures 4.13, 4.14, and 4.15. It can be seen that the LC network at the input acts as a low pass filter and high frequencies are reflected. It should be noted that in this analysis the discontinuity effect of the lines on the top layer has not been taken into account.

The numerical results obtained for this balun are very similar to the experimental results reported [11]. The measured performance (Figure 4.16) shows good amplitude balance at approximately -5 dB for the frequency range 6 to 18 GHz. The reported phase difference at the output is 180 +/- 2 degrees.

The analysis programs developed can be useful in
Figure 4.13 Calculated amplitude balance for TI balun.

Figure 4.14 Calculated output phase difference for TI balun.
Figure 4.15 Calculated input reflection of TI balun.

Figure 4.16 Measured performance of a planar balun fabricated at TI (courtesy Texas Instruments, Inc., Dallas, Texas).
CHAPTER V
SUMMARY AND CONCLUDING REMARKS

5.1 Summary

A quasi-TEM transmission line model has been used for the analysis of general asymmetric multiple-conductor coupled line systems in inhomogeneous dielectric media occurring in two-level MMIC components. Procedures for finding the normal mode characterization of a coupled line system and subsequently the impedance or scattering matrix of a coupled line section have been presented. These procedures, which have been implemented numerically in FORTRAN programs, and verified for sample cases, have been used for the analysis and design of several two-layer MMIC elements.

An analysis/design procedure for two-conductor, four-port directional couplers has been presented. A two-layer 3-dB directional coupler design example using typical MMIC substrate dimensions, and microwave frequencies in the quasi-static approximation range, has also been presented. It has been shown that by proper choice of terminating impedances and quarter-wave length, good match, isolation, and quadrature performance can be achieved.
Similarly analysis/design procedures and examples have been presented for three-conductor, four-port re-entrant mode directional couplers suitable for MMIC integration.

Procedures developed have also been used in the analysis of a two-layer planar balun and comparisons have been made with experimental results.

5.2 Concluding Remarks

The analysis procedures presented, which have in the past, typically been applied to single level MMIC components, have been used in the analysis and design of two-layer MMIC components. The expressions given are convenient for numerical implementation and analysis results can be computed efficiently and rapidly. Using an iterative procedure of adjusting physical dimensions and computing normal mode parameters and circuit performance, design of various passive circuit elements can be accomplished.

It has been shown that the tight coupling achievable in two-layer coupled line configurations can be used to design 3-dB directional couplers without the use of interdigitated structures. Couplers can thus be made more compact.

Two-layer configurations also make possible the adaptation of the re-entrant mode coupler and Marchand balun to monolithic circuit topologies. Such designs,
which were originally coaxial structures, are not achievable in a single layer configurations but are easily adapted to two-layer structures.
BIBLIOGRAPHY


APPENDIX

DOCUMENTATION SOFTWARE DEVELOPED
PROGRAM NLINE

PROGRAM FOR THE ANALYSIS OF A GENERAL N-CONDUCTOR COUPLED TRANSMISSION LINE SECTION

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Running NLINE ........................................87
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Output File NOUT.DAT ...............................89
PROGRAM NLINE
PROGRAM FOR ANALYSIS OF GENERAL N-CONDUCTOR COUPLED TRANSMISSION LINE SECTION

1-------------N+1
2-------------N+2
3-------------N+3
...
N-------------2N

INPUT: C MATRICES OR L AND C MATRICES
OUTPUT: NORMAL MODE PARAMETERS
Z MATRIX
S MATRIX
FREQUENCY SWEEP

LINK: LINK THIS PROGRAM WITH IMSL LIBRARY
      LINK NLINE, SYSSLIBRARY=IMSL/LIBRARY

BY: ANTHONY J. VERSAMINI
    MIMICAD CENTER, UNIVERSITY OF COLORADO, BOULDER

CHARACTER*12 ANS, INFILE, OUTFILE, NAME
COMPLEX ALPHA(34), COTH(34, 34), CSCH(34, 34), LC(34, 34)
COMPLEX MI(34, 34), MV(34, 34), S(34, 34), Z(34, 34), YC(34, 34)
COMPLEX YMA1(34, 34), YMA2(34, 34), YM1(34, 34), YM2(34, 34)
COMPLEX J
REAL CA(34, 34), CD(34, 34), L(34, 34)
REAL B(34), BETA(34), EPS(34), VP(34), Z0(34)
INTEGER I, K, M, N, NL, NFR, F, Q
REAL C, DF, E0, F0, F, FST, FND
REAL LL, PI, SUM, U0, W
EXTERNAL AMACH, GVCRG

C=2.99792458E8
PI=4.0*ATAN(1.0)
E0=8.854187E-12
U0=4*PI*1E-7
J=(0.0, 1.0)

FORMAT(A12)
WRITE(*, *)'----------------------------------------'
WRITE(*, *)'PROGRAM NLINE'
WRITE(*, *)' FOR ANALYSIS OF A GENERAL N-CONDUCTOR COUPLED'
WRITE(*, *)' TRANSMISSION LINE SECTION'
WRITE(*, *)'----------------------------------------'
WRITE(*, *)' MIMICAD CENTER'
WRITE(*, *)' DEPARTMENT OF ELECTRICAL ENGINEERING'
WRITE(*, *)' UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425'
WRITE(*, *)'
WRITE(*, *)'
C------INPUT SECTION------
WRITE(*, *)'ENTER OUTPUT FILENAME'
WRITE(*,*) 'NOTE: FILE.DAT <= 12 CHARACTERS'
READ(5,5) OUTFILE
OPEN (UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
WRITE(*,*) '
WRITE(*,*) 'ENTER NUMBER OF LINES N'
READ(*,*) NL
WRITE(*,*) '
WRITE(*,*) 'ENTER 1 IF CD(N,N) AND L(N,N) ARE TO BE INPUT'
WRITE(*,*) 'ENTER 2 IF CD(N,N) AND CA(N,N) ARE TO BE INPUT'
READ(*,*) P
WRITE(*,*) '
WRITE(*,*) 'READ LINE PARAMETER DATA FROM INPUT FILE (Y/N)?'
READ(5,5) ANS
WRITE(*,*) '
IF ((ANS.EQ. 'Y') .OR. (ANS.EQ. 'y')) THEN
WRITE(*,*) 'ENTER INPUT FILE NAME (FILE.DAT <= 12 CHAR.)'
READ(5,5) INFILE
WRITE(*,*) '
OPEN (UNIT=1, FILE=INFILE, STATUS='UNKNOWN')
DO 10 I=1, NL
    DO 10 K=1, NL
        READ(1,*) CD(I,K)
10 CONTINUE
IF (P.EQ.2) THEN
    DO 20 I=1, NL
        DO 20 K=1, NL
            READ(1,*) CA(I,K)
20 CONTINUE
ELSE
    DO 25 I=1, NL
        DO 25 K=1, NL
            READ(1,*) L(I,K)
25 CONTINUE
ENDIF
ELSE
WRITE(*,*) 'ENTER INPUT FILENAME FOR LINE PARAMETERS
> TO BE STORED'
READ(5,5) INFILE
OPEN (UNIT=1, FILE=INFILE, STATUS='UNKNOWN')
WRITE(*,*) '
WRITE(*,*) 'ENTER CAPACITANCE COEFFICIENTS IN DIELECTRIC
> (pF/m)'
DO 30 I=1, NL
    DO 30 K=1, NL
        WRITE(*,27) I,K
    FORMAT(1X, 'CD(',I2,',',I2,') = ?')
    READ(*,*) CD(I,K)
30 CONTINUE
WRITE(*,*) '
IF (P.EQ.2) THEN
WRITE(*,*) 'ENTER CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
DO 40 I=1, NL
    DO 40 K=1, NL
        WRITE(*,37) I,K
    FORMAT(1X, 'CA(',I2,',',I2,') = ?')
    READ(*,*) CA(I,K)
40 CONTINUE
ELSE
WRITE(*,*) 'ENTER INDUCTANCE COEFFICIENTS (nH/m)'
DO 45 I=1, NL
    DO 45 K=1, NL
        WRITE(*,43) I,K
    FORMAT(1X, 'L(',I2,',',I2,') = ?')
    READ(*,*) L(I,K)
43
WRITE (1,*) L(I,K)

CONTINUE
ENDIF
WRITE (*,*) '  '
ENDIF

C-----WRITE INPUT LINE PARAMETERS TO OUTFILE-----
WRITE (2,*) '  '
WRITE (2,*) 'CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)'
DO 50 I=1,NL
   DO 50 K=1,NL
      WRITE (2,47) I,K,CD(I,K)
      FORMAT (1X,'CD(',I2,')=',F10.4)
   END
50 CONTINUE
WRITE (2,*) '  '
IF (P.EQ.2) THEN
   WRITE (2,*) 'CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
   DO 60 I=1,NL
      DO 60 K=1,NL
         WRITE (2,57) I,K,CA(I,K)
         FORMAT (1X,'CA(',I2,')=',F10.4)
      END
60 CONTINUE
ELSE
   WRITE (2,*) 'INDUCTANCE COEFFICIENTS (nH/m)'
   DO 65 I=1,NL
      DO 65 K=1,NL
         WRITE (2,63) I,K,L(I,K)
         FORMAT (1X,'L(',I2,')=',F10.4)
      END
65 CONTINUE
ENDIF
WRITE (2,*) '  '

C-----CALCULATE CA FOR INPUT CD AND L-----
IF (P.EQ.1) THEN
   DO 75 I=1,NL
      DO 75 K=1,NL
         LC(I,K)=L(I,K)
      END
    CONTINUE
CALL MATINC(LC,NL)
   DO 80 I=1,NL
      DO 80 K=1,NL
         CA(I,K)=400*PI*8.854187*LC(I,K)
      END
80 CONTINUE
ENDIF

C-----CALCULATE NORMAL MODE PARAMETERS-----
C-----NORMAL MODE EFFECTIVE DIELECTRIC CONSTANTS-----
C-----VOLTAGE EIGENVECTOR MATRIX-----
CALL GVCRG(NL,CD,34,CA,34,ALPHA,BETA,MV,34)
DO 85 I=1,NL
   IF (BETA(I).NE.0.0) THEN
      EPS(I)=ALPHA(I)/BETA(I)
   ELSE
      EPS(I)=AMACH(2)
   END
85 CONTINUE

C-----PHASE VELOCITIES-----
DO 90 I=1,NL
   VP(I)=C/SQRT(EPS(I))
90 CONTINUE

C-----NORMALIZE VOLTAGE EIGENVECTOR MATRIX-----
DO 95 K=1,NL
   DO 100 I=2,NL
      MV(I,K)=MV(I,K)/MV(1,K)
   END
100 CONTINUE
MV(1,K)=1.0
95 CONTINUE
WRITE (2,*) 'NORMAL MODE PARAMETERS'
WRITE (2,*) '  '
WRITE(2,*),'NORMALIZED VOLTAGE EIGENVECTOR MATRIX'
NAME='NMV'
CALL PRINTZ(NL,NL,MV,NAME)
C------CHARACTERISTIC ADMITTANCE Y(mode,line)------
DO 105 I=1,NL
   DO 105 K=1,NL
      SUM=0
      DO 110 N=1,NL
         SUM=SUM+CD(K,N)*MV(N,I)
110   CONTINUE
   YC(I,K)=VP(I)*1E-12*SUM/MV(K,I)
105   CONTINUE
C------CURRENT EIGENVECTOR MATRIX------
DO 115 I=1,NL
   DO 115 K=1,NL
      MI(I,K)=YC(K,I)*MV(I,K)
115   CONTINUE
WRITE(2,*),'CURRENT EIGENVECTOR MATRIX'
WRITE(2,*),'CURRENT EIGENVECTOR MATRIX'
NAME='MI'
CALL PRINTZ(NL,NL,MI,NAME)
WRITE(2,*),'CHARACTERISTIC ADMITTANCES YC(mode,line)'
WRITE(2,*),'CHARACTERISTIC ADMITTANCES YC(mode,line)'
NAME='YC'
CALL PRINTZ(NL,NL,YC,NAME)
C------INVERT MV------
CALL MATINC(MV,NL)
C
C------TRANSMISSION LINE LENGTH------
WRITE(*,*)'ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT'
WRITE(*,*)'ENTER 2 TO USE A QUARTER WAVE SECTION'
READ(*,*)M
WRITE(*,*)'
IF (M.EQ.1) THEN
   WRITE(*,*)'ENTER L IN METERS'
   READ(*,*)LL
ELSE
   WRITE(*,*)'ENTER CENTER OPERATING FREQUENCY F0 (Hz)'
   READ(*,*)F0
   SUM=0
   DO 120 I=1,NL
      SUM=SUM+SQRT(EPS(I))
120   CONTINUE
   LL=NL*C/(4*F0*SUM)
ENDIF
WRITE(*,*)'
C------WRITE NORMAL MODE PARAMETERS TO OUTFILE------
WRITE(2,*),'EFFECTIVE DIELECTRIC CONSTANTS'
WRITE(2,*),'EFFECTIVE DIELECTRIC CONSTANTS'
DO 125 I=1,NL
   WRITE(2,123)I,EPS(I)
123   FORMAT(1X,'EPS(",I2,") =',F10.4)
125   CONTINUE
WRITE(2,*),'PHASE VELOCITIES'
WRITE(2,*),'PHASE VELOCITIES'
DO 130 I=1,NL
   WRITE(2,127)I,VP(I)
127   FORMAT(1X,'VP("I2") =',E10.4)
130   CONTINUE
WRITE(2,*),'CENTER FREQUENCY F0 = "F0/1E9" GHz'
WRITE(2,*)'
WRITE(2,*)'LENGTH OF TRANSMISSION LINE: L = ',LL,' METERS'
WRITE(2,*)'
C-----TERMINATING IMPEDANCES-----
WRITE(*,*)'ENTER 1 IF ALL PORT TERMINATING
>IMPEDANCES ARE TO BE INPUT'
WRITE(*,*)'ENTER 2 TO TAKE ALL TERMINATING IMPEDANCES
>TO BE 50 ohm'
READ(*,*)Q
IF (Q.EQ.1) THEN
WRITE(*,*)'
WRITE(*,*)'ENTER PORT TERMINATING IMPEDANCES (ohm)'
WRITE(*,*)'
DO 135 I=1,2*N
WRITE(*,133)I
133 FORMAT(1X,Z0(','',I2,'') = ?)
READ(*,*)Z0(I)
135 CONTINUE
ELSE
DO 140 I=1,2*N
Z0(I)=50.0
140 CONTINUE
ENDIF
WRITE(2,*)'PORT TERMINATING IMPEDANCES (ohm)'
DO 145 I=1,2*N
WRITE(2,143)I,Z0(I)
143 FORMAT(1X,'Z0(','',I2,'') = ',F10.4)
C WRITE(*,143)I,Z0(I)
145 CONTINUE
WRITE(2,*)'
WRITE(*,*)'
C-----CALCULATE Z AND S FOR FREQUENCY RANGE-----
WRITE(6,*)'ENTER START, STOP, AND STEP FREQUENCIES (Hz)'
READ(5,*)FST,FND,DF
WRITE(*,*)'
F=FST
NFR=(FND-FST)/DF+1
DO 500 N=1,NFR
C-----CALCULATE PROPAGATION CONSTANTS B(I)-----
DO 505 I=1,NL
C(I)=2*PI*F*SQRT(EP(I))/C
505 CONTINUE
C-----CALCULATE COH AND CSCH DIAGONAL MATRICES-----
DO 510 I=1,NL
DO 510 K=1,NL
COTH(I,K)=0.0
CSCH(I,K)=0.0
510 CONTINUE
DO 515 I=1,NL
COTH(I,I)=-J/TAN(B(I)*LL)
CSCH(I,I)=-J/SIN(B(I)*LL)
515 CONTINUE
C-----CALCULATE Y MATRIX-----
CALL CMTULT(NL,NL,NL,MI=COTH,YM1)
CALL CMTULT(NL,NL,NL,YM1,MY,YM1)
CALL CMTULT(NL,NL,NL,MY,CSCH,YM2)
CALL CMTULT(NL,NL,NL,YM2,MY,YM2)
DO 520 I=1,NL
DO 520 K=1,NL
YM2(I,K)=-YM2(I,K)
520 CONTINUE
DO 525 I=1,NL
DO 525 K=1,NL
Z(I,K)=YM1(I,K)
Z(NL+I,NL+K)=YM1(I,K)
Z(I,NL+K)=YM2(I,K)
Z(NL+I,K)=YM2(I,K)
CONTINUE
WRITE (2,*)
WRITE (2,*)' F = ',F/1e9,' GHz'
WRITE (2,*)
WRITE (2,*)' ADMITTANCE MATRIX'
NAME='Y'
CALL PRINTZ (2*NL,2*NL,Z,NAME)

C-----CALCULATE Z MATRIX-----
CALL MATINC (Z,2*NL)
WRITE (2,*)
WRITE (2,*)' IMPEDANCE MATRIX'
NAME='Z'
CALL PRINTZ (2*NL,2*NL,Z,NAME)
CALL ZTOS (Z,Z0,S,2*NL)
WRITE (2,*)
WRITE (2,*)' SCATTERING MATRIX'
NAME='S'
CALL PRINTZ (2*NL,2*NL,S,NAME)
CALL VSWRND (2*NL,S,NAME)
F=F+DF

CONTINUE
WRITE (*,*)' ANALYSIS COMPLETE'
WRITE (6,*)' RESULTS IN DATA FILE: ',OUTFILE,'.DAT'
END

SUBROUTINE ZTOS(Z,Z0,S,N)
C-----THIS SUBROUTINE COMPUTES THE ELEMENTS OF THE S-MATRIX FROM
C-----THOSE OF Z-MATRIX OF AN N-MULTIPOINT NETWORK. THE ELEMENTS
C-----OF THE Z0(N) ARE THE CHARACTERISTIC IMPEDANCES OF THE TRANS.
C-----LINES CONNECTED TO THE N-MULTIPOINT NETWORK.
C
DIMENSION Z0(34)
COMPLEX Z1(34,34),S(34,34),Z(34,34)
COMPLEX C(34,34)
DO 10 I=1,N
DO 10 J=1,N
Z1(I,J)=Z(I,J)
10 S(I,J)=0.
DO 20 I=1,N
DO 20 J=1,N
C(I,J)=Z(I,J)
20 C(I,J)=C(I,J)+Z0(I)
CALL MATINC (C,N)
CALL CMULT (N,N,N,Z1,C,S)
DO 30 I=1,N
DO 30 J=1,N
CON1=SQRT(Z0(I)/Z0(J))
30 S(I,J)=S(I,J)/CON1
RETURN
END

SUBROUTINE CMULT(L,M,N,A,B,C)
C-----THIS SUBROUTINE SETS THE MULTIPLICATION OF THE TWO MATRIX
C-----A(L,M) AND B(M,N) TO OBTAIN THE MATRIX C(L,M).
C
COMPLEX A(34,34),B(34,34),C(34,34)
DO 3 I=1,L
DO 3 J=1,N
C(I,J)=0.0
DO 3 K=1,M
3 C(I,J)=C(I,J)+A(I,K)*B(K,J)
RETURN
END
SUBROUTINE MATINC (A,N)
C-----THIS SUBROUTINE COMPUTES THE INVERSE OF THE MATRIX A(N,N).
C-----*****WARNING*****; THE INVERSE OF A IS FILLED INTO A ITSELF.
C
DIMENSION INDEX (34,3)
COMPLEX T, SWAP, PIVOT, A(34,34)
EQUIVALENCE (IROW, JROW), (ICOLUM, JCOLUMN)
DO 10 J=1,N
10 INDEX (J,3) = 0
DO 90 I=1,N
AMAX = 0.0
DO 40 J=1,N
1 IF (INDEX (J,3) .EQ. 1) GO TO 40
2 DO 30 K=1,N
3 IF (INDEX (K,3) .EQ. 1) 20, 30, 115
4 IF (AMAX .GE. CABS (A(J,K))) GO TO 30
5 IROW = J
6 ICOLUMN = K
7 AMAX = CABS (A(J,K))
8 CONTINUE
90 CONTINUE
10 INDEX (ICOLUMN, 3) = INDEX (ICOLUMN, 3) + 1
11 INDEX (I, 1) = IROW
12 INDEX (I, 2) = ICOLUMN
13 IF (IROW .EQ. ICOLUMN) GO TO 60
14 DO 50 L=1,N
15 SWAP = A(IROW, L)
16 A(IROW, L) = A(ICOLUMN, L)
17 A(ICOLUMN, L) = SWAP
18 PIVOT = A(ICOLUMN, ICOLUMN)
19 A(ICOLUMN, ICOLUMN) = 1.0
20 DO 70 L=1,N
21 A(ICOLUMN, L) = A(ICOLUMN, L) / PIVOT
22 DO 90 L=1,N
23 IF (L .EQ. ICOLUMN) GO TO 90
24 T = A(L, ICOLUMN)
25 A(L, ICOLUMN) = 0.0
26 DO 80 L=1,N
27 A(L, L) = A(L, L) - A(ICOLUMN, L) * T
28 CONTINUE
29 DO 110 I=1,N
30 L=N-I+1
31 IF (INDEX (L, 1) .EQ. INDEX (L, 2)) GO TO 110
32 JROW = INDEX (L, 1)
33 JCOLUMN = INDEX (L, 2)
34 DO 100 K=1,N
35 SWAP = A(K, JROW)
36 A(K, JROW) = A(K, JCOLUMN)
37 A(K, JCOLUMN) = SWAP
38 CONTINUE
39 CONTINUE
40 CONTINUE
41 RETURN
END

C--------------------------------------------------------
SUBROUTINE PRINTZ (M, N, AMAT, NAME)
CHARACTER*12 NAME
COMPLEX AMAT (34, 34)
INTEGER I, J, M, N
WRITE (2, 1) NAME
DO 3 J=1,N
1 WRITE (2, 2) J
DO 3 I=1,M
2 WRITE (2, 4) I, AMAT (I, J), CABS (AMAT (I, J)), ANGLE (AMAT (I, J))
3 FORMAT (1X, 'ELEMENTS OF MATRIX ', A15)
1 FORMAT (/1X, 'ELEMENTS OF COLUMN #', 12, //4X, 'ROW #', 5X, 'REAL'
2 > ', 'PART', 10X, 'IMAGINARY PT', 12X, 'MAGNITUDE', 10X, 'DEG.' )
4 FORMAT(3X,I3,2X,2(E18.10,2X),2X,E18.10,3X,F8.2)
WRITE(2,*),
RETURN
END

C---------------------------------------------
SUBROUTINE VSWRND(NEXPORT,SM,NAME)
CHARACTER*12 NAME
COMPLEX SM(34,34)
REAL SDB(34,34),VSWR(34)
DO 10 I=1,NEXPORT
   VSWR(I)=(1+CABS(SM(I,I)))/(1-CABS(SM(I,I)))
DO 10 J=1,NEXPORT
   SDB(I,J)=20*ALOG10(CABS(SM(I,J)))
10 CONTINUE
WRITE(2,*), PORT VSWR'
DO 20 I=1,NEXPORT
   WRITE(2,*),',VSWR(I)
20 CONTINUE
WRITE(2,*),'ELEMENTS OF ',NAME,' MATRIX IN dB'
DO 30 I=1,NEXPORT
   WRITE(2,27)I,J,SDB(I,J)
30 CONTINUE
FORMAT(1X,'S(\'I2,\',I2,\') = ',F10.4)
RETURN
END

C---------------------------------------------
FUNCTION ANGLE(C)
COMPLEX C
REAL ANGLE,PI
PI=4.0*ATAN(1.0)
IF (REAL(C).NE.0.0) THEN
   ANGLE=ATAN2(AIMAG(C),REAL(C))*180/PI
ELSEIF (AIMAG(C).GT.0.0) THEN
   ANGLE=90.0
ELSEIF (AIMAG(C).LT.0.0) THEN
   ANGLE=-90.0
ENDIF
RETURN
END

C---------------------------------------------
$ RUN NLINE

---------------------

PROGRAM NLINE
FOR ANALYSIS OF A GENERAL N-CONDUCTOR COUPLED
TRANSMISSION LINE SECTION

1-----------------N+1
2-----------------N+2
3-----------------N+3

.
.
.

N------------------2N

MIMICAD CENTER
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425

---------------------

ENTER OUTPUT FILENAME
NOTE: FILE.DAT <= 12 CHARACTERS
NOUT

ENTER NUMBER OF LINES N
2

ENTER 1 IF CD(N,N) AND L(N,N) ARE TO BE INPUT
ENTER 2 IF CD(N,N) AND CA(N,N) ARE TO BE INPUT
1

READ LINE PARAMETER DATA FROM INPUT FILE(Y/N)?
Y

ENTER INPUT FILE NAME (FILE.DAT <= 12 CHAR.)
AIN

ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2

ENTER CENTER OPERATING FREQUENCY F0 (Hz)
10E9

ENTER 1 IF ALL PORT TERMINATING IMPEDANCES ARE TO BE INPUT
ENTER 2 TO TAKE ALL TERMINATING IMPEDANCES TO BE 50 ohm
2

ENTER START, STOP, AND STEP FREQUENCIES (Hz)
10E9,10E9,1

ANALYSIS COMPLETE
RESULTS IN DATA FILE : NOUT .DAT

$
CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)
CD(1, 1) = 259.6000
CD(1, 2) = -177.8000
CD(2, 1) = -177.8000
CD(2, 2) = 254.8000

INDUCTANCE COEFFICIENTS (nH/m)
L(1, 1) = 656.4000
L(1, 2) = 476.1000
L(2, 1) = 476.1000
L(2, 2) = 626.9000

NORMAL MODE PARAMETERS

NORMALIZED VOLTAGE EIGENVECTOR MATRIX
ELEMENTS OF MATRIX $NMV$

ELEMENTS OF COLUMN# 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1000000000E+01</td>
<td>0.0000000000E+00</td>
<td>0.1000000000E+01</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-0.3153687716E+01</td>
<td>0.0000000000E+00</td>
<td>0.3153687716E+01</td>
<td>180.00</td>
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ELEMENTS OF COLUMN# 2

<table>
<thead>
<tr>
<th>ROW#</th>
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<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1000000000E+01</td>
<td>0.0000000000E+00</td>
<td>0.1000000000E+01</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.8359066844E+00</td>
<td>0.0000000000E+00</td>
<td>0.8359066844E+00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

CURRENT EIGENVECTOR MATRIX
ELEMENTS OF MATRIX $MI$

ELEMENTS OF COLUMN# 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9719306976E-01</td>
<td>0.0000000000E+00</td>
<td>0.9719306976E-01</td>
<td>0.00</td>
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<tr>
<td>2</td>
<td>-0.1162725389E+00</td>
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<td>0.1162725389E+00</td>
<td>180.00</td>
</tr>
</tbody>
</table>

ELEMENTS OF COLUMN# 2

<table>
<thead>
<tr>
<th>ROW#</th>
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<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1172408834E-01</td>
<td>0.0000000000E+00</td>
<td>0.1172408834E-01</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.3717560554E-02</td>
<td>0.0000000000E+00</td>
<td>0.3717560554E-02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

CHARACTERISTIC ADMITTANCES $Y_C$(mode, line)
ELEMENTS OF MATRIX $Y_C$

ELEMENTS OF COLUMN# 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9719306976E-01</td>
<td>0.0000000000E+00</td>
<td>0.9719306976E-01</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.1172408834E-01</td>
<td>0.0000000000E+00</td>
<td>0.1172408834E-01</td>
<td>0.00</td>
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ELEMENTS OF COLUMN# 2

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3686875477E-01</td>
<td>0.0000000000E+00</td>
<td>0.3686875477E-01</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.4447339103E-02</td>
<td>0.0000000000E+00</td>
<td>0.4447339103E-02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

EFFECTIVE DIELECTRIC CONSTANTS

$\epsilon_r(1) = 6.4024$
EPS( 2 ) = 8.0527

PHASE VELOCITIES

VP( 1 ) = 0.1185E+09
VP( 2 ) = 0.1056E+09

CENTER FREQUENCY \( F_0 = 10.00000 \) GHz

LENGTH OF TRANSMISSION LINE: \( L = 2.7923929E-03 \) METERS

PORT TERMINATING IMPEDANCES (ohm)
ZO( 1 ) = 50.0000
ZO( 2 ) = 50.0000
ZO( 3 ) = 50.0000
ZO( 4 ) = 50.0000

\( F = 10.00000 \) GHz

ADMITTANCE MATRIX

ELEMENTS OF MATRIX \( Y \)

ELEMENTS OF COLUMN# 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0000000000E+00</td>
<td>-0.1000923454E-02</td>
<td>0.1000923454E-02</td>
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<tr>
<td>2</td>
<td>0.0000000000E+00</td>
<td>0.2462547738E-02</td>
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</tr>
<tr>
<td>3</td>
<td>0.0000000000E+00</td>
<td>0.2975199930E-01</td>
<td>0.2975199930E-01</td>
<td>90.00</td>
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<tr>
<td>4</td>
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<td>-0.2150994912E-01</td>
<td>0.2150994912E-01</td>
<td>-90.00</td>
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ELEMENTS OF COLUMN# 2

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<th>DEG.</th>
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</thead>
<tbody>
<tr>
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<td>0.0000000000E+00</td>
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<td>2</td>
<td>0.0000000000E+00</td>
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<tr>
<td>4</td>
<td>0.0000000000E+00</td>
<td>0.3019787185E-01</td>
<td>0.3019787185E-01</td>
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ELEMENTS OF COLUMN# 3

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<tr>
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<tr>
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<td>0.2462547738E-02</td>
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ELEMENTS OF COLUMN# 4

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<tbody>
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<td>-0.2150995284E-01</td>
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</tr>
<tr>
<td>4</td>
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<td>-90.00</td>
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</table>

IMPEEDANCE MATRIX

ELEMENTS OF MATRIX \( Z \)

ELEMENTS OF COLUMN# 1

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<tr>
<th>ROW#</th>
<th>REALPART</th>
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<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
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<tr>
<td>2</td>
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<td>90.00</td>
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<tr>
<td>3</td>
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<td>-0.6986171722E+02</td>
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</tbody>
</table>
4 0.0000000000E+00 -0.4976251221E+02 0.4976251221E+02 -90.00

**ELEMENTS OF COLUMN # 2**

<table>
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<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
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</thead>
<tbody>
<tr>
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<td>0.0000000000E+00</td>
<td>0.5697022915E+01</td>
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<tr>
<td>2</td>
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<td>0.2315598726E+01</td>
<td>0.2315598726E+01</td>
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<tr>
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**ELEMENTS OF COLUMN # 3**

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**SCATTERING MATRIX**

**ELEMENTS OF MATRIX S**

**ELEMENTS OF COLUMN # 1**

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**ELEMENTS OF COLUMN # 3**

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PORT  VSFR  
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PROGRAM ASSYMCPL

PROGRAM FOR THE ANALYSIS OF A GENERAL 2-CONDUCTOR COUPLED TRANSMISSION LINE DIRECTIONAL COUPLER

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PROGRAM ASSYMCP

PROGRAM FOR ANALYSIS OF TWO LINE DIRECTIONAL COUPLER

1------------4
2------------3

INPUT : 1 A CAPACITANCE MATRICES CD AND CA
        OR B CAPACITANCE AND INDUCTANCE MATRICES CD AND L
        OR 2 NORMAL MODE PARAMETERS

OUTPUT: NORMAL MODE PARAMETERS
        PHASE CONSTANTS, EFFECTIVE DIELECTRIC CONSTANTS,
        CHARACTERISTIC IMPEDANCES, VOLTAGE RATIOS
        FOR c AND p MODES
        QUARTER WAVE LENGTH OF TRANSMISSION LINE
        OPTIMUM TERMINATING IMPEDANCES
        Z MATRIX
        S MATRIX
        PORT VSWR AND S MATRIX IN dB
        FREQUENCY SWEEP

BY: ANTHONY J. VERGAMINI
    MIMICAD CENTER, UNIVERSITY OF COLORADO, BOULDER

CHARACTER*12 ANS, INFILEIN, INFILNMP, OUTFILE, NAME
REAL EC,EP,RC,RP,VC,VP,L
REAL C,F0,FST,FND,FGH,F,DF,ZC1D,ZP1D
DOUBLE PRECISION A,A1,A2,A3,A4,EN,ED
INTEGER M, NFR, P
COMPLEX J,COTH,COTHP,CSCHC, CSCHP
COMPLEX LMC(22,22), S(22,22), Z(22,22)
DIMENSION CD(4,4), CA(4,4), ZC(4), ZP(4)
DIMENSION ZO(22)
REAL LM(4,4)
COMPLEX K1, K2
FORMAT (A)

C
C C=2.99792458E8
PI=4.0*ATAN (1.0)
J=(0.0, 1.0)
C

WRITE(*,*)'-----------------------------------------------'
WRITE(*,*)' PROGRAM ASSYMCP'
WRITE(*,*)' FOR ANALYSIS OF TWO LINE DIRECTIONAL COUPLER'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)' INPUT  1------------4  THRU'
WRITE(*,*)' COUPLED  2------------3  ISOLATED'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)' MIMICAD CENTER'
WRITE(*,*)' DEPARTMENT OF ELECTRICAL ENGINEERING'
WRITE(*,*)' UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
C----------------INPUT SECTION----------------------'
WRITE(6,*)'ENTER OUTPUT FILE NAME'
WRITE(6,*)'NOTE: FILE.DAT <= 12 CHARACTERS'
READ (5,5)OUTFILE
OPEN(UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
WRITE(*,*)
M=1
WRITE(6,*)'ENTER 1 IF LINE PARAMETERS ARE TO BE INPUT'
WRITE(6,*)'ENTER 2 IF NORMAL MODE PARAMETERS ARE TO BE INPUT'
READ(5,*)M
WRITE(6,*)
IF (M.EQ.1) THEN
WRITE(6,*)'ENTER 1 IF CD AND L MATRICES ARE TO BE INPUT'
WRITE(6,*)'ENTER 2 IF CD AND CA MATRICES ARE TO BE INPUT'
READ(5,*)P
WRITE(6,*)
WRITE(6,*)'READ LINE PARAMETER DATA FROM INPUT FILE (Y/N)?'
READ(5,5)ANS
WRITE(*,*)
IF ((ANS.EQ.'Y').OR.(ANS.EQ.'y')) THEN
WRITE(6,*)'ENTER INPUT FILE NAME (NAME.DAT <= 12 CHAR.)'
READ(5,5)INFILEIN
OPEN(UNIT=1, FILE=INFILEIN, STATUS='UNKNOWN')
WRITE(2,*)'CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)'
DO 10 I=1,2
DO 10 K=1,2
READ(1,*)CD(I,K)
WRITE(2,7)I,K,CD(I,K)
FORMAT(1X,'CD(',I2,'.',I2,') = ',F10.4)
CONTINUE
WRITE(2,*)
IF (P.EQ.2) THEN
WRITE(2,*)'CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
DO 15 I=1,2
DO 15 K=1,2
READ(1,*)CA(I,K)
WRITE(2,13)I,K,CA(I,K)
FORMAT(1X,'CA(',I2,'.',I2,') = ',F10.4)
CONTINUE
ELSE
WRITE(2,*)'INDUCTANCE COEFFICIENTS (nH/m)'
DO 17 I=1,2
DO 17 K=1,2
READ(1,*)LM(I,K)
WRITE(2,16)I,K,LM(I,K)
FORMAT(1X,'L(',I2,'.',I2,') = ',F10.4)
CONTINUE
ENDIF
WRITE(2,*)
ELSE
WRITE(6,*)'ENTER INPUT FILENAME FOR LINE PARAMETERS
>TO BE STORED'
READ(5,5)INFILEIN
OPEN(UNIT=1, FILE=INFILEIN, STATUS='UNKNOWN')
WRITE(6,*)'ENTER CAPACITANCE COEFFICIENTS IN
>DIELECTRIC (pF/m)'
WRITE(2,*)'CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)'
DO 20 I=1,2
DO 20 K=1,2
WRITE(6,19)I,K
FORMAT(1X,'CD(',I2,'.',I2,') = ?')
READ(5,*)CD(I,K)
WRITE(2,7)I,K,CD(I,K)
WRITE(1,*)CD(I,K)
CONTINUE
WRITE(6,*)
WRITE(2,*)
IF (P.EQ.2) THEN
WRITE(6,*)'ENTER CAPACITANCE COEFFICIENTS
>IN AIR (pF/m)'
}
WRITE (2, *) 'CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
DO 30 I=1, 2
   DO 30 K=1, 2
      WRITE (6, 23) I, K
      FORMAT (1X, 'CA(', I2, ',', I2, ',', I2, ') = ?')
      READ (5, *) CA(I, K)
      WRITE (2, 13) I, K, CA(I, K)
      WRITE (1, *) CA(I, K)
   CONTINUE
ELSE
   WRITE (6, *) 'ENTER INDUCTANCE COEFFICIENTS (nH/m)'
   WRITE (2, *) 'INDUCTANCE COEFFICIENTS (nH/m)'
   DO 35 I=1, 2
   DO 35 K=1, 2
      WRITE (6, 33) I, K
      FORMAT (1X, 'L(', I2, ',', I2, ',', I2, ') = ?')
      READ (5, *) LM(I, K)
      WRITE (2, 16) I, K, LM(I, K)
      WRITE (1, *) LM(I, K)
   CONTINUE
   ENDIF
C------CALCULATE CA FOR INPUT CD AND L------
IF (P.EQ.1) THEN
   DO 45 I=1, 2
   DO 45 K=1, 2
      LMC(I, K) = LM(I, K)
   CONTINUE
   CALL MATINC (LMC, 2)
   DO 50 I=1, 2
   DO 50 K=1, 2
      CA(I, K) = 400*PI*8.854187*LMC(I, K)
   CONTINUE
   ENDIF
C------CALCULATE NORMAL MODE PARAMETERS------
C------CALCULATE EFF. DIEL. CONSTANTS------
A1 = (CD(1, 1) * CA(2, 2) - CA(1, 1) * CD(2, 2)) ** 2
A3 = -CD(2, 2) * CA(1, 2) + CA(2, 2) * CD(1, 2)
A4 = -CD(1, 1) * CA(1, 2) + CA(1, 1) * CD(1, 2)
A2 = 4 * A3 * A4
A = A1 + A2
EN = CD(1, 1) * CA(2, 2) + CA(1, 1) * CD(2, 2) - 2 * CA(1, 2) * CD(1, 2)
ED = 2 * (CA(1, 1) * CA(2, 2) - CA(1, 2)) ** 2
EC = (EN + SQRT(A)) / ED
EP = (EN - SQRT(A)) / ED
C------CALCULATE VOLTAGE RATIOS Rc, Rpi------
RC = (CD(1, 1) - EC*CA(1, 1)) / (-CD(1, 2) + EC*CA(1, 2))
RP = (CD(1, 1) - EP*CA(1, 1)) / (-CD(1, 2) + EP*CA(1, 2))
C------CALCULATE PHASE VELOCITIES------
VC = C/SQRT(EC)
VP = C/SQRT(EP)
C------CALCULATE CHARACTERISTIC IMPEDANCES------
ZC(1) = 1.0E12 / (VC*(CD(1, 1) + CD(1, 2)*RC))
ZC(2) = 1.0E12 / (VC*(CD(2, 2) + CD(1, 2)/RC))
ZP(1) = 1.0E12 / (VP*(CD(1, 1) + CD(1, 2)*RP))
ZP(2) = 1.0E12 / (VP*(CD(2, 2) + CD(1, 2)/RP))
ELSE
   WRITE (6, *) 'READ NORMAL MODE PARAMETERS FROM INPUT FILE (Y/N) ?'
   READ (5, 5) ANS
   IF ((ANS.EQ. 'Y') OR (ANS.EQ. 'y')) THEN
      WRITE (6, *) 'ENTER INPUT FILE NAME (NAME.DAT<= 12 CHAR.)'
   READ (5, 5) INFILEMP
   OPEN (UNIT=1, FILE=INFILEMP, STATUS='UNKNOWN')
   READ (1, *) RC, RP
   READ (1, *) EC, EP
   READ (1, *) ZC(1), ZC(2), ZP(1), ZP(2)
ELSE
WRITE(6,*)'ENTER FILENAME FOR NORMAL MODE
PARAMETERS TO BE STORED'
READ(5,5)INFILENMP
OPEN(UNIT=1,FILE=INFILENMP,STATUS='UNKNOWN')
WRITE(6,*)'ENTER VOLTAGE RATIOS RC,RP'
READ(5,*)RC,RP
WRITE(1,*)'RC,RP
WRITE(6,*)'
WRITE(6,*)'ENTER EFF. DIELECTRIC CONSTANTS Eeffc,Eeffp'
READ(5,*)EC,EP
WRITE(1,*)EC,EP
WRITE(6,*)'
WRITE(6,*)'ENTER Z1c,Z2c,Z1p,Z2p (ohm)'
READ(5,*)ZC(1),ZC(2),ZP(1),ZP(2)
WRITE(1,*)ZC(1),ZC(2),ZP(1),ZP(2)
ENDIF
VC=C/SORT(EC)
VP=C/SORT(EP)
ENDIF

C----WRITE NORMAL MODE PARAMETERS TO SCREEN AND OUTPUT FILE-----

WRITE(6,*)
WRITE(6,*)'*****NORMAL MODE PARAMETERS*****'
WRITE(6,*)
WRITE(6,*)'Rc, Rpi = ',RC,RP
WRITE(6,*)'Vc, Vpi = ',VC,VP
WRITE(6,*)
WRITE(6,*)'Eeff(c) = ',EC
WRITE(6,*)'Z1(c), Z2(c) = ',ZC(1),ZC(2)
WRITE(6,*)
WRITE(6,*)'Eeff(pi) = ',EP
WRITE(6,*)'Z1(pi), Z2(pi) = ',ZP(1),ZP(2)
WRITE(6,*)
WRITE(2,*)
WRITE(2,*)'*****NORMAL MODE PARAMETERS*****'
WRITE(2,*)
WRITE(2,*)'Rc, Rpi = ',RC,RP
WRITE(2,*)'Vc, Vpi = ',VC,VP
WRITE(2,*)
WRITE(2,*)'Eeff(c) = ',EC
WRITE(2,*)'Z1(c), Z2(c) = ',ZC(1),ZC(2)
WRITE(2,*)
WRITE(2,*)'Eeff(pi) = ',EP
WRITE(2,*)'Z1(pi), Z2(pi) = ',ZP(1),ZP(2)
WRITE(2,*)
WRITE(6,*)'ENTER CENTER OPERATING FREQUENCY IN Hz'
READ(*,*)F0
WRITE('','
F0=F0/1E9
WRITE(2,*)'CENTER FREQUENCY F0 = ',F0, ' GHz'

C----TRANSMISSION LINE LENGTH-----

WRITE(6,*)'ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT'
WRITE(6,*)'ENTER 2 TO USE QUARTER WAVE SECTION'
READ(5,*)M
IF(M.EQ.2)THEN
L=C/(2*F0*(SORT(EC)+SORT(EP)))
ELSE
WRITE('','
WRITE(6,*)'ENTER L IN METERS'
READ(5,*)L
ENDIF
WRITE(2,*)
WRITE(2,*)'TRANSMISSION LINE LENGTH L = ',L,' METERS'
WRITE(6,*)'

C----TERMINATING IMPEDANCES-----

WRITE(6,*)'ENTER 1 IF ALL PORT TERMINATING
>IMPEDANCES ARE TO BE INPUT
WRITE(6,*)'ENTER 2 TO USE Z0(i)=SQRT(Z1,2(c)*Z1,2(pi))'
WRITE(6,*)'ENTER 3 TO CALCULATE MATCHING TERMINATING
IMPEDANCES (S11=0, S22=0)'
READ(5,*)M
WRITE(*,*) '
ZC1D=ZC(1)
ZP1D=ZF(1)
IF (M.EQ.1) THEN
  WRITE(6,*)'ENTER TERMINATING IMPEDANCES Z0(i):'
  DO 75 I=1,4
    WRITE(6,73)I
    FORMAT(1X,'Z0( ',I2,') = ?')
  73  READ(5,*)Z0(I)
    CALL NMP2ZM(F0,L,RC,RP,VC,VP,ZC1D,ZP1D,Z)
    CALL ZTOS(Z,Z0,S,4)
ELSE
  Z0(1)=SQRT(ZP(1)**2*ZC(1))
  Z0(2)=SQRT(ZP(2)**2*ZC(2))
  Z0(3)=Z0(2)
  Z0(4)=Z0(1)
ENDIF
IF (M.EQ.3) THEN
WRITE(2,*),'
WRITE(2,*),'OPTIMIZED TERMINATING IMPEDANCES (ohm)'
WRITE(2,*),'
WRITE(2,*),' ITERATION Z0(1)=Z0(4) Z0(2)=Z0(3)'
DO 85 I=1,10
  WRITE(2,*)'I-1,Z0(1),Z0(2)
    CALL NMP2ZM(F0,L,RC,RP,VC,VP,ZC1D,ZP1D,Z)
    CALL ZTOS(Z,Z0,S,4)
    K1=(S(1,4)**2-S(1,1)**2-1)/S(1,1)
    K2=(S(2,3)**2-S(2,2)**2-1)/S(2,2)
    Z0(1)=Z0(1)*SQRT((K1/2-1)/(K1/2+1))
    Z0(2)=Z0(2)*SQRT((K2/2-1)/(K2/2+1))
    Z0(3)=Z0(2)
    Z0(4)=Z0(1)
  85  CONTINUE
ENDIF
WRITE(2,*),'PORT TERMINATING IMPEDANCES:,'
DO 95 I=1,4
  WRITE(2,97)I,Z0(I)
  97  FORMAT(1X,'Z0( ',I2,') = ',F10.4)
WRITE(2,*),'
WRITE(6,*)'DO A FREQUENCY SWEEP (Y,N)?'
READ(5,5)ANS
WRITE(2,*),'Z AND S MATRIX AT CENTER FREQUENCY'
NAME='Z'
CALL PRINTZ(4,4,Z,NAME)
NAME='S'
CALL PRINTZ(4,4,S,NAME)
CALL VSWRNB(4,S,NAME)
IF ((ANS.EQ. ’Y’).OR.(ANS.EQ. ’y’)) THEN
  C-----FREQUENCY SWEEP------
WRITE(*,*)'
WRITE(6,*),'ENTER START, STOP, AND STEP FREQUENCIES'
READ(5,*)FST,FND,DF
F=FST
NFR=(FND-FST)/DF+1
DO 100 I=1,NFR
  WRITE(2,*)'
    WRITE(2,*),' FREQUENCY = ',F
    CALL NMP2ZM(F,L,RC,RP,VC,VP,ZC1D,ZP1D,Z)
    CALL ZTOS(Z,Z0,S,4)
    NAME='Z'
  100 CONTINUE
CALL PRINTZ (4, 4, Z, NAME)
NAME = 'S'
CALL PRINTZ (4, 4, S, NAME)
CALL VSWMDB (4, S, NAME)
F = F + DF
100
CONTINUE
ENDIF
WRITE (6, *) 'ANALYSIS COMPLETE'
WRITE (6, *) 'RESULTS IN DATA FILE: ', OUTFILE, '.DAT'
CLOSE (UNIT=1)
CLOSE (UNIT=2)
END
SUBROUTINE NMP22M (F, L, RC, RP, VC, VP, ZC1, ZP1, Z)
COMPLEX J, COTHCC, COTHFP, CSCHC, CSCHF
COMPLEX Z (22, 22)
REAL D1, D2, F, GC, GP, L, RC, RP, VC, VP, W, ZC1, ZP1, PI
J = (0.0, 1.0)
PI = 4.0 * ATAN (1.0)
W = F * 2.0 * PI
GC = W / VC
GP = W / VP
COTHCC = J / TAN (GC*L)
COTHFP = J / TAN (GP*L)
CSCHC = J / SIN (GC*L)
CSCHF = J / SIN (GP*L)
D1 = 1.0 - RC / RP
D2 = 1.0 - RP / RC
Z (1, 1) = ZC1 * COTHCC / D1 + ZP1 * COTHFP / D2
Z (1, 2) = ZC1 * RC * COTHCC / D1 + ZP1 * RP * COTHFP / D2
Z (1, 3) = ZC1 * RC * CSCHCC / D1 + ZP1 * RP * CSCHFP / D2
Z (1, 4) = ZC1 * CSCHCC / D1 + ZP1 * CSCHFP / D2
Z (2, 2) = ZC1 * RC * Z * COTHCC / D1 + ZP1 * RP * Z * COTHFP / D2
Z (2, 3) = ZC1 * RC * Z * CSCHCC / D1 + ZP1 * RP * Z * CSCHFP / D2
Z (4, 4) = Z (1, 1)
Z (2, 1) = Z (1, 2)
Z (3, 4) = Z (1, 2)
Z (4, 3) = Z (1, 2)
Z (3, 1) = Z (1, 3)
Z (2, 4) = Z (1, 3)
Z (4, 2) = Z (1, 3)
Z (4, 1) = Z (1, 4)
Z (3, 3) = Z (2, 2)
Z (3, 2) = Z (2, 3)
RETURN
END
C*****************************************************************************
C THIS SUBROUTINE COMPUTES THE ELEMENTS OF THE S-MATRIX FROM
C THOSE OF Z-MATRIX OF AN N-MULTIPORT NETWORK. THE ELEMENTS
C OF THE ZO(N) ARE THE CHARACTERISTIC IMPEDANCES OF THE TRANS.
C LINES CONNECTED TO THE N-MULTIPORT NETWORK.
SUBROUTINE ZTOS (Z, Z0, S, N)
DIMENSION Z0 (20)
COMPLEX Z1 (22, 22), S (22, 22), Z (22, 22)
COMPLEX C (22, 22)
DO 10 I = 1, N
DO 10 J = 1, N
Z1 (I, J) = Z (I, J)
10 S (I, J) = 0.
DO 20 I = 1, N
DO 15 J = 1, N
C (I, J) = Z (I, J)
C (I, I) = C (I, I) + Z0 (I)
20 CONTINUE
15 RETURN
C*****************************************************************************
20   Z1(I,I)=Z1(I,I)-Z0(I)
     CALL MATINC(C,N)
     CALL CMTULT(N,N,N,Z1,C,S)
     DO 30 I=1,N
         DO 30 J=1,N
             CON1=SQRT(Z0(I)/Z0(J))
             S(I,J)=S(I,J)/CON1
     RETURN
     END

C***********************************************************************************************
C  THIS SUBROUTINE SETS THE MULTIPLICATION OF THE TWO MATRIX
C  A(L,N) AND B(M,N) TO OBTAIN THE MATRIX C(L,M).
C***********************************************************************************************
SUBROUTINE CMTULT(L,M,N,A,B,C)
     COMPLEX A(22,22), B(22,22), C(22,22)
     DO 3 I=1,L
         DO 3 J=1,N
             C(I,J)=0.0
             DO 3 K=1,M
                 C(I,J)=C(I,J)+A(I,K)*B(K,J)
     RETURN
     END

C***********************************************************************************************
C  THIS SUBROUTINE COMPUTES THE INVERSE OF THE MATRIX A(N,N).
C  *****WARNING****; THE INVERSE OF A IS FILLED INTO A ITSELF.
C***********************************************************************************************
SUBROUTINE MATINC(A,N)
     DIMENSION INDEX(20,3)
     COMPLEX T, SWAP, PIVOT, A(22,22)
     EQUIVALENCE (IROW, JROW), (ICOLUM, JCOLUMN)
     DO 10 J=1,N
         INDEX(J,3)=0
     DO 90 I=1,N
         AMAX=0.0
     DO 80 J=1,N
         IF (INDEX(J,3).EQ.1) GO TO 40
     DO 30 K=1,N
         IF (INDEX(K,3)-1) 20, 30, 115
     20  IF (AMAX.GE.CABS(A(J,K))) GO TO 30
         IROW=J
         ICOLUMN=K
         AMAX=CABS(A(J,K))
     30  CONTINUE
     40  CONTINUE
     INDEX(ICOLUMN,3)=INDEX(ICOLUMN,3)+1
     INDEX(I,1)=IROW
     INDEX(I,2)=ICOLUMN
     IF (IROW.EQ.ICOLUMN) GO TO 60
     DO 50 L=1,N
         SWAP=A(IROW,L)
         A(IROW,L)=A(ICOLUMN,L)
     50  A(ICOLUMN,L)=SWAP
     DO 60 K=1,N
         PIVOT=A(ICOLUMN,ICOLUMN)
         A(ICOLUMN,ICOLUMN)=1.0
     60  DO 70 L=1,N
         A(ICOLUMN,L)=A(ICOLUMN,L)/PIVOT
     DO 90 L1=1,N
         IF (L1.EQ.ICOLUMN) GO TO 90
         T=A(L1,ICOLUMN)
         A(L1,ICOLUMN)=0.0
         DO 80 L=1,N
             A(L1,L)=A(L1,L)-A(ICOLUMN,L)*T
     80  CONTINUE
     DO 110 I=1,N
L=N-I+1
IF(INDEX(L,1).EQ.INDEX(L,2))GO TO 110
JROW=INDEX(L,1)
JCOLUMN=INDEX(L,2)
DO 100 K=1,N
SWAP=A(K,JROW)
A(K,JROW)=A(K,JCOLUMN)
100 A(K,JCOLUMN)=SWAP
110 CONTINUE
115 CONTINUE
RETURN
END

C******************************************************************************
SUBROUTINE PRINT2(M,N,AMAT,NAME)
C-----THIS SUBROUTINE IS USED TO PRINT THE ELEMENT OF THE
C-----MATRIX AMAT(M,N). THE COLUMNS ARE PRINTED ONE AT A TIME.
C
C COMPLEX AMAT(22,22)
CHARACTER*12 NAME
C
WRITE(2,*), ', NAME
DO 3 J=1,N
WRITE(2,1)NAME
DO 3 I=1,M
WRITE(2,4)I, AMAT(I,J),CABS(AMAT(I,J)),ANGLE(AMAT(I,J))
3 WRITE(2,1)NAME
RETURN
END

C******************************************************************************
SUBROUTINE VSRNDB(NEXIT,SM,NAME)
C-----THIS SUBROUTINE IS TO COMPUTE VSR AT EACH EXTERNAL PORT AND
C-----EXPRESS ELEMENTS OF S MATRIX IN [DB] (20*LOGSIJ) & PRINT THESE
C
REAL COLSM(22),VSR
COMPLEX SM(22,22)
CHARACTER*12 NAME
C
WRITE(2,1)NAME
WRITE(6,1)NAME
DO 10 I=1,NEXIT
VSR = (1 + CABS(SM(I,I)) / (1 - CABS(SM(I,I))))
DO 20 J=1,NEXIT
COLSM(J) = CABS(SM(I,J))
20 CONTINUE
WRITE(2,2)I,VSR,(20*ALOG10(COLSM(J)),J=1,NEXIT)
C
10 CONTINUE
WRITE(2,*)',
C-----FORMAT STATEMENTS SECTION-----
1 FORMAT(/,4X,'PORT#',7X,'VSR',15X,
> 'ELEMENTS OF MATRIX ',A5,' IN [DB]',
> '---------',7X,'-----',15X,
> '--------------------------',/)
2 FORMAT(5X,I3,3X,F10.4,7X,F10.4)
C
RETURN
END

FUNCTION ANGLE(C)
C-----THIS FUNCTION COMPUTES THE ARGUMENT OF A COMPLEX QUANTITY.
C
COMPLEX C
REAL ANGLE, PI
C
PI = 4. * ATAN(1.)
IF (REAL(C) .NE. 0.) THEN
   ANGLE = ATAN2(IMAG(C), REAL(C)) * 180 / PI
ELSE IF (IMAG(C) .GT. 0.) THEN
   ANGLE = 90.
ELSE IF (IMAG(C) .LT. 0.) THEN
   ANGLE = -90.
END IF
RETURN
END
C*********************************************************************************
$ RUN ASSYM CPL

-------------------------------

PROGRAM ASSYM CPL
FOR ANALYSIS OF TWO LINE DIRECTIONAL COUPLER

INPUT 1-----------------4
COUPLED 2-----------------3
THRU ISOLATED

MIMICAD CENTER
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425

-------------------------------

ENTER OUTPUT FILE NAME
NOTE: FILE.DAT <= 12 CHARACTERS
AOUT

ENTER 1 IF CD AND L MATRICES ARE TO BE INPUT
ENTER 2 IF CD AND CA MATRICES ARE TO BE INPUT
1

READ LINE PARAMETER DATA FROM INPUT FILE (Y/N)?
Y

ENTER INPUT FILE NAME (NAME.DAT <= 12 CHAR.)
AIN

*****NORMAL MODE PARAMETERS*****

Rc, Rpi = 0.8359067 -3.153700
Vc, Vpi = 1.0564544E+08 1.1848107E+08

Eeff(c) = 8.052669
Zl(c), Z2(c) = 85.29450 224.8535

Eeff(pi) = 6.402409
Zl(pi), Z2(pi) = 10.28877 27.12325

ENTER CENTER OPERATING FREQUENCY IN Hz
10E9

ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT
ENTER 2 TO USE QUARTER WAVE SECTION
2

ENTER 1 IF ALL PORT TERMINATING IMPEDANCES ARE TO BE INPUT
ENTER 2 TO USE Z0(i)=SQR(T{Zl,2(c)*Z2,2(pi)})
ENTER 3 TO CALCULATE MATCHING TERMINATING IMPEDANCES (S11=0, S22=0)
3

DO A FREQUENCY SWEEP (Y,N)?
N

ANALYSIS COMPLETE
RESULTS IN DATA FILE: AOUT .DAT

$
CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)
CD (1, 1) = 259.6000
CD (1, 2) = -177.8000
CD (2, 1) = -177.8000
CD (2, 2) = 254.8000

INDUCTANCE COEFFICIENTS (nH/m)
L(1, 1) = 656.4000
L(1, 2) = 476.1000
L(2, 1) = 476.1000
L(2, 2) = 626.9000

*****NORMAL MODE PARAMETERS*****
Rc, Rpi = 0.8359067 -3.153700
Vc, Vpi = 1.0564544E+08 1.1848107E+08

Eeff(c) = 8.052669
Z1(c), Z2(c) = 85.29450 224.8535

Eeff(p) = 6.402409
Z1(pi), Z2(pi) = 10.28877 27.12325

CENTER FREQUENCY F0 = 10.00000 GHz

TRANSMISSION LINE LENGTH L = 2.7923926E-03 METERS

OPTIMIZED TERMINATING IMPEDANCES (ohm)

<table>
<thead>
<tr>
<th>ITERATION</th>
<th>Z0(1) = Z0(4)</th>
<th>Z0(2) = Z0(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>29.62391</td>
<td>78.09455</td>
</tr>
<tr>
<td>1</td>
<td>56.74392</td>
<td>40.67979</td>
</tr>
<tr>
<td>2</td>
<td>45.75137</td>
<td>50.36908</td>
</tr>
<tr>
<td>3</td>
<td>49.25776</td>
<td>46.76228</td>
</tr>
<tr>
<td>4</td>
<td>48.00214</td>
<td>47.97420</td>
</tr>
<tr>
<td>5</td>
<td>48.43106</td>
<td>47.54651</td>
</tr>
<tr>
<td>6</td>
<td>48.28049</td>
<td>47.69342</td>
</tr>
<tr>
<td>7</td>
<td>48.33231</td>
<td>47.64195</td>
</tr>
<tr>
<td>8</td>
<td>48.31417</td>
<td>47.65697</td>
</tr>
<tr>
<td>9</td>
<td>48.32042</td>
<td>47.65347</td>
</tr>
</tbody>
</table>

PORT-TERMINATING IMPEDANCES:
Z0 (1) = 48.3182
Z0 (2) = 47.6556
Z0 (3) = 47.6556
Z0 (4) = 48.3182

Z AND S MATRIX AT CENTER FREQUENCY

ELEMENTS OF MATRIX Z

ELEMENTS OF COLUMN# 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>0.5887295723E+01</td>
<td>0.5887295723E+01</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>0.5697010994E+01</td>
<td>0.5697010994E+01</td>
<td>90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.4976250458E+02</td>
<td>0.4976250458E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00000000000E+00</td>
<td>-0.6986170959E+02</td>
<td>0.6986170959E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

ELEMENTS OF COLUMN# 2

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>0.5697010994E+01</td>
<td>0.5697010994E+01</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>0.2315589905E+01</td>
<td>0.2315589905E+01</td>
<td>90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.6883018494E+02</td>
<td>0.6883018494E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>PORT#</td>
<td>VSWR</td>
<td>ELEMENTS OF MATRIX S IN [DB]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
<td>-----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.0857</td>
<td>-27.7261 -2.9107 -27.9599 -3.1415</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.0856</td>
<td>-2.9107 -27.7318 -3.1415 -27.9599</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>1.0856</td>
<td>-27.9599 -3.1415 -27.7318 -2.9107</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>1.0857</td>
<td>-3.1415 -27.9599 -2.9107 -27.7261</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PROGRAM RENTCPL

PROGRAM FOR THE ANALYSIS OF A 3-CONDUCTOR COUPLED TRANSMISSION LINE RE-ENTRANT TYPE DIRECTIONAL COUPLER

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PROGRAM RENTCPL
PROGRAM FOR ANALYSIS OF SYMMETRIC THREE CONDUCTOR COUPLED
TRANSMISSION LINE
RE-ENTRANT TYPE COUPLER

1-------------------4
OPEN-----------------OPEN
2-------------------3

INPUT: C MATRICES OR C AND L MATRICES
OUTPUT: NORMAL MODE PARAMETERS
          OPTIMIZED TERMINATING IMPEDANCES
          Z MATRIX
          S MATRIX
          FREQUENCY SWEEP

BY: ANTHONY J. VERGAMINI
    MIMICAD CENTER, UNIVERSITY OF COLORADO, BOULDER

CHARACTER*12 ANS, INFILE, OUTFILE, NAME
COMPLEX J, Z (34, 34), ZN (34, 34), S (34, 34), CA (34, 34)
COMPLEX COTH, COTHB, COTHC, CSCHA, CSCHB, CSCHC, K1, K2
DIMENSION CA (34, 34), CD (34, 34), Z0 (34)
REAL L (34, 34)
INTEGER I, K, M, N, NFR, P, Q
REAL A1, A2, A3, A4, A5, BA, BB, BC, C, DF, E0, EA, EB, EC, F0, F, FGH, FST, FND
REAL LL, PI, RI, R2, RV1, RV2, R11, R12, RD, U0, VA, VB, VC, VBC1, VBC2, W
REAL ZA1, ZA3, ZB1, ZB3, ZC1, ZC3, ZB2, ZC2

C=2.99792 45838E8
PI=4.0*ATAN(1.0)
E0=3.854187E-12
U0=4*PI*1E-7
J=(0.0, 1.0)

FORM (A12)
WRITE (*, *)
WRITE (*, *) ' PROGRAM RENTCPL'
WRITE (*, *) ' FOR ANALYSIS OF RE-ENTRANT TYPE DIRECTIONAL'
WRITE (*, *) ' COUPLER'
WRITE (*, *)
WRITE (*, *) ' INPUT 1-------------------4 THRU'
WRITE (*, *) ' OPEN ============= OPEN'
WRITE (*, *) ' COUPLED 2-------------------3 ISOLATED'
WRITE (*, *)
WRITE (*, *)
WRITE (*, *) ' MIMICAD CENTER'
WRITE (*, *) ' DEPARTMENT OF ELECTRICAL ENGINEERING'
WRITE (*, *) ' UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425'
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *)
WRITE (*, *) ' ENTER OUTPUT FILENAME'
WRITE (*, *) ' NOTE: FILE.DAT <= 12 CHARACTERS'
READ (S, 5) OUTFILE
WRITE (*, *)
OPEN (UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
WRITE (*, *) ' ENTER 1 IF CD AND L MATRICES ARE TO BE INPUT'
WRITE (*, *) ' ENTER 2 IF CD AND CA MATRICES ARE TO BE INPUT'
READ(*,*) P
WRITE(*,*)',
WRITE(*,*)'READ LINE PARAMETER DATA FROM INPUT FILE (Y/N)'
READ(5,5)ANS
WRITE(*,*)'
IF (ANS.EQ.'Y') .OR. (ANS.EQ.'y') THEN
   WRITE(*,*)'ENTER INPUT FILENAME (FILE.DAT <= 12 CHAR.)'
   READ(5,5)INFIL
   WRITE(*,*)'
   OPEN(UNIT=1,FILE=INFIL,STATUS='UNKNOWN')
   WRITE(2,*)'CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)'
   DO 10 I=1,3
      DO 10 K=1,3
         READ(1,*)CD(I,K)
         WRITE(2,37)I,K,CD(I,K)
    10 CONTINUE
   WRITE(2,*)'
   IF (P.EQ.2) THEN
      WRITE(2,*)'CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
      DO 15 I=1,3
         DO 15 K=1,3
            READ(1,*)CA(I,K)
            WRITE(2,47)I,K,CA(I,K)
    15 CONTINUE
   ELSE
      WRITE(2,*)'INDUCTANCE COEFFICIENTS (nH/m)'
      DO 17 I=1,3
         DO 17 K=1,3
            READ(1,*)L(I,K)
            WRITE(2,48)I,K,L(I,K)
      17 CONTINUE
   ENDIF
   WRITE(2,*)'
   WRITE(*,*)'ENTER INPUT FILE NAME FOR LINE PARAMETERS TO BE STORED'
   READ(5,5)INFIL
   WRITE(*,*)'
   OPEN(UNIT=1,FILE=INFIL,STATUS='UNKNOWN')
   WRITE(*,*)'ENTER CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)'
   WRITE(2,*)'
   WRITE(*,*)'
   WRITE(2,*)'
   IF (P.EQ.2) THEN
      WRITE(*,*)'ENTER CAPACITANCE COEFFICIENTS IN AIR (pF/m)'
      WRITE(*,*)'
      WRITE(2,*)'
      WRITE(2,*)'
      WRITE(*,*)'
      WRITE(*,*)'
      WRITE(2,43)I,K
      FORMAT(1X,'CA(''I2,'',''I2,'') = '')
      READ(*,*)CA(I,K)
      WRITE(2,47)I,K,CA(I,K)
      FORMAT(1X,'CA(''I2,'',''I2,'') = '',F10.4)
      WRITE(1,*)CA(I,K)
ELSE
WRITE(*,*)'ENTER INDUCTANCE COEFFICIENTS (nH/m)'
WRITE(*,*)'
WRITE(2,*),'INDUCTANCE COEFFICIENTS (nH/m)'
DO 45 I=1,3
   DO 45 K=1,3
      WRITE(*,46)I,K
      FORMAT(1X,'L(',I2,',',I2,') = ?')
      READ(*,*)L(I,K)
      WRITE(2,48)I,K,L(I,K)
   FORMAT(1X,'L(',I2,',',I2,') = ',F10.4)
   WRITE(1,*),L(I,K)
45 CONTINUE
ENDIF
ENDIF
WRITE(2,*)'
C------FOR INPUT CA CALC L------CHANGE TO SI UNITS------
IF (F.EQ.2) THEN
   DO 70 I=1,3
      DO 70 K=1,3
         CD(I,K)=1E-12*CD(I,K)
         CA(I,K)=1E-12*CA(I,K)
      70 CONTINUE
   DO 75 K=1,3
      CAC(I,K)=CA(I,K)
   75 CONTINUE
   CALL MATINC(CAC,3)
   DO 80 I=1,3
      DO 80 K=1,3
         L(I,K)=U0*E0*CAC(I,K)
      80 CONTINUE
   ELSE
      DO 85 I=1,3
         DO 85 K=1,3
            CD(I,K)=1E-12*CD(I,K)
            L(I,K)=1E-9*L(I,K)
         85 CONTINUE
   ENDIF
C------CALCULATE NORMAL MODE PARAMETERS------
A1=L(1,1)*CD(1,1)+L(1,2)*CD(1,2)+L(1,3)*CD(1,3)
A2=L(1,1)*CD(1,2)+L(1,2)*CD(2,2)+L(1,3)*CD(1,2)
A3=L(1,1)*CD(1,3)+L(1,2)*CD(1,2)+L(1,3)*CD(1,1)
A4=L(1,2)*CD(1,1)+L(2,2)*CD(1,2)+L(1,2)*CD(1,3)
A5=2*L(1,2)*CD(1,2)+L(2,2)*CD(2,2)
C------PHASE VELOCITIES------
VA=1/SQRT(A1-A3)
VBC1=(A1+A3+A5)/2
VBC2=SQR((A1+A3-A5)**2+8*A2*A4)/2
VB=1/SQRT(VBC1+VBC2)
VC=1/SQRT(VBC1-VBC2)
C------EFFECTIVE DIELECTRIC CONSTANTS------
EA=(C/VA)**2
EB=(C/VB)**2
EC=(C/VC)**2
C------VOLTAGE AND CURRENT RATIO PARAMETERS------
R1=-(A1+A3-A5)/(2*A2)
R2=SQR(((A1+A3-A5)/(2*A2))**2+2*A4/A2)
RV1=R1+R2
RV2=R1-R2
RI1=-2/RV2
RI2=-2/RV1
C------CHARACTERISTIC IMPEDANCES------
ZA1=1/(VA*(CD(1,1)-CD(1,3)))
ZB1=1/(VB*(CD(1,1)+CD(1,3)+RV1*CD(1,2)))
C----TRANSMISSION LINE LENGTH-----
WRITE(*,*) 'ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT'
WRITE(*,*) 'ENTER 2 TO USE A QUARTER WAVE SECTION'
READ(*,*) M
WRITE(*,*) '
IF (M.EQ.2) THEN
WRITE(*,*) 'ENTER CENTER FREQUENCY IN Hz'
READ(*,*)F0
FGH=F0/2E9
LL=3*C/(4*F0*(SQRTEA)+SQRTEB)+SQRTEC)
ELSE
WRITE(*,*) 'ENTER L IN METERS'
READ(*,*) LL
ENDIF
WRITE(2,*) 'NORMAL MODE PARAMETERS'
WRITE(2,*) '
WRITE(2,*) RV1 , RV2 = ',RV1,RV2
WRITE(2,*) RI1 , RI2 = ',RI1,RI2
WRITE(2,*) 'EreA , EreB , EreC = ',EreA,EreB,EreC
WRITE(2,*) 'VA , VB , VC = ',VA,VB,VC, '(m/s)'
WRITE(2,*) ZA1 = ZA3 = ',ZA1
WRITE(2,*) ZB1 = ZB3 = ',ZB1
WRITE(2,*) ZB2 = ',ZB2,' (ohm)'
WRITE(2,*) ZC1 = ZC3 = ',ZC1
WRITE(2,*) ZC2 = ',ZC2
WRITE(2,*) '
WRITE(2,*) CENTER FREQUENCY  F0 = ',FGH,' GHz'
WRITE(2,*) '
WRITE(2,*) LENGTH OF TRANSMISSION LINE:  L = ',LL,' METERS'
WRITE(2,*) '
C----TERMINATING IMPEDANCES-----
WRITE(*,*) '
WRITE(*,*) 1 ENTER PORT TERMINATING IMPEDANCES (ohm)'
WRITE(*,*) 2 OPTIMIZE Z0(i) FOR S11=0, S22=0'
READ(*,*) Q
WRITE(*,*) '
IF (Q.EQ.1) THEN
DO 90 I=1,4
90 WRITE(*,97) I
FORMAT(1X,'Z0(',I2,') = ?')
READ(*,*)Z0(I)
97 CONTINUE
ELSE
DO 100 I=1,4
100 Z0(I)=50
CONTINUE
WRITE(2,*) 'OPTIMIZED TERMINATING IMPEDANCES (ohm)'
WRITE(2,*) '
WRITE(2,*) ITERATION Z0(1)=Z0(4) Z0(2)=Z0(3)'
DO 110 I=1,10
WRITE(2,*) I-1,Z0(1),Z0(2)
CALL NMPP2Z3(F0,LL,RV1,RV2,VA,VB,VC,ZA1,ZB1,ZB2,ZC1,ZC2,ZN)
CALL ZTOS2(ZN,Z0,S,4)
K1=(S(1,4)**2-S(1,1)**2-1)/S(1,1)
K2=(S(2,3)**2-S(2,2)**2-1)/S(2,2)
Z0(1)=Z0(1)*SQRTE((K1/2-1)/(K1/2+1))
Z0(2)=Z0(2)*SQRTE((K2/2-1)/(K2/2+1))
Z0(3)=Z0(2)
Z0(4)=Z0(1)
110 CONTINUE
ENDDO
WRITE(2,'(A)',A='PORT TERMINATING IMPEDANCES')
DO 120 I=1,4
     WRITE(2,'(A)'A=',Z0(I))
120 CONTINUE
WRITE(2,'(A)'A=' ')
C-----CALCULATE Z AND S FOR FREQUENCY RANGE-----
WRITE(*,'(A)'A='ENTER START, STOP, AND STEP FREQUENCIES (Hz)'
READ(5,*)FST,FND,DF
WRITE(*,'(A)'A='')
F=FST
FNST=(FND-FST)/DF+1
DO 500 I=1,NFR
     CALL NMP23(F,LL,RV1,RV2,VA,VB,VC,ZA1,ZB1,ZB2,ZC1,ZC2,ZN)
     CALL ZTOS(ZN,Z0,S,4)
     WRITE(2,'(A)'A='F = ',F/1E9,' GHz')
     WRITE(2,'(A)'A='')
     NAME='ZN'
     CALL PRINTZ(4,4,ZN,NAME)
     NAME='S'
     CALL PRINTZ(4,4,S,NAME)
     CALL VSWRNDBE(4,S,NAME)
     F=F+DF
500 CONTINUE
WRITE(*,'(A)'A='ANALYSIS COMPLETE'
WRITE(6,'(A)'A='RESULTS IN DATA FILE: ',OUTFILE,'.DAT'
END

C-------------------------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------------------
C SUBROUTINE NMP23(F,LL,RV1,RV2,VA,VB,VC,ZA1,ZB1,ZB2,ZC1,ZC2,ZN)
REAL BA,BB,BC,RV1,RV2,VA,VB,VC,ZA1,ZB1,ZB2,ZC1,ZC2
REAL F,LL,PI,RD,W
COMPLEX COTH,A,CO,CS,CSH,CSH
COMPLEX J,ZN(34,34),Z(34,34)
C
J=(0.0,1.0)
PI=4*ATAN(1.0)
C
W=2*PI*F
BA=W/VA
BB=W/VB
BC=W/VC
COTH=-J/TAN(BA*LL)
COTB=-J/TAN(BB*LL)
COTH=-J/TAN(BC*LL)
CSH=-J/SIN(BA*LL)
CSH=-J/SIN(BB*LL)
CSH=-J/SIN(BC*LL)
RD=RV1-RV2
Z(1,1)=(ZA1*COTH-(RV2*ZB1*COTB-RV1*ZC1*COTH)}/RD)/2
Z(1,2)=(ZB2*COTHB-ZC2*COTHC)/RD
Z(1,3)=(ZA1*COTH+(RV2*ZB1*COTB-RV1*ZC1*COTH)}/RD)/2
Z(1,4)=(ZA1*CSH+(RV2*ZB1*CSHB-RV1*ZC1*CSHCH)}/RD)/2
Z(1,5)=(ZB2*CSHB-ZC2*CSCH)/RD
Z(1,6)=(ZA1*CSH+(RV2*ZB1*CSHB-RV1*ZC1*CSHCH)}/RD)/2
Z(2,2)=(RV1*ZB2*COTB-RV2*ZC2*COTHC)/RD
Z(2,5)=(RV1*ZB2*CSHB-RV2*ZC2*CSCH)/RD
Z(3,3)=Z(1,1)
Z(4,4)=Z(1,1)
Z(6,6)=Z(1,1)
Z(2,1)=Z(1,2)
Z(2,3)=Z(1,2)
Z(3,2)=Z(1,2)
Z(4,5) = Z(1,2)
Z(5,4) = Z(1,2)
Z(5,6) = Z(1,2)
Z(6,5) = Z(1,2)
Z(3,1) = Z(1,3)
Z(4,6) = Z(1,3)
Z(6,4) = Z(1,3)
Z(4,1) = Z(1,4)
Z(3,6) = Z(1,4)
Z(6,3) = Z(1,4)
Z(5,1) = Z(1,5)
Z(2,4) = Z(1,5)
Z(4,2) = Z(1,5)
Z(3,5) = Z(1,5)
Z(5,3) = Z(1,5)
Z(2,6) = Z(1,5)
Z(6,2) = Z(1,5)
Z(6,1) = Z(1,6)
Z(3,4) = Z(1,6)
Z(4,3) = Z(1,6)
Z(5,5) = Z(2,2)
Z(5,2) = Z(2,5)

C------REDUCE Z MATRIX TO FOUR PORT------
ZN(1,1) = Z(1,1)
ZN(1,2) = Z(1,3)
ZN(1,3) = Z(1,6)
ZN(1,4) = Z(1,4)
ZN(2,1) = Z(3,1)
ZN(2,2) = Z(3,3)
ZN(2,3) = Z(3,6)
ZN(2,4) = Z(3,4)
ZN(3,1) = Z(6,1)
ZN(3,2) = Z(6,3)
ZN(3,3) = Z(6,6)
ZN(3,4) = Z(6,4)
ZN(4,1) = Z(4,1)
ZN(4,2) = Z(4,3)
ZN(4,3) = Z(4,6)
ZN(4,4) = Z(4,4)

END

C-----------------------------------------------
C-----------------------------------------------
C SUBROUTINE Ztos(Z, Z0, S, N)
C------THIS SUBROUTINE COMPUTES THE ELEMENTS OF THE S-MATRIX FROM
C------THOSE OF THE Z-MATRIX OF AN N-MULTIPOORT NETWORK. THE ELEMENTS
C------OF THE Z0(N) ARE THE CHARACTERISTIC IMPEDANCES OF THE TRANS.
C------LINES CONNECTED TO THE N-MULTIPOORT NETWORK.
C
DIMENSION Z0(34)
COMPLEX Z1(34,34), S(34,34), Z(34,34)
COMPLEX C(34,34)
DO 10 I=1,N
DO 10 J=1,N
10    Z1(I,J) = Z(I,J)
      S(I,J) = 0.
    DO 20 I=1,N
    DO 15 J=1,N
15      C(I,J) = Z(I,J)
        C(I,I) = C(I,I) + Z0(I)
20      Z1(I,I) = Z1(I,I) - Z0(I)
    CALL MATINC(C,N)
    CALL CMULT(N,N,N,Z1,C,S)
DO 30 I=1,N
DO 30 J=1,N
    CON1 = SQRT(Z0(I)/Z0(J))
30    S(I,J) = S(I,J)/CON1
RETURN
END

C-------------------
SUBROUTINE CMULT(L,M,N,A,B,C)
C-----THIS SUBROUTINE SETS THE MULTIPLICATION OF THE TWO MATRIX
C-----A(L,M) AND B(M,N) TO OBTAIN THE MATRIX C(L,M).
C
COMPLEX A(34,34),B(34,34),C(34,34)
DO 3 I=1,L
DO 3 J=1,N
C(I,J)=0.0
DO 3 K=1,M
3 C(I,J)=C(I,J)+A(I,K)*B(K,J)
RETURN
END

C-------------------
SUBROUTINE MATINC(A,N)
C-----THIS SUBROUTINE COMPUTES THE INVERSE OF THE MATRIX A(N,N).
C-----*****WARNING*****; THE INVERSE OF A IS FILLED INTO A ITSELF.
C
DIMENSION INDEX(34,3)
COMPLEX T,SWAP,PIVOT,A(34,34)
EQUIVALENCE (IROW,JROW),(ICOLUM,JCOLUMN)
DO 10 J=1,N
10 INDEX(J,3)=0
DO 90 I=1,N
AMAX=0.0
DO 40 J=1,N
IF(INDEX(J,3).EQ.1) GO TO 40
DO 30 K=1,N
IF(INDEX(K,3)-1) 20,30,115
20 IF(AMAX.GE.CABS(A(J,K))) GO TO 30
IROW=J
ICOLUM=K
AMAX=CABS(A(J,K))
30 CONTINUE
40 CONTINUE
INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
INDEX(I,1)=IROW
INDEX(I,2)=ICOLUM
IF(IROW.EQ.ICOLUMN) GO TO 60
DO 50 L=1,N
SWAP=A(IROW,L)
A(IROW,L)=A(ICOLUMN,L)
A(ICOLUMN,L)=SWAP
50 PIVOT=A(ICOLUMN,ICOLUMN)
A(ICOLUMN,ICOLUMN)=1.0
DO 70 L=1,N
70 A(ICOLUMN,L)=A(ICOLUMN,L)/PIVOT
DO 90 LL=1,N
IF(LL.EQ.ICOLUMN) GO TO 90
T=A(LL,ICOLUMN)
A(LL,ICOLUMN)=0.0
DO 80 L=1,N
80 A(LL,L)=A(LL,L)-A(LL,L)*T
90 CONTINUE
DO 110 I=1,N
L=N-I+1
IF(INDEX(L,1).EQ.INDEX(L,2)) GO TO 110
JROW=INDEX(L,1)
JCOLUMN=INDEX(L,2)
DO 100 K=1,N
SWAP=A(K,JROW)
A(K,JROW)=A(K,JCOLUMN)
100 A(K,JCOLUMN)=SWAP
110 CONTINUE
CONTINUE
RETURN
END

C------------------------
SUBROUTINE PRINTZ(M,N,AMAT,NAME)
CHARACTER*12 NAME
COMPLEX AMAT(34,34)
INTEGER I,J,M,N
WRITE(2,1)NAME
DO 3 J=1,N
   WRITE(2,2)J
   DO 3 I=1,M
      WRITE(2,4)I,AMAT(I,J),CABS(AMAT(I,J)),ANGLE(AMAT(I,J))
 3 FORMAT(1X,'ELEMENTS OF MATRIX ',A15)
1 FORMAT(1X,'ELEMENTS OF COLUMN #:',I2,//4X,'ROW #:',5X,'REAL'
   ,10X,'IMAGINARY PT',12X,'MAGNITUDE',10X,'DEG.')
4 FORMAT(3X,I3,2X,(E18.10,2X),2X,E18.10,3X,F8.2)
WRITE(2,*)
RETURN
END

C------------------------
SUBROUTINE VSWRNDB(NEXPORT,SM,NAME)
CHARACTER*12 NAME
COMPLEX SM(34,34)
REAL COLSM(34)
WRITE(2,1)NAME
DO 10 I=1,NEXPORT
   VSWR=(1+CABS(SM(I,I)))/(1-CABS(SM(I,I)))
   DO 20 J=1,NEXPORT
      COLSM(J)=CABS(SM(I,J))
20 CONTINUE
   WRITE(2,2)I,VSWR,(20*ALOG10(COLSM(J)),J=1,NEXPORT)
10 CONTINUE
1 FORMAT(1X,'PORT #:',5X,'VSWR',20X,'ELEMENTS OF ',A5,' MATRIX IN dB')
2 FORMAT(I3,3X,F10.4,8X,4F10.4)
RETURN
END

C------------------------
FUNCTION ANGLE(C)
COMPLEX C
REAL ANGLE,PI
PI=4.0*ATAN(1.0)
IF (REAL(C).NE.0.0) THEN
   ANGLE=ATAN2(AIMAG(C),REAL(C))*180/PI
ELSEIF (AIMAG(C).GT.0.0) THEN
   ANGLE=90.0
ELSEIF (AIMAG(C).LT.0.0) THEN
   ANGLE=-90.0
ENDIF
RETURN
END
$ RUN RENTCPL

------------------------

PROGRAM RENTCPL
FOR ANALYSIS OF RE-ENTRANT TYPE DIRECTIONAL COUPLER

INPUT  1------------------------4 THRU
OPEN    2------------------------3 ISOLATED
COUPLER

MIMICAD CENTER
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425

------------------------

ENTER OUTPUT FILENAME
NOTE: FILE.DAT <= 12 CHARACTERS
ROUT

ENTER 1 IF CD AND L MATRICES ARE TO BE INPUT
ENTER 2 IF CD AND CA MATRICES ARE TO BE INPUT
1

READ LINE PARAMETER DATA FROM INPUT FILE (Y/N)?
Y

ENTER INPUT FILENAME (FILE.DAT <= 12 CHAR.)
SIN

ENTER 1 IF TRANSMISSION LINE LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2

ENTER CENTER FREQUENCY IN Hz
10E9

1 ENTER PORT TERMINATING IMPEDANCES (ohm)
2 OPTIMIZE ZO(i) FOR S11=0, S22=0
2

ENTER START, STOP, AND STEP FREQUENCIES (Hz)
10E9, 10E9, 1

ANALYSIS COMPLETE
RESULTS IN DATA FILE : ROUT .DAT

$
<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>175.000</td>
</tr>
<tr>
<td>-152.600</td>
</tr>
<tr>
<td>-23.40000</td>
</tr>
<tr>
<td>-152.600</td>
</tr>
<tr>
<td>496.9000</td>
</tr>
<tr>
<td>-152.600</td>
</tr>
<tr>
<td>-23.40000</td>
</tr>
<tr>
<td>-152.600</td>
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<td>175.000</td>
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<td>820.4000</td>
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<tr>
<td>484.2000</td>
</tr>
<tr>
<td>549.5000</td>
</tr>
<tr>
<td>484.2000</td>
</tr>
<tr>
<td>492.8000</td>
</tr>
<tr>
<td>484.2000</td>
</tr>
<tr>
<td>549.5000</td>
</tr>
<tr>
<td>484.2000</td>
</tr>
<tr>
<td>820.4000</td>
</tr>
</tbody>
</table>
CAPACITANCE COEFFICIENTS IN DIELECTRIC (pF/m)

CD(1, 1) = 175.0000
CD(1, 2) = -152.6000
CD(1, 3) = -23.4000
CD(2, 1) = -152.6000
CD(2, 2) = 496.9000
CD(2, 3) = -152.6000
CD(3, 1) = -23.4000
CD(3, 2) = -152.6000
CD(3, 3) = 175.0000

INDUCTANCE COEFFICIENTS (nH/m)

L(1, 1) = 820.4000
L(1, 2) = 484.2000
L(1, 3) = 549.5000
L(2, 1) = 484.2000
L(2, 2) = 492.8000
L(2, 3) = 484.2000
L(3, 1) = 549.5000
L(3, 2) = 484.2000
L(3, 3) = 820.4000

NORMAL MODE PARAMETERS

RV1 = 1.072693
RV2 = 0.1061617
R11 = -18.83918
R12 = -1.864466
EreA = 4.830499
EreB = 8.425365
EreC = 5.684505
VA = 1.3640325E+08
VB = 1.0328240E+08
VC = 1.2574027E+08

ZA1 = 36.95163
ZA2 = 800.6438
ZA3 = 45.58846
(ZA) = (ohm)

ZB1 = 58.73647
ZB2 = -3.344424
ZC1 = 10.00000
ZC2 = 3.0040496E-03

CENTER FREQUENCY F0 = 10.00000 GHz

LENGTH OF TRANSMISSION LINE: L = 3.0040496E-03 METERS

OPTIMIZED TERMINATING IMPEDANCES (ohm)

<table>
<thead>
<tr>
<th>ITERATION</th>
<th>Z0(1)=Z0(4)</th>
<th>Z0(2)=Z0(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50.000000</td>
<td>50.000000</td>
</tr>
<tr>
<td>1</td>
<td>68.84904</td>
<td>68.84902</td>
</tr>
<tr>
<td>2</td>
<td>73.94189</td>
<td>73.94191</td>
</tr>
<tr>
<td>3</td>
<td>75.20798</td>
<td>75.20796</td>
</tr>
<tr>
<td>4</td>
<td>75.51351</td>
<td>75.51351</td>
</tr>
<tr>
<td>5</td>
<td>75.58669</td>
<td>75.58669</td>
</tr>
<tr>
<td>6</td>
<td>75.60417</td>
<td>75.60419</td>
</tr>
<tr>
<td>7</td>
<td>75.60835</td>
<td>75.60835</td>
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<tr>
<td>8</td>
<td>75.60936</td>
<td>75.60936</td>
</tr>
<tr>
<td>9</td>
<td>75.60960</td>
<td>75.60960</td>
</tr>
</tbody>
</table>

PORT TERMINATING IMPEDANCES

Z0(1) = 75.60965
Z0(2) = 75.60966
Z0(3) = 75.60966
Z0(4) = 75.60965

F = 10.00000 GHz

ELEMENTS OF MATRIX ZN

ELEMENTS OF COLUMN# 1
<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>0.5771224976E+01</td>
<td>0.5771224976E+01</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>0.1276407623E+02</td>
<td>0.1276407623E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.5932983398E+02</td>
<td>0.5932983398E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00000000000E+00</td>
<td>-0.9693731689E+02</td>
<td>0.9693731689E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 2**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>0.1276407623E+02</td>
<td>0.1276407623E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>0.5771224976E+01</td>
<td>0.5771224976E+01</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.9693731689E+02</td>
<td>0.9693731689E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00000000000E+00</td>
<td>-0.5932983398E+02</td>
<td>0.5932983398E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 3**

<table>
<thead>
<tr>
<th>ROW#</th>
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<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>-0.5932983398E+02</td>
<td>0.5932983398E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>-0.9693731689E+02</td>
<td>0.9693731689E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>0.1276407623E+02</td>
<td>0.1276407623E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00000000000E+00</td>
<td>0.5771224976E+01</td>
<td>0.5771224976E+01</td>
<td>90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 4**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
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<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>-0.5932983398E+02</td>
<td>0.5932983398E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>-0.9693731689E+02</td>
<td>0.9693731689E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
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**ELEMENTS OF MATRIX S**

**ELEMENTS OF COLUMN# 1**

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<th>DEG.</th>
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**ELEMENTS OF COLUMN# 4**

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PROGRAM MBALUN

PROGRAM FOR THE ANALYSIS OF A PLANAR COUPLED TRANSMISSION LINE MARCHAND TYPE BALUN
ANALYSIS FOR TWO COUPLED LINE SECTIONS ONLY

MBALUN.FOR code listing .........................122
Running MBALUN .................................132
Input File MIN.DAT ..............................133
Output File MOUT.DAT .........................134
C----- PROGRAM MBALUN -----C
C PROGRAM FOR ANALYSIS OF PLANAR MARCHAND BALUN STRUCTURE
C ANALYSIS FOR TWO COUPLED LINE SECTIONS ONLY
C
C 1-----------------------------OPEN
C 2 3--------------------------SHORT
C
C INPUT : C MATRICES
C OUTPUT: NORMAL MODE PARAMETERS FOR TWO SECTIONS
C        Z MATRIX
C        S MATRIX
C        FREQUENCY SWEEP
C
C BY: ANTHONY J. VERCAMINI
C MIMICAD CENTER, UNIVERSITY OF COLORADO, BOULDER
C
C CHARACTER*12 ANS, INFILE, OUTFILE, NAME
C COMPLEX J (34, 34), ZB (34, 34), ZCC (34, 34), ZPP (34, 34)
C COMPLEX Z (34, 34), S (34, 34)
C DIMENSION A (2), A1 (2), A2 (2), A3 (2), A4 (2), CA (2, 4), CD (2, 4)
C DIMENSION EN (2), ED (2), EC (2), EP (2), EC (2), RP (2), VC (2), VP (2)
C DIMENSION ZT (34), ZC (2, 2), ZP (2, 2), ZO (3)
C INTEGER I, K, M, N, NFR, TYP
C REAL F, F0, FGH, FST, FND, DF, LD, RCD, RPD, VCD, VPD, ZC1D, ZP1D
C REAL L (2)
C
C C=2.99792458e8
C PI=4.0*ATAN(1.0)
C
C S FORMAT(A12)
C WRITE(*,*)'---------------------------------------------'
C WRITE(*,*)','
C WRITE(*,*)'PROGRAM MBALUN'
C WRITE(*,*)'FOR ANALYSIS OF PLANAR MARCHAND BALUN'
C WRITE(*,*)'ANALYSIS FOR TWO COUPLED LINE SECTIONS ONLY'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'1-----------------------------OPEN'
C WRITE(*,*)'SHORT-------------------2 3----------------SHORT'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C WRITE(*,*)'
C C-----INPUT SECTION-----
C WRITE(*,*)'ENTER OUTPUT FILENAME'
C READ(5,5) OUTFILE
C WRITE(*,*)'
C OPEN(UNIT=2, FILE=OUTFILE, STATUS='UNKNOWN')
C WRITE(*,*)'READ CAPACITANCE DATA FROM INPUT FILE (Y/N)'
C READ(5,5) ANS
C WRITE(*,*)'
C IF ((ANS.EQ. 'Y').OR. (ANS.EQ. 'y')) THEN
C WRITE(*,*)'ENTER INPUT FILENAME'
C READ(5,5) INFFILE
C WRITE(*,*)'
OPEN (UNIT=1, FILE=INFILE, STATUS='UNKNOWN')
DO 6 N=1,2
   DO 7 I=1,2
      DO 7 K=1,2
      READ (1,*) CD(N,I,K)
    CONTINUE
DO 8 I=1,2
   DO 8 K=1,2
      READ (1,*) CA(N,I,K)
  CONTINUE
GOTO 10
ENDIF
DO 10 N=1,2
WRITE (*,17) N
17 FORMAT (1X, 'ENTER CAPACITANCE MATRICES >FOR SECTION', I2, ' IN pF/m')
   DO 20 I=1,2
      DO 20 K=1,2
      WRITE (*,27) I,K
      FORMAT (1X, 'CD(', I2, ',', I2, ') = ?')
      READ (*,*) CD(N,I,K)
    CONTINUE
WRITE (*,*) '
   DO 30 I=1,2
      DO 30 K=1,2
      WRITE (*,33) I,K
      FORMAT (1X, 'CA(', I2, ',', I2, ') = ?')
      READ (*,*) CA(N,I,K)
30 CONTINUE
WRITE (2,*) '
10 CONTINUE
   DO 35 N=1,2
      WRITE (2,36) N
36 FORMAT (1X, 'CAPACITANCE MATRICES FOR SECTION', I2, ' IN pF/m')
   DO 37 I=1,2
      DO 37 K=1,2
      WRITE (2,34) I,K,CD(N,I,K)
      FORMAT (1X, 'CD(', I2, ',', I2, ') = ',F10.4)
    CONTINUE
WRITE (2,*) '
   DO 38 I=1,2
      DO 38 K=1,2
      WRITE (2,39) I,K,CA(N,I,K)
      FORMAT (1X, 'CA(', I2, ',', I2, ') = ',F10.4)
38 CONTINUE
WRITE (2,*) '
35 CONTINUE
WRITE (*,*) 'ENTER CENTER FREQUENCY IN Hz'
READ (*,*) F0
WRITE (*,*) '
F0=F0/1E9
C------CALCULATE NORMAL MODE PARAMETERS------
DO 40 N=1,2
   A1(N)=(CD(N,1,1)*CA(N,2,2)-CA(N,1,1)*CD(N,2,2))**2
   A3(N)=-CD(N,2,2)*CA(N,1,2)+CA(N,2,2)*CD(N,1,2)
   A4(N)=-CD(N,1,1)*CA(N,1,2)+CA(N,1,1)*CD(N,1,2)
   A2(N)=4*A3(N)*A4(N)
A(N)=A1(N)+A2(N)
   EN(N)=CD(N,1,1)*CA(N,2,2)+CA(N,1,1)*CD(N,2,2)
      -2*CA(N,1,2)*CD(N,1,2)
   ED(N)=2*(CA(N,1,1)*CA(N,2,2)-CA(N,1,2)**2)
   EC(N)=(EN(N)+SQRT(A(N)))/ED(N)
   EP(N)=(EN(N)-SQRT(A(N)))/ED(N)
   RC(N)=(CD(N,1,1)-EC(N)*CA(N,1,1))/(-CD(N,1,2)+EC(N)*CA(N,1,2))
   RP(N)=(CD(N,1,1)-EP(N)*CA(N,1,1))/(-CD(N,1,2)+EP(N)*CA(N,1,2))
VC(N) = C/SQRT(EC(N))
VP(N) = C/SQRT(EP(N))
ZG(N,1) = 1.0E12/VC(N)*(CD(N,1,1) + CD(N,1,2)*RC(N))
ZG(N,2) = 1.0E12/VC(N)*(CD(N,2,2) + CD(N,1,2)/RC(N))
ZP(N,1) = 1.0E12/VP(N)*(CD(N,1,1) + CD(N,1,2)*RP(N))
ZP(N,2) = 1.0E12/VP(N)*(CD(N,2,2) + CD(N,1,2)/RP(N))

WRITE(*,77)N
77 FORMAT(1X,'ENTER 1 IF SECTION ',I2,' LENGTH IS TO BE INPUT')
WRITE(*,*)N
READ(*,*)M
WRITE(*,*,*)
IF (N.EQ.2) THEN
  L(N) = C/(2*F0*(SQRT(EC(N)) + SQRT(EP(N)))))
ELSE
  WRITE(*,78)N
78 FORMAT(1X,'ENTER L(',I2,') IN METERS')
READ(*,*)L(N)
ENDIF
WRITE(2,*)'NORMAL MODE PARAMETERS FOR SECTION ',N
WRITE(2,*)
WRITE(2,*)  Rc ,  Rpi = ',RC(N),RP(N)
WRITE(2,*)  Vc ,  Vpi = ',VC(N),VP(N)
WRITE(2,*)  Eeffc ,  Eeffpi = ',EC(N),EP(N)
WRITE(2,*)  Zlc ,  Zlpi = ',ZC(N,1),ZP(N,1)
WRITE(2,*)  Z2c ,  Z2pi = ',ZC(N,2),ZP(N,2)
WRITE(2,*)

40 CONTINUE
WRITE(2,*)'CENTER FREQUENCY  F0 = ',F0,' GHz'
WRITE(2,*)
DO 50 N=1,2
WRITE(2,79)N,L(N)
79 FORMAT(1X,'LENGTH OF SECTION ',I2,' L = ',E10.4,' METERS')
50 CONTINUE
WRITE(2,*)
C-----CALCULATE Z MATRICES AT CENTER FREQUENCY-----
DO 60 N=1,2
LD = L(N)
RCD = RC(N)
RPD = RP(N)
VCD = VC(N)
VPD = VP(N)
ZC1D = ZC(N,1)
ZP1D = ZP(N,1)
IF (N.EQ.1) THEN
  CALL NMP2ZM(F0,LD,RCD,RPD,VCD,VPD,ZC1D,ZP1D,Z1)
ELSEIF (N.EQ.2) THEN
  CALL NMP2ZM(F0,LD,RCD,RPD,VCD,VPD,ZC1D,ZP1D,Z2)
ENDIF
60 CONTINUE
NAME = 'Z1'
C
CALL PRINTZ(4,4,Z1,NAME)
NAME = 'Z2'
C
CALL PRINTZ(4,4,Z2,NAME)
CALL REDUCE(Z1,Z2,ZA,ZBB)
NAME = 'ZA'
C
CALL PRINTZ(3,3,ZA,NAME)
NAME = 'ZBB'
C
CALL PRINTZ(2,2,ZBB,NAME)
CALL SEGMENT(ZA,ZBB,ZCC,ZV,2,1,1)
NAME = 'Z'
CALL PRINTZ(3,3,ZCC,NAME)
WRITE(*,*)'ENTER 3 FOR A 3-PORT CHARACTERIZATION'
WRITE(*,*)'ENTER 2 FOR A 2-PORT CHARACTERIZATION'
READ(*,*)TYP
WRITE(*,*)
IF (TYP.EQ.2) THEN
C-----TERMINATING IMPEDANCES-----
WRITE(*,*)'ENTER 1 IF ALL TERMINATING IMPEDANCES ARE TO BE INPUT'
WRITE(*,*)'ENTER 2 TO INPUT Z0(1) AND CALCULATE Z0(1)'
READ(*,*)M
WRITE(*,*)''
IF (M.EQ.2) THEN
WRITE(*,*)''
WRITE(*,*)'ENTER Z0(1) (ohm)'
READ(*,*)Z0(1)
ZPP(1,1)=ZCC(2,2)-(ZCC(2,1)*ZCC(1,2)/(ZCC(1,1)+Z0(1)))
ZPP(1,2)=ZCC(2,3)-(ZCC(2,1)*ZCC(1,3)/(ZCC(1,1)+Z0(1)))
ZPP(2,1)=ZCC(3,2)-(ZCC(3,1)*ZCC(1,2)/(ZCC(1,1)+Z0(1)))
ZPP(2,2)=ZCC(3,3)-(ZCC(3,1)*ZCC(1,3)/(ZCC(1,1)+Z0(1)))
NAME='ZPP'
CALL PRINTZ(2,2,ZPP,NAME)
Z0(2)=ZPP(1,1)-ZPP(1,2)
Z0(3)=ZPP(2,2)-ZPP(1,2)
C
Z0(2)=Z0(2)
Z0(3)=Z0(3)/2
C
IF (TYP.EQ.2) THEN
Z0(2)=2*Z0(2)
ENDIF
ELSE
DO 65 I=1,TYP
WRITE(*,67)I
67 FORMAT(1X,'Z0(',I2,') = ? (ohm)')
READ(*,*)Z0(I)
65 CONTINUE
ENDIF
WRITE(2,*),
WRITE(2,*)'PORT TERMINATING IMPEDANCES'
DO 70 I=1,TYP
WRITE(2,73)I,Z0(I)
73 FORMAT(1X,'Z0(',I2,') = ',F10.4,' (ohm)')
70 CONTINUE
WRITE(2,*),
IF (TYP.EQ.2) THEN
CALL ZTOS(ZZ,Z0,S,2)
NAME='S'
CALL PRINTZ(2,2,S,NAME)
CALL VSWRNDB(2,S,NAME)
ELSE
CALL ZTOS(ZCC,Z0,S,3)
NAME='S'
CALL PRINTZ(3,3,S,NAME)
CALL VSWRNDB(3,S,NAME)
ENDIF
C-----CALCULATE Z AND S FOR FREQUENCY RANGE-----
WRITE(*,*)'
WRITE(6,*)'DO A FREQUENCY SWEEP (Y/N)?'
READ(5,5)ANS
IF ((ANS.EQ.‘Y’).OR.(ANS.EQ.‘Y’)) THEN
WRITE(*,*)'
WRITE(6,*)'ENTER START, STOP, AND STEP FREQUENCIES (Hz)'
READ(5,*)FST,FND,DF
F=FST
NFR=(FND-FST)/DF+1
DO 80 I=1,NFR
DO 90 N=1,2
  LD=L(N)
  RCD=RC(N)
  RPD=RP(N)
  VCD=VC(N)
  VPD=VP(N)
  ZC1D=ZC(N,1)
  ZP1D=ZP(N,1)
  IF (N.EQ.1) THEN
    CALL NMP2ZM(F, LD, RCD, RPD, VCD, VPD, ZC1D, ZP1D, Z1)
  ELSEIF (N.EQ.2) THEN
    CALL NMP2ZM(F, LD, RCD, RPD, VCD, VPD, ZC1D, ZP1D, Z2)
  ENDIF
  CONTINUE
  CALL REDECE(Z1, Z2, ZA, ZBB)
  CALL SEGMENT(ZA, ZBB, ZCC, ZV, 2, 1, 1)
  IF (TYP.EQ.2) THEN
    Z(1,1)=ZCC(1,1)
    Z(1,2)=ZCC(1,2)-ZCC(1,3)
    Z(2,1)=ZCC(2,1)-ZCC(3,1)
    Z(2,2)=ZCC(2,2)+ZCC(3,3)-ZCC(2,3)-ZCC(3,2)
    CALL ZTOS(Z,Z0,S,2)
  ELSE
    CALL ZTOS(ZCC, Z0, S, 3)
  ENDIF
  WRITE(2,*)
  WRITE(2,*) F = ', F
  WRITE(2,*)
  CALL PRINTZ(TYP, TYP, S, NAME)
  CALL VSWRNDN(TYP, S, NAME)
  IF=DF+DF
  CONTINUE
ENDIF
WRITE(*,*)
WRITE(*,*),' ANALYSIS COMPLETE'
WRITE(6,*),' RESULTS IN DATA FILE : ', OUTFILE', .DAT'
END

SUBROUTINE NMP2ZM(F, L, RC, RP, VC, VP, ZC1, ZP1, Z)
COMPLEX J, COTH, COTHPI, CSCHC, CSCHP
COMPLEX Z(34,34)
REAL D1, D2, F, GC, GP, L, RC, RP, VC, VP, W, ZC1, ZP1, PI
J=(0.0,1.0)
PI=4.0*ATAN(1.0)
W=2*PI*F
GC=W/VC
GP=W/VP
COTH=-J/TAN(GC*PI)
COTHPI=-J/TAN(GP*PI)
CSCHC=-J/SIN(GC*PI)
CSCHP=-J/SIN(GP*PI)
D1=1.0-RC/RP
D2=1.0-RP/RC
Z(1,1)=ZC1*COTH/D1+ZP1*COTHPI/D2
Z(1,2)=ZC1*RC*COTH/D1+ZP1*RP*COTHPI/D2
Z(1,3)=ZC1*RC*CSCHC/D1+ZP1*RP*CSCHP/D2
Z(1,4)=ZC1*CSCHC/D1+ZP1*CSCHP/D2
Z(2,2)=ZC1*RC**2*COTH/D1+ZP1*RP**2*COTHPI/D2
Z(2,3)=ZC1*RC**2*CSCHC/D1+ZP1*RP**2*CSCHP/D2
Z(4,4)=Z(1,1)
Z(2,1)=Z(1,2)
Z(3,4)=Z(1,2)
Z(4,3)=Z(1,2)
Z(3,1)=Z(1,3)
Z(2,4)=Z(1,3)
Z(4,2)=Z(1,3)
Z(4,1)=Z(1,4)
Z(3,3)=Z(2,2)
Z(3,2)=Z(2,3)
RETURN
END

SUBROUTINE REDUCE(Z1,Z2,ZA,ZBB)
COMPLEX Z1(34,34),Z2(34,34),ZA(34,34),ZBB(34,34)
INTEGER I,K
C-----REDUCE SECTION 1 TO 3 PORT
CALL MATINC(Z1,4)
DO 100 I=2,4
   DO 100 K=2,4
       Z1(I-1,K-1)=Z1(I,K)
   100 CONTINUE
CALL MATINC(Z1,3)
ZA(1,1)=Z1(1,1)
ZA(1,2)=Z1(1,3)
ZA(1,3)=Z1(1,2)
ZA(2,1)=Z1(3,1)
ZA(2,2)=Z1(3,3)
ZA(2,3)=Z1(3,2)
ZA(3,1)=Z1(2,1)
ZA(3,2)=Z1(2,3)
ZA(3,3)=Z1(2,2)
C-----REDUCE SECTION 2 TO 2 PORT-----
CALL MATINC(Z2,4)
DO 200 I=2,4
   DO 200 K=2,4
       Z2(I-1,K-1)=Z2(I,K)
   200 CONTINUE
CALL MATINC(Z2,3)
DO 300 I=2,3
   DO 300 K=2,3
       Z2(I-1,K-1)=Z2(I,K)
   300 CONTINUE
ZBB(1,1)=Z2(2,2)
ZBB(1,2)=Z2(2,1)
ZBB(2,1)=Z2(1,2)
ZBB(2,2)=Z2(1,1)
RETURN
END

C-----------------------------
SUBROUTINE SEGMENT(ZA,ZBB,ZC,ZV,NP1,NP2,NC)
C-----THIS SUBROUTINE USES THE SEGMENTATION METHOD TO COMBINE
C-----THE TWO MatRICES ZA AND ZBB OF THE SEGMENTS A AND B TO OBTAIN
C-----THE Z-MATRIX ZC OF THE OVERALL SEGMENT 'C'. IT ALSO YIELDS
C-----THE VOLTAGES 'ZV' AT THE CONNECTED PORTS 'NP1.' 'NP2'
C-----DENOTES THE EXTERNAL PORTS OF THE SEGMENT 'A' AND 'NP2'
C-----DENOTES THOSE OF 'B'. RELATION 3.21-3.24 ARE USED HERE.
C
COMPLEX ZA(34,34),ZBB(34,34)
COMPLEX ZC(34,34),Z(50,50)
COMPLEX ZPP(34,34),Z1(34,34)
COMPLEX ZQP(34,34),Z2(34,34)
COMPLEX ZK(34,34),Z1(34,34)
COMPLEX ZQ(34,34)
COMPLEX ZV(34,34)
N=NP1+NP2+2*NC
DO 10 I=1,N
   DO 10 J=1,N
       Z(I,J)=0
   10 IF(NP1.EQ.0) GOTO 2
   DO 20 I=1,NP1
   DO 20 J=1,NP1
20  Z(I,J)=ZA(I,J)
DO 40 I=1,NP1
DO 40 J=1+NP1+NP2,NP1+NP2+NC
40  Z(I,J)=ZA(I,J-NP2)
2 CONTINUE
IF(NP2.EQ.0) GOTO 3
DO 30 I=NP1+1,NP1+NP2
DO 30 J=1,NP1+NP2
30  Z(I,J)=ZBB(I-NP1,J-NP1)
DO 50 I=NP1+1,NP1+NP2
DO 50 K=NP1+NP2+NC+1,N
50  Z(I,K)=ZBB(I-NP1,K-NP1-NC)
3 CONTINUE
DO 60 I=N-NC+1,N
DO 60 J=J,N
60  Z(I,J)=ZBB(I-NP1-NC,J-NP1-NC)
DO 70 I=NP1+NP2+1,NP1+NP2+NC
DO 70 J=1,NP1+NP2+NC
70  Z(I,J)=ZA(I-NP2,J-NP2)
80  I=2,N
DO 80 J=1,I-1
80  Z(I,J)=Z(J,I)
DO 100 I=1,NC
DO 100 J=1,NC
100  ZI(I,J)=Z(I+NP1+NP2,JJ+NP1+NP2)+Z(I+N-NC,JJ+N-NC)
CALL MATINC(ZI,NC)
IF(NP1.EQ.0) GOTO 22
DO 200 I=1,NC
DO 200 J=1,NP1
200  ZX(I,J)=-Z(I+NP1+NP2,J)
22 CONTINUE
IF(NP2.EQ.0) GOTO 33
DO 300 I=1,NC
DO 300 J=1+NP1,NP1+NP2
300  ZX(I,J)=Z(I+N-NC,J)
33 CONTINUE
IF(NP1.EQ.0) GOTO 44
CALL CMTULT(NC,NC,NP1+NP2,ZI,ZX,ZY)
DO 400 I=1,NP1
DO 400 J=1,NC
400  ZZ(I,J)=Z(I,J+NP1+NP2)
44 CONTINUE
IF(NP2.EQ.0) GOTO 55
DO 500 I=NP1+1,NP1+NP2
DO 500 J=1,NC
500  ZZ(I,J)=-Z(I,J+NC)
55 CONTINUE
CALL CMTULT(NP1+NP2,NC,NP1+NP2,ZZ,ZY,ZZP)
DO 600 I=1,NP1+NP2
DO 600 J=1,NP1+NP2
600  ZPP(I,J)=Z(I,J)
DO 700 I=1,NP1+NP2
DO 700 J=1,NP1+NP2
700  ZC(I,J)=ZPP(I,J)+ZZP(I,J)
IF(NP1.EQ.0) GOTO 88
DO 800 I=1,NC
DO 800 J=1,NP1
800  ZQP(I,J)=-ZX(I,J)
88 CONTINUE
IF(NP2.EQ.0) GOTO 99
DO 900 I=1,NC
DO 900 J=1,NP1+NP2
900  ZQP(I,J)=0.
99 CONTINUE
DO 925 I=1,NC
DO 925 J=1,NC
925    ZI (I, J) = Z(I+NP1+NP2, J+NP1+NP2)
CALL CMTULT (NC, NC, NP1+NP2, ZI, ZY, ZX)
DO 950 I = 1, NC
DO 950 J = 1, NP1+NP2
950    ZV(I, J) = ZQP(I, J) + ZX(I, J)
RETURN
END

C-----------------------------------------------
C SUBROUTINE ZTOS (Z, Z0, S, N)
C-----THIS SUBROUTINE COMPUTES THE ELEMENTS OF THE S-MATRIX FROM
C-----THOSE OF Z-MATRIX OF AN N-MULTIPORT NETWORK. THE ELEMENTS
C-----OF THE Z0(N) ARE THE CHARACTERISTIC IMPEDANCES OF THE TRANS.
C-----LINES CONNECTED TO THE N-MULTIPORT NETWORK.
C
DIMENSION Z0(34)
COMPLEX ZL(34, 34), S(34, 34), Z(34, 34)
COMPLEX C(34, 34)
DO 10 I = 1, N
DO 10 J = 1, N
   ZL(I, J) = Z(I, J)
10    S(I, J) = 0.
DO 20 I = 1, N
DO 20 J = 1, N
   C(I, J) = ZL(I, J) + Z0(I)
20    S(I, J) = S(I, J) + ZL(I, J) - Z0(I)
CALL MATINC(C, N)
CALL CMTULT(N, N, N, ZL, C, S)
DO 30 I = 1, N
DO 30 J = 1, N
   CON1 = SQRT(Z0(I) / Z0(J))
30    S(I, J) = S(I, J) / CON1
RETURN
END

C-----------------------------------------------
C SUBROUTINE CMTULT (L, M, N, A, B, C)
C-----A(L, M) AND B(M, N) TO OBTAIN THE MATRIX C(L, M).
C
COMPLEX A(34, 34), B(34, 34), C(34, 34)
DO 3 I = 1, L
DO 3 J = 1, N
   C(I, J) = 0.0
3    DO 3K = 1, M
   C(I, J) = C(I, J) + A(I, K) * B(K, J)
RETURN
END

C-----------------------------------------------
C SUBROUTINE MATINC(A, N)
C-----THIS SUBROUTINE COMPUTES THE INVERSE OF THE MATRIX A(N, N).
C-----WARNING****; THE INVERSE OF A IS FILLED INTO A ITSELF.
C
DIMENSION INDEX(34, 3)
COMPLEX T, SWAP, PIVOT, A(34, 34)
EQUIVALENCE (IROW, JROW), (ICOLUM, JCOLUMN)
DO 10 J = 1, N
10 INDEX(J, 3) = 0
DO 30 I = 1, N
   AMAX = 0.0
   DO 40 J = 1, N
      IF (INDEX(J, 3) .EQ. 1) GO TO 40
   DO 30 K = 1, N
      IF (INDEX(K, 3) - 1) 20, 30, 115
   20 IF (AMAX .GE. CABS(A(J, K))) GO TO 30
   IROW = J
   ICOLUM = K
30    AMAX = CABS(A(J, K))
40    INDEX(J, 3) = 1
RETURN
END
AMAX=CAoS(A(J,K))

CONTINUE

40 CONTINUE
INDEX(ICOLUM,3)=INDEX(ICOLUM,3)+1
INDEX(I,1)=IROW
INDEX(I,2)=ICOLUM
IF(IROW.EQ.ICOLUM) G0 TO 60
DO 50 L=1,N
SWAP=A(IROW,L)
A(IROW,L)=A(ICOLUM,L)
A(ICOLUM,L)=SWAP
50 PIVOT=A(ICOLUM,ICOLUM)
A(ICOLUM,ICOLUM)=1.0
DO 70 L=1,N
A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
70 DO 90 L=1,N
IF(L.NE.ICOLUM) G0 TO 90
T=A(L,L,ICOLUM)
A(L,ICOLUM)=0.0
DO 80 L=1,N
80 A(L,L)=A(L,L)-A(ICOLUM,L)*T
90 CONTINUE
DO 110 I=1,N
L=N-I+1
IF(INDEX(L,1).EQ.INDEX(L,2)) G0 TO 110
JROW=INDEX(L,1)
JCOLUMN=INDEX(L,2)
DO 100 K=1,N
SWAP=A(K,JROW)
A(K,JROW)=A(K,JCOLUMN)
100 A(K,JCOLUMN)=SWAP
110 CONTINUE
115 RETURN
END

C--------------------------------------
SUBROUTINE PRINTZ(M,N,AMAT,NAME)
CHARACTER*12 NAME
COMPLEX AMAT(34,34)
INTEGER I,J,M,N
WRITE(2,1)NAME
DO 3 J=1,N
WRITE(2,2)J
DO 3 I=1,M
3 WRITE(2,4)I,AMAT(I,J),CABS(AMAT(I,J)),ANGLE(AMAT(I,J))
1 FORMAT(1X,'ELEMENTS OF MATRIX ','A15)
2 FORMAT('/1X,'ELEMENTS OF COLUMN#','/1X,'ROW#','/5X,'REAL'
>','/10X,'IMAGINARY PT','/12X,'MAGNITUDE','/10X,'DEG.'
4 FORMAT(3X,I3,2X,2(E18.10,2X),2X,E18.10,3X,F8.2)
WRITE(2,*)
RETURN
END

C--------------------------------------
SUBROUTINE VSWRNB(NEXPORT,SM,NAME)
CHARACTER*12 NAME
COMPLEX SM(34,34)
REAL COLSM(34)
WRITE(2,1)NAME
DO 10 I=1,NEXPORT
VSWR=(1+CABS(SM(I,I)))/(1-CABS(SM(I,I)))
DO 20 J=1,NEXPORT
COLSM(J)=CABS(SM(I,J))
20 CONTINUE
WRITE(2,2)I,VSWR,(20*ALOG10(COLSM(J))),J=1,NEXPORT
10 CONTINUE
1 FORMAT('/1X,'PORT#','/7X,'VSWR','/12X,'ELEMENTS OF ','A5,
> 'MATRIX IN dB')

2 FORMAT (5X, I3, 3X, F10.4, 7X, 5F10.4)

RETURN

END

C-----------------------------------------------

FUNCTION ANGLE(C)
COMPLEX C
REAL ANGLE, PI
PI=4.0*ATAN(1.0)
IF (REAL(C).NE.0.0) THEN
  ANGLE=ATAN2(AIMAG(C), REAL(C))*180/PI
ELSEIF (AIMAG(C).GT.0.0) THEN
  ANGLE=90.0
ELSEIF (AIMAG(C).LT.0.0) THEN
  ANGLE=-90.0
ENDIF
RETURN
END

C-----------------------------------------------
$ RUN MBALUN

PROGRAM MBALUN
FOR ANALYSIS OF PLANAR MARCHAND BALUN
ANALYSIS FOR TWO COUPLED LINE SECTIONS ONLY

1--------------------------OPEN
SHORT------------------2 3------------------SHORT

MIMICAD CENTER
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425

ENTER OUTPUT FILENAME
MOUT
READ CAPACITANCE DATA FROM INPUT FILE (Y/N)?
Y
ENTER INPUT FILENAME
MIN
ENTER CENTER FREQUENCY IN Hz
30E9
ENTER 1 IF SECTION 1 LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2
ENTER 1 IF SECTION 2 LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2
ENTER 3 FOR A 3-PORT CHARACTERIZATION
ENTER 2 FOR A 2-PORT CHARACTERIZATION
3
ENTER 1 IF ALL TERMINATING IMPEDANCES ARE TO BE INPUT
ENTER 2 TO INPUT Z0(1) AND CALCULATE Z0(i)
1
Z0 (1) = ? (ohm)
83
Z0 (2) = ? (ohm)
26
Z0 (3) = ? (ohm)
26
DO A FREQUENCY SWEEP (Y/N)?
N
ANALYSIS COMPLETE
RESULTS IN DATA FILE : MOUT .DAT
$$
344.8000
-117.8000
-117.8000
118.6000
45.9000
-19.8000
-19.8000
20.2000
1455.6000
-1228.5000
-1228.5000
1229.1000
213.8000
-190.3000
-190.3000
193.2000
**CAPACITANCE MATRICES FOR SECTION 1 IN pF/m**

<table>
<thead>
<tr>
<th>CD(1,1)</th>
<th>CD(1,2)</th>
<th>CD(2,1)</th>
<th>CD(2,2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>344.8000</td>
<td>-117.8000</td>
<td>-117.8000</td>
<td>118.6000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CA(1,1)</th>
<th>CA(1,2)</th>
<th>CA(2,1)</th>
<th>CA(2,2)</th>
</tr>
</thead>
</table>

**CAPACITANCE MATRICES FOR SECTION 2 IN pF/m**

<table>
<thead>
<tr>
<th>CD(1,1)</th>
<th>CD(1,2)</th>
<th>CD(2,1)</th>
<th>CD(2,2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1455.6000</td>
<td>-1228.5000</td>
<td>-1228.5000</td>
<td>1229.1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CA(1,1)</th>
<th>CA(1,2)</th>
<th>CA(2,1)</th>
<th>CA(2,2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>213.8000</td>
<td>-190.3000</td>
<td>-190.3000</td>
<td>193.2000</td>
</tr>
</tbody>
</table>

**NORMAL MODE PARAMETERS FOR SECTION 1**

<table>
<thead>
<tr>
<th>Rc</th>
<th>Rpi</th>
<th>Vc</th>
<th>Vpi</th>
<th>Eeffc</th>
<th>Eeffpi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9521148</td>
<td>0.4768021</td>
<td>1.0222246E+08</td>
<td>1.2374132E+08</td>
<td>8.600996</td>
<td>5.869646</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z1c</th>
<th>Z1pi</th>
<th>Z2c</th>
<th>Z2pi</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.05016</td>
<td>-1.532906</td>
<td>-1908.951</td>
<td>69.58942</td>
</tr>
</tbody>
</table>

**NORMAL MODE PARAMETERS FOR SECTION 2**

<table>
<thead>
<tr>
<th>Rc</th>
<th>Rpi</th>
<th>Vc</th>
<th>Vpi</th>
<th>Eeffc</th>
<th>Eeffpi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9450694</td>
<td>0.4402424</td>
<td>1.0177906E+08</td>
<td>1.1911193E+08</td>
<td>8.676100</td>
<td>6.334770</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Z1c</th>
<th>Z1pi</th>
<th>Z2c</th>
<th>Z2pi</th>
</tr>
</thead>
<tbody>
<tr>
<td>33.35302</td>
<td>-2.123929</td>
<td>-138.7651</td>
<td>8.836864</td>
</tr>
</tbody>
</table>

**CENTER FREQUENCY**

F₀ = 30.00000 GHz

**LENGTH OF SECTION**

1 L = 0.9330E-03 METERS

2 L = 0.9147E-03 METERS

**ELEMENTS OF MATRIX Z**

**ELEMENTS OF COLUMN# 1**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>-0.2247552872E+01</td>
<td>0.2247552872E+01</td>
<td>-90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>0.2858209038E+02</td>
<td>0.2858209038E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.3972168732E+02</td>
<td>0.3972168732E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 2**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>0.2858209229E+02</td>
<td>0.2858209229E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>-0.1616114807E+03</td>
<td>0.1616114807E+03</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.1558307495E+03</td>
<td>0.1558307495E+03</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 3**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00000000000E+00</td>
<td>-0.3972168732E+02</td>
<td>0.3972168732E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00000000000E+00</td>
<td>-0.1558307495E+03</td>
<td>0.1558307495E+03</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00000000000E+00</td>
<td>-0.1611499634E+03</td>
<td>0.1611499634E+03</td>
<td>-90.00</td>
</tr>
</tbody>
</table>
PORT TERMINATING IMPEDANCES
Z0( 1) = 83.0000 (ohm)
Z0( 2) = 26.0000 (ohm)
Z0( 3) = 26.0000 (ohm)

ELEMENTS OF MATRIX S

ELEMENTS OF COLUMN # 1

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2589625120E-01</td>
<td>0.9384029359E-01</td>
<td>0.9734791517E-01</td>
<td>74.57</td>
</tr>
<tr>
<td>2</td>
<td>-0.7077007741E-01</td>
<td>0.6968884468E+00</td>
<td>0.7004726529E+00</td>
<td>95.80</td>
</tr>
<tr>
<td>3</td>
<td>0.8967116475E-01</td>
<td>-0.7012992501E+00</td>
<td>0.7070088983E+00</td>
<td>-82.71</td>
</tr>
</tbody>
</table>

ELEMENTS OF COLUMN # 2

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.7077000290E-01</td>
<td>0.6968883872E+00</td>
<td>0.7004725933E+00</td>
<td>95.80</td>
</tr>
<tr>
<td>2</td>
<td>0.5175309777E+00</td>
<td>-0.1379618645E+00</td>
<td>0.5356041193E+00</td>
<td>-14.93</td>
</tr>
<tr>
<td>3</td>
<td>0.4700832069E+00</td>
<td>-0.3857588768E-01</td>
<td>0.4716633558E+00</td>
<td>-4.69</td>
</tr>
</tbody>
</table>

ELEMENTS OF COLUMN # 3

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8967101574E-01</td>
<td>-0.7012991905E+00</td>
<td>0.7070087790E+00</td>
<td>-82.71</td>
</tr>
<tr>
<td>2</td>
<td>0.4700831771E+00</td>
<td>-0.3857624531E-01</td>
<td>0.4716633558E+00</td>
<td>-4.69</td>
</tr>
<tr>
<td>3</td>
<td>0.5152475238E+00</td>
<td>-0.1104184389E+00</td>
<td>0.5269461274E+00</td>
<td>-12.10</td>
</tr>
</tbody>
</table>

PORT#  VSWR  ELEMENTS OF S  MATRIX IN dB
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2157</td>
<td>-20.2335</td>
<td>-3.0922</td>
</tr>
<tr>
<td>2</td>
<td>3.3067</td>
<td>-3.0922</td>
<td>-5.4231</td>
</tr>
<tr>
<td>3</td>
<td>3.2278</td>
<td>-3.0115</td>
<td>-6.5274</td>
</tr>
</tbody>
</table>
PROGRAM MBALUN3

PROGRAM FOR THE ANALYSIS OF A PLANAR COUPLED TRANSMISSION LINE MARCHAND TYPE BALUN
ANALYSIS FOR TWO COUPLED LINE SECTIONS AND THIRD COPLANAR COUPLED LINE SECTION AT OUTPUT

MBALUN3.FOR code listing ....................... 137
Running MBALUN3 .................................. 147
Input File M3IN.DAT ............................... 149
Output File M3OUT.DAT ........................... 150
C-----
PROGRAM MBALUN3
C
PROGRAM FOR ANALYSIS OF PLANAR MARCHAND BALUN STRUCTURE
ANALYSIS OF TWO COUPLED LINE SECTIONS AND A THIRD COPLANAR
COUPLED LINE SECTION AT OUTPUT

1------------------------*-----------OPEN
SHORT-------------------/------------------SHORT
      |  
      |  2 3

INPUT : C MATRICES OF THE THREE SECTIONS
OUTPUT: NORMAL MODE PARAMETERS OF EACH SECTION
Z MATRIX
S MATRIX
FREQUENCY SWEEP

BY: ANTHONY J. VERGAMINI
MIMICAD CENTER, UNIVERSITY OF COLORADO, BOULDER

C---------------------------
CHARACTER*12 ANS,INFILE,OUTFILE,NAME
COMPLEX Z(34,34),ZB(34,34),Z23(34,34)
COMPLEX ZA(34,34),ZBB(34,34),ZC(34,34),ZD(34,34),ZFP(34,34)
COMPLEX Z(34,34),S(34,34)
DIMENSION A(3),A1(3),A2(3),A3(3),A4(3),CA(3,4,4),CD(3,4,4)
DIMENSION ZV(34),ZC(3,2),ZF(3,2),Z0(34)
INTEGER I,K,M,N,NFR,TYP
REAL F,F0,FGH,FST,FND,DF,LD,RCD,RPD,VCD,VPD,ZC1D,ZP1D
REAL L(3)

C=2.99792456E8
PI=4.0*ATAN(1.0)
J=(0.0,1.0)

C dumped
FORMAT(A12)
WRITE(*,*),
WRITE(*,*), 'PROGRAM MBALUN3'
WRITE(*,*), 'FOR ANALYSIS OF PLANAR MARCHAND BALUN'
WRITE(*,*), 'AND COPLANAR COUPLED LINE SECTION AT OUTPUT'
WRITE(*,*),
1------------------------*-----------OPEN'
SHORT------------------/------------------SHORT'
      |  
      |  2 3'
WRITE(*,*),
WRITE(*,*), 'MIMICAD CENTER'
WRITE(*,*), 'DEPARTMENT OF ELECTRICAL ENGINEERING'
WRITE(*,*), 'UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425'
WRITE(*,*),

C------INPUT SECTION-----
WRITE(*,*),'ENTER OUTPUT FILENAME'
READ(5,5)OUTFILE
WRITE(*,*),
OPEN(UNIT=2,FILE=OUTFILE,STATUS='UNKNOWN')
WRITE(*,*),'READ CAPACITANCE DATA FROM INPUT FILE (Y/N) ?'
READ(5,5)ANS
WRITE(*,*)

IF ((ANS.EQ.'Y').OR.(ANS.EQ.'y')) THEN
  WRITE(*,*)'ENTER INPUT FILENAME'
  READ (5,5) INFILE
  WRITE(*,*)''
  OPEN (UNIT=1,FILE=INFILE,STATUS='UNKNOWN')
  DO 6 N=1,3
    DO 7 I=1,2
      DO 7 K=1,2
        READ (1,*) CD(N,I,K)
      CONTINUE
    DO 8 I=1,2
      DO 8 K=1,2
        READ (1,*) CA(N,I,K)
      CONTINUE
    6  CONTINUE
  GOTO 10
ENDIF

DO 10 N=1,3
  WRITE(*,17) N
  17 FORMAT(1X,'ENTER CAPACITANCE MATRICES
           >FOR SECTION',I2,' IN pF/m')
    DO 20 I=1,2
      DO 20 K=1,2
        WRITE(*,27) I,K
        FORMAT(1X,'CD(',I2,',',I2,') = ?')
        READ(*,*) CD(N,I,K)
      CONTINUE
    DO 30 I=1,2
      DO 30 K=1,2
        WRITE(*,36) I,K
        FORMAT(1X,'CA(',I2,',',I2,') = ?')
        READ(*,*) CA(N,I,K)
      CONTINUE
    10 CONTINUE
    WRITE(2,*)''

DO 35 N=1,3
  WRITE(2,39) N
  39 FORMAT(1X,'CAPACITANCE MATRICES FOR SECTION',I2,' IN pF/m')
    DO 40 I=1,2
      DO 40 K=1,2
        WRITE(2,97) I,K,CD(N,I,K)
        FORMAT(1X,'CD(',I2,',',I2,') = ',F10.4)
      CONTINUE
    DO 50 I=1,2
      DO 50 K=1,2
        WRITE(2,98) I,K,CA(N,I,K)
        FORMAT(1X,'CA(',I2,',',I2,') = ',F10.4)
      CONTINUE
    35 CONTINUE
    WRITE(2,*)''

WRITE(*,*)'ENTER CENTER FREQUENCY IN Hz'
READ(*,*)F0
WRITE(*,*)''
FGH=F0/1E9

C-----CALCULATE NORMAL MODE PARAMETERS-----

DO 40 N=1,3
  A1(N)=(CD(N,1,1)*CA(N,2,2)-CA(N,1,1)*CD(N,2,2))*2
  A3(N)=-CD(N,2,2)*CA(N,1,2)+CA(N,2,2)*CD(N,1,2)
  A4(N)=-CD(N,1,1)*CA(N,1,2)+CA(N,1,1)*CD(N,1,2)
  A2(N)=4*A3(N)*A4(N)
  A(N)=A1(N)+A2(N)
  EN(N)=CD(N,1,1)*CA(N,2,2)+CA(N,1,1)*CD(N,2,2)
  +2*CA(N,1,2)*CD(N,1,2)
ED(N)=2*(CA(N,1,1)*CA(N,2,2)-CA(N,1,2)**2)
EC(N)=(EN(N)+SQRT(A(N)))/ED(N)
EP(N)=(EN(N)-SQRT(A(N)))/ED(N)
RC(N)=(CD(N,1,1)-EC(N)*CA(N,1,1))/(-CD(N,1,2)+EC(N)*CA(N,1,2))
RP(N)=(CD(N,1,1)-EP(N)*CA(N,1,1))/(-CD(N,1,2)+EP(N)*CA(N,1,2))
VC(N)=C/SQRT(EC(N))
VP(N)=C/SQRT(EP(N))
ZC(N,1)=1.0E12/(VC(N)*(CD(N,1,1)+CD(N,1,2)*RC(N)))
ZC(N,2)=1.0E12/(VC(N)*(CD(N,2,2)+CD(N,1,2)/RC(N)))
ZP(N,1)=1.0E12/(VP(N)*(CD(N,1,1)+CD(N,1,2)*RP(N)))
ZP(N,2)=1.0E12/(VP(N)*(CD(N,2,2)+CD(N,1,2)/RP(N)))
WRITE(*,51)
FORMAT(1X,'ENTER 1 IF SECTION ',I2,' LENGTH IS TO BE INPUT')
WRITE(*,*)'ENTER 2 TO USE A QUARTER WAVE SECTION'
READ(*,*)M
WRITE(*,*)'
IF (M.EQ.2) THEN
  L(N)=C/(2*F0*(SQRT(EC(N))+SQRT(EP(N))))
ELSE
  WRITE(*,53)
  FORMAT(1X,'ENTER L(',I2,') IN METERS')
  READ(*,*)L(N)
  WRITE(*,*)'
ENDIF
WRITE(2,*)'NORMAL MODE PARAMETERS FOR SECTION ',N
WRITE(2,*)'
WRITE(2,*)' RCI , RPI = ',RC(N),RP(N)
WRITE(2,*)' VC , VPI = ',VC(N),VP(N)
WRITE(2,*)' EFCI , EFPNI = ',EC(N),EP(N)
WRITE(2,*)' ZCI , ZPI = ',ZC(N,1),ZP(N,1)
WRITE(2,*)' ZCI , ZPI = ',ZC(N,2),ZP(N,2)
WRITE(2,*)'
CONTINUE
WRITE(2,*)'CENTER FREQUENCY F0 = ',F0,' GHz'
WRITE(2,*)'
DO 50 N=1,3
WRITE(2,57)N,L(N)
CONTINUE
WRITE(2,*)'
C------CALCULATE Z MATRICES AT CENTER FREQUENCY------
DO 60 N=1,3
L=L(N)
RCD=RC(N)
RDP=RP(N)
VCD=VC(N)
VPD=VP(N)
ZCD=ZC(N,1)
ZPD=ZP(N,1)
IF (N.EQ.1) THEN
  CALL NMP2ZM(F0,L,RCD,RDP,VCD,VPD,ZCD,ZPD,Z1)
ELSEIF (N.EQ.2) THEN
  CALL NMP2ZM(F0,L,RCD,RDP,VCD,VPD,ZCD,ZPD,Z2)
ELSEIF (N.EQ.3) THEN
  CALL NMP2ZM(F0,L,RCD,RDP,VCD,VPD,ZCD,ZPD,Z3)
ENDIF
CONTINUE
NAME='Z1'
CALL PRINTZ(4,4,Z1,NAME)
NAME='Z2'
CALL PRINTZ(4,4,Z2,NAME)
NAME='Z3'
CALL PRINTZ(4,4,Z3,NAME)
CALL REDUCE(Z1,Z2,ZA,ZBB)
NAME='ZA'
CALL PRINTZ(3,3,ZA,NAME)
NAME='ZBB'
C    CALL PRINTZ(2,2,ZBB,NAME)
CALL SEGMENT(ZBB,ZCC,ZV,2,1,1)
NAME='ZCC'
C    CALL PRINTZ(3,3,ZCC,NAME)
CALL SEGMENT(ZCC,ZD,ZV,1,2,2)
NAME='Z'
C    CALL PRINTZ(3,3,ZD,NAME)
WRITE(*,*),'ENTER 3 FOR A 3-PORT CHARACTERIZATION'
WRITE(*,*),'ENTER 2 FOR A 2-PORT CHARACTERIZATION'
READ(*,*)TYP
WRITE(*,*),'
IF (TYP.EQ.2) THEN
    Z(1,1)=ZD(1,1)
    Z(1,2)=ZD(1,2)-ZD(1,3)
    Z(2,1)=ZD(2,1)-ZD(3,1)
    Z(2,2)=ZD(2,2)+ZD(3,3)-ZD(2,3)-ZD(3,2)
NAME='Z'
C    CALL PRINTZ(2,2,Z,NAME)
ENDIF
C-------- TERMINATING IMPEDANCES --------
WRITE(*,*),'ENTER 1 IF ALL TERMINATING IMPEDANCES ARE TO BE INPUT'
WRITE(*,*),'ENTER 2 TO ENTER Z0(1) AND CALCULATE Z0(i)'
READ(*,*)M
WRITE(*,*),'
IF (M.EQ.2) THEN
    WRITE(*,*),'
    WRITE(*,*),'ENTER Z0(1) (ohm)'
    READ(*,*)Z0(1)
    WRITE(*,*),'
    ZPP(1,1)=ZD(2,2)-(ZD(2,1)*ZD(1,2))/(ZD(1,1)+Z0(1))
    ZPP(1,2)=ZD(2,3)-(ZD(2,1)*ZD(1,3))/(ZD(1,1)+Z0(1))
    ZPP(2,1)=ZD(3,2)-(ZD(3,1)*ZD(1,2))/(ZD(1,1)+Z0(1))
    ZPP(2,2)=ZD(3,3)-(ZD(3,1)*ZD(1,3))/(ZD(1,1)+Z0(1))
NAME='ZPP'
C    CALL PRINTZ(2,2,ZPP,NAME)
C    Z0(2)=ZPP(1,1)-ZPP(1,2)
    Z0(3)=ZPP(2,2)-ZPP(1,2)
    Z0(2)=Z0(3)
C    z0(2)=(z0(2)+z0(3))/2
C    z0(3)=z0(2)
    IF (TYP.EQ.2) THEN
        Z0(2)=2*Z0(2)
ENDIF
ELSE
    DO 65 I=1,TYP
    WRITE(*,67)I
67 FORMAT(1X,'ENTER Z0(’,I2,’) (ohm)’)
    READ(*,*)Z0(I)
65 CONTINUE
ENDIF
WRITE(2,*),'
WRITE(2,*),' PORT TERMINATING IMPEDANCES'
DO 70 I=1,TYP
    WRITE(2,73)I,Z0(I)
73 FORMAT(1X,'Z0(’,I2,’)= ’,F10.4)
70 CONTINUE
WRITE(2,*),'
IF (TYP.EQ.2) THEN
    CALL ZTOS(Z0,S,2)
    NAME='S'
    CALL PRINTZ(2,2,S,NAME)
    CALL VSWRND(2,S,NAME)
ELSE
    CALL ZTOS(ZD,Z0,S,3)
    NAME='S'
ENDIF
CALL PRINTZ(3,3,S,NAME)
CALL VSWRNDB(3,S,NAME)
ENDIF
C-----CALCULATE Z AND S FOR FREQUENCY RANGE-----
WRITE(*,*)' ' 
WRITE(6,*)' DO A FREQUENCY SWEEP (Y/N) ?'
READ(5,5) ANS
WRITE(*,*)' '
IF ((ANS.EQ.'Y').OR.(ANS.EQ.'Y')) THEN 
WRITE(6,*)' ENTER START, STOP, AND STEP FREQUENCIES (Hz) '
READ(5,*) FST, FND, DF 
F=FST 
NFR=(FND-FST)/DF+1
DO 80 I=1,NFR 
 DO 90 N=1,3 
LD=L(N) 
RCD=RC(N) 
RPD=RP(N) 
VCD=VC(N) 
VFD=VF(N) 
ZC1D=ZC(N,1) 
ZP1D=ZP(N,1) 
IF (N.EQ.1) THEN 
 CALL NMP2ZM(F,LD, RCD, RPD, VCD, VFD, ZC1D, ZP1D, Z1) 
 ELSEIF (N.EQ.2) THEN 
 CALL NMP2ZM(F,LD, RCD, RPD, VCD, VFD, ZC1D, ZP1D, Z2) 
 ELSEIF (N.EQ.3) THEN 
 CALL NMP2ZM(F,LD, RCD, RPD, VCD, VFD, ZC1D, ZP1D, Z3) 
ENDIF
90 CONTINUE 
CALL REDUCE(Z1, Z2, ZA, ZBB) 
CALL SEGMENT(ZA, ZBB, ZCC, ZV, 2, 1, 1) 
CALL SEGMENT(ZCC, Z3, ZD, ZV, 1, 2, 2) 
IF (TYP.EQ.2) THEN 
Z(1,1)=ZD(1,1) 
Z(1,2)=ZD(1,2)-ZD(1,3) 
Z(2,1)=ZD(2,1)-ZD(3,1) 
Z(2,2)=ZD(2,2)+ZD(3,3)-ZD(2,3)-ZD(3,2) 
 CALL ZTOS(Z,Z0,S,2) 
ELSE 
 CALL ZTOS(ZD,Z0,S,3) 
ENDIF 
WRITE(2,*)' ' 
WRITE(2,*)' F = ',F 
WRITE(2,*)' ' 
CALL PRINTZ(TYP,TYP,S,NAME) 
CALL VSWRNDB(TYP,S,NAME) 
F=F+DF 
80 CONTINUE 
ENDIF 
WRITE(*,*)' ANALYSIS COMPLETE' 
WRITE(6,*)' RESULT IN DATA FILE: ',OUTFILE,'.DAT'
END

C------------------------------------------------------------------------
C
SUBROUTINE NMP2ZM(F,L,RC,RP,VC,VP,ZC1,ZP1,Z) 
COMPLEX J,COTH,COTHF,COSH,COSHFP 
COMPLEX Z(34,34)
REAL DI,D2,F,GC,GF,L,RC,RP,VC,VP,W,ZC1,ZP1,PI 
J=(0.0,1.0) 
PI=4.0*ATAN(1.0) 
W=2*PI*F 
GC=W/VC 
GF=W/VP 
COTHC=-J/TAN(GC*L) 
COTHF=-J/TAN(GF*L)
\[
\begin{align*}
\text{CSCHC} &= -J/\text{SIN}(\text{GC}\times \text{L}) \\
\text{CSCHF} &= -J/\text{SIN}(\text{GF}\times \text{L}) \\
\text{D1} &= \text{1.0}\times\text{RC}/\text{RP} \\
\text{D2} &= \text{1.0}\times\text{RP}/\text{RC} \\
\text{Z}(1,1) &= \text{ZC1}\times\text{COTH}\times\text{D1}+\text{ZP1}\times\text{COTH}\times\text{D2} \\
\text{Z}(1,2) &= \text{ZC1}\times\text{RC}\times\text{COTH}\times\text{D1}+\text{ZP1}\times\text{RP}\times\text{COTH}\times\text{D2} \\
\text{Z}(1,3) &= \text{ZC1}\times\text{RC}\times\text{CSCHC}\times\text{D1}+\text{ZP1}\times\text{RP}\times\text{CSCHF}\times\text{D2} \\
\text{Z}(1,4) &= \text{ZC1}\times\text{CSCHC}\times\text{D1}+\text{ZP1}\times\text{CSCHF}\times\text{D2} \\
\text{Z}(2,2) &= \text{ZC1}\times\text{RC}\times\text{2}\times\text{COTH}\times\text{D1}+\text{ZP1}\times\text{RP}\times\text{2}\times\text{COTH}\times\text{D2} \\
\text{Z}(2,3) &= \text{ZC1}\times\text{RC}\times\text{2}\times\text{CSCHC}\times\text{D1}+\text{ZP1}\times\text{RP}\times\text{2}\times\text{CSCHF}\times\text{D2} \\
\text{Z}(4,4) &= \text{Z}(1,1) \\
\text{Z}(2,1) &= \text{Z}(1,2) \\
\text{Z}(3,4) &= \text{Z}(1,2) \\
\text{Z}(4,3) &= \text{Z}(1,2) \\
\text{Z}(3,1) &= \text{Z}(1,3) \\
\text{Z}(2,4) &= \text{Z}(1,3) \\
\text{Z}(4,2) &= \text{Z}(1,3) \\
\text{Z}(4,1) &= \text{Z}(1,4) \\
\text{Z}(3,3) &= \text{Z}(2,2) \\
\text{Z}(3,2) &= \text{Z}(2,3) \\
\text{Z}(3,2) &= \text{Z}(2,3) \\
\text{RETURN} \\
\text{END}
\end{align*}
\]

```
C------------
SUBROUTINE REDUCE(21,22,ZA,ZBB)
COMPLEX Z1(34,34),Z2(34,34),ZA(34,34),ZBB(34,34)
INTEGER I,K
C-----REDUCE SECTION 1 TO 3 PORT
CALL MATINC(Z1,4)
DO 100 I=2,4
   DO 100 K=2,4
      Z1(I-1,K-1)=Z1(I,K)
   100 CONTINUE
CALL MATINC(Z1,3)
ZA(1,1)=Z1(1,1)
ZA(1,2)=Z1(1,3)
ZA(1,3)=Z1(1,2)
ZA(2,1)=Z1(3,1)
ZA(2,2)=Z1(3,3)
ZA(2,3)=Z1(3,2)
ZA(3,1)=Z1(2,1)
ZA(3,2)=Z1(2,3)
ZA(3,3)=Z1(2,2)
C-----REDUCE SECTION 2 TO 2 PORT-----
CALL MATINC(Z2,4)
DO 200 I=2,4
   DO 200 K=2,4
      Z2(I-1,K-1)=Z2(I,K)
   200 CONTINUE
CALL MATINC(Z2,3)
DO 300 I=2,3
   DO 300 K=2,3
      Z2(I-1,K-1)=Z2(I,K)
   300 CONTINUE
ZBB(1,1)=Z2(2,2)
ZBB(1,2)=Z2(2,1)
ZBB(2,1)=Z2(1,2)
ZBB(2,2)=Z2(1,1)
RETURN
END
C------------
SUBROUTINE SEGMENT(ZA,ZBB,ZA,ZV,NP1,NP2,NC)
C-----THIS SUBROUTINE USES THE SEGMENTATION METHOD TO COMBINE
C-----THE TWO MATRICES ZA AND ZBB OF THE SEGMENTS A AND B TO OBTAIN
C-----THE Z-MATRIX ZC OF THE OVERALL SEGMENT 'C'. IT ALSO YIELDS
C-----THE VOLTAGES 'ZV' AT THE CONNECTED PORTS 'DENOTED BY NC.'NP1'
C-----DENOTES THE EXTERNAL PORTS OF THE SEGMENT 'A' AND 'NP2'
```
C------DENOTES THOSE OF 'B'. RELATION 3.21-3.24 ARE USED HERE.

C
C
COMPLEX ZA(34,34), ZBB(34,34)
COMPLEX ZC(34,34), Z(50,50)
COMPLEX ZPP(34,34), ZI(34,34)
COMPLEX ZZP(34,34), ZZ(34,34)
COMPLEX ZX(34,34), ZY(34,34)
COMPLEX ZQP(34,34)
COMPLEX ZV(34,34)
N=NP1+NP2+2*NC
DO 10 I=1,N
DO 10 J=1,N
10 Z(I,J)=0.
IF(NP1.EQ.0) GOTO 2
DO 20 I=1,NP1
DO 20 J=1,NP1
20 Z(I,J)=ZA(I,J)
DO 40 I=1,NP1
DO 40 J=1+NP1+NP2,NP1+NP2+NC
40 Z(I,J)=ZA(I,J-NP2)
2 CONTINUE
IF(NP2.EQ.0) GOTO 3
DO 30 I=NP1+1,NP1+NP2
DO 30 J=I,NP1+NP2
30 Z(I,J)=ZBB(I-NP1,J-NP1)
DO 50 L=NP1+1,NP1+NP2
DO 50 K=NP1+NP2+NC+1,N
50 Z(I,K)=ZBB(I-NP1,K-NP1-NC)
3 CONTINUE
DO 60 I=N-NC+1,N
DO 60 J=I,N
60 Z(I,J)=ZBB(I-NP1-NC,J-NP1-NC)
DO 70 I=NP1+NP2+1,NP1+NP2+NC
DO 70 J=I,NP1+NP2+NC
70 Z(I,J)=ZA(I-NP2,J-NP2)
DO 80 I=2,N
DO 80 J=1,1
80 Z(I,J)=Z(J,I)
DO 100 I=1,NC
DO 100 JJ=1,NC
100 ZI(I,JJ)=Z(I+NP1+NP2, JJ+NP1+NP2)+Z(I+N-NC, JJ+N-NC)
CALL MATINC(ZI,NC)
IF(NP1.EQ.0) GOTO 22
DO 200 I=1,NC
DO 200 J=1,NP1
200 ZX(I,J)=-Z(I+NP1+NP2,J)
22 CONTINUE
IF(NP2.EQ.0) GOTO 33
DO 300 I=1,NC
DO 300 J=1+NP1, NP1+NP2
300 ZX(I,J)=Z(I+N-NC,J)
33 CONTINUE
IF(NP1.EQ.0) GOTO 44
CALL CMTULT(NC, NC, NP1+NP2, ZI, ZX, ZY)
DO 400 I=1,NP1
DO 400 J=1,NC
400 ZZ(I,J)=Z(I,J+NP1+NP2)
44 CONTINUE
IF(NP2.EQ.0) GOTO 55
DO 500 I=NP1+1, NP1+NP2
DO 500 J=1,NC
500 ZZ(I,J)=-Z(I,J+N-NC)
55 CONTINUE
CALL CMTULT(NP1+NP2, NC, NP1+NP2, ZZ, ZY, ZZP)
DO 600 I=1,NP1+NP2
DO 600 J=1,NP1+NP2
600  ZPP(I,J) = Z(I,J)
    DO 700 I=1,NP1+NP2
    DO 700 J=1,NP1+NP2
700  ZC(I,J) = ZPP(I,J) + ZZP(I,J)
    IF(NP1.EQ.0) GOTO 88
    DO 800 I=1,NC
    DO 800 J=1,NP1
800  ZQP(I,J) = -ZX(I,J)
    CONTINUE
    IF(NP2.EQ.0) GOTO 99
790  DO 900 I=1,NC
    DO 900 J=1+NP1,NP1+NP2
900  ZQP(I,J) = 0.
    CONTINUE
    DO 925 I=1,NC
    DO 925 J=1,NC
925  ZI(I,J) = Z(I+NP1+NP2,J+NP1+NP2)
    CALL CMTULT(NC,NC,NP1+NP2,ZI,ZY,ZX)
    DO 950 I=1,NC
    DO 950 J=1,NP1+NP2
950  ZV(I,J) = ZQP(I,J) + ZX(I,J)
    RETURN
END

C---------------------------------------------------------------------

SUBROUTINE ZTOS(Z, Z0, S, N)
C-----THIS SUBROUTINE COMPUTES THE ELEMENTS OF THE S-MATRIX FROM
C-----THOSE OF Z-MATRIX OF AN N-MULTIPORT NETWORK. THE ELEMENTS
C-----OF THE Z0(N) ARE THE CHARACTERISTIC IMPEDANCES OF THE TRANS.
C-----LINES CONNECTED TO THE N-MULTIPORT NETWORK.
C
DIMENSION Z0(34)
COMPLEX Z1(34,34), S(34,34), Z(34,34)
COMPLEX C(34,34)
DO 10 I=1,N
  DO 10 J=1,N
    Z1(I,J) = Z(I,J)
10    S(I,J) = 0.
    DO 20 I=1,N
      DO 20 J=1,N
        C(I,J) = Z1(I,J) + Z0(I)
      20      C(I,J) = C(I,J) + Z0(I)
        CALL MATINC(C,N)
        CALL CMTULT(N,N,N,Z1,C,S)
        DO 30 I=1,N
      30      CON1 = SQRT(Z0(I)/Z0(J))
    CON1 = SQRT(Z0(I)/Z0(J))
      S(I,J) = S(I,J)/CON1
    RETURN
END

C---------------------------------------------------------------------

SUBROUTINE CMTULT(L,M,N,A,B,C)
C-----THIS SUBROUTINE SETS THE MULTIPLICATION OF THE TWO MATRIX
C-----A(L,M) AND B(M,N) TO OBTAIN THE MATRIX C(L,M).
C
COMPLEX A(34,34), B(34,34), C(34,34)
DO 3 I=1,L
  DO 3 J=1,N
    C(I,J) = 0.0
  3      C(I,J) = C(I,J) + A(I,K)*B(K,J)
RETURN
END

C---------------------------------------------------------------------

SUBROUTINE MATINC(A,N)
C-----THIS SUBROUTINE COMPUTES THE INVERSE OF THE MATRIX A(N,N).
C

C--------WARNING--------; THE INVERSE OF A IS FILLED INTO A ITSELF.
C
DIMENSION INDEX (34, 3)
COMPLEX T, SWAP, PIVOT, A (34, 34)
EQUIVALENCE (IROW, JROW), (ICOL, JCOLUMN)
DO 10 J = 1, N
10 INDEX (J, 3) = 0
DO 90 I = 1, N
   AMAX = 0.0
   DO 40 J = 1, N
      IF (INDEX (J, 3) .EQ. 1) GO TO 40
      DO 30 K = 1, N
         IF (INDEX (K, 3) - 1) 20, 30, 115
30     IF (AMAX GE CABS (A (J, K))) GO TO 30
      IROW = J
      ICOLUMN = K
      AMAX = CABS (A (J, K))
   CONTINUE
40    CONTINUE
INDEX (ICOLUMN, 3) = INDEX (ICOLUMN, 3) + 1
INDEX (I, 1) = IROW
INDEX (I, 2) = ICOLUMN
IF (IROW .EQ. ICOLUMN) GO TO 60
DO 50 L = 1, N
   SWAP = A (IROW, L)
   A (IROW, L) = A (ICOLUMN, L)
   A (ICOLUMN, L) = SWAP
50    PIVOT = A (ICOLUMN, ICOLUMN)
A (ICOLUMN, ICOLUMN) = 1.0
DO 70 L = 1, N
   A (ICOLUMN, L) = A (ICOLUMN, L) / PIVOT
70    DO 90 L1 = 1, N
   IF (L1 .EQ. ICOLUMN) GO TO 90
   T = A (L1, ICOLUMN)
   A (L1, ICOLUMN) = 0.0
   DO 80 L = 1, N
   A (L1, L) = A (L1, L) - A (ICOLUMN, L) * T
80    CONTINUE
90    DO 110 I = 1, N
      L = N - I + 1
      IF (INDEX (L, 1) .EQ. INDEX (L, 2)) GO TO 110
      JROW = INDEX (L, 1)
      JCOLUMN = INDEX (L, 2)
      DO 100 K = 1, N
         SWAP = A (K, JROW)
         A (K, JROW) = A (K, JCOLUMN)
      100    A (K, JCOLUMN) = SWAP
110   CONTINUE
115   CONTINUE
RETURN
END

SUBROUTINE PRINTZ (M, N, AMAT, NAME)
CHARACTER*12 NAME
COMPLEX AMAT (34, 34)
INTEGER I, J, M, N
WRITE (2, 1) NAME
DO 3 J = 1, N
   WRITE (2, 2) J
3    DO 3 I = 1, M
   WRITE (2, 4) I, AMAT (I, J), CABS (AMAT (I, J)), ANGLE (AMAT (I, J))
1 FORMAT (1X, 'ELEMENTS OF MATRIX ', A15)
2 FORMAT (/1X, 'ELEMENTS OF COLUMN#', I2, //4X, 'ROW#', 5X, 'REAL'
   ', 'PART', 10X, 'IMAGINARY PT', 12X, 'MAGNITUDE', 10X, 'DEG. ')
4 FORMAT (3X, I3, 2X, 2(E18.10, 2X), 2X, E18.10, 3X, F8.2)
WRITE (2, *)' '
SUBROUTINE VSWRND (NEXPORT, SM, NAME)
CHARACTER*12 NAME
COMPLEX SM(34,34)
REAL COLSM(34)
WRITE (2,1) NAME
DO 10 I=1,NEXPORT
  VSWR=(1+ABS(SM(I,I)))/(1-ABS(SM(I,I)))
    DO 20 J=1,NEXPORT
      COLSM(J)=ABS(SM(I,J))
    CONTINUE
  WRITE (2,2) I, VSWR, (20*LOG10(COLSM(J)), J=1,NEXPORT)
10 CONTINUE
1 FORMAT (/ , 4X, 'PORT#', 7X, 'VSWR', 12X, 'ELEMENTS OF ', A5,
      ' MATRIX IN dB')
2 FORMAT (5X, I3, 3X, F10.4, 7X, 5F10.4)
RETURN
END

FUNCTION ANGLE(C)
COMPLEX C
REAL ANGLE, PI
PI=4.0*ATAN(1.0)
IF (REAL(C).NE.0.0) THEN
  ANGLE=ATAN2(AIMAG(C), REAL(C)) * 180/PI
ELSEIF (AIMAG(C).GT.0.0) THEN
  ANGLE=90.0
ELSEIF (AIMAG(C).LT.0.0) THEN
  ANGLE=-90.0
ENDIF
RETURN
END
$ RUN MBALUN3

---------------------------------------------------------------------

PROGRAM MBALUN3

FOR ANALYSIS OF PLANAR MARCHAND BALUN
ANALYSIS FOR TWO COUPLED LINE SECTIONS
AND COPLANAR COUPLED LINE SECTION AT OUTPUT

1------------------------OPEN
SHORT----------------\ /--------------SHORT
     |
     |
2 3

MIMICAD CENTER
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF COLORADO, BOULDER, CO 80309-0425

---------------------------------------------------------------------

ENTER OUTPUT FILENAME
M3OUT

READ CAPACITANCE DATA FROM INPUT FILE (Y/N)?
Y

ENTER INPUT FILENAME
M3IN

ENTER CENTER FREQUENCY IN Hz
30E9

ENTER 1 IF SECTION 1 LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2

ENTER 1 IF SECTION 2 LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
2

ENTER 1 IF SECTION 3 LENGTH IS TO BE INPUT
ENTER 2 TO USE A QUARTER WAVE SECTION
1

ENTER L(3) IN METERS
0.15E-3

ENTER 3 FOR A 3-PORT CHARACTERIZATION
ENTER 2 FOR A 2-PORT CHARACTERIZATION
3

ENTER 1 IF ALL TERMINATING IMPEDANCES ARE TO BE INPUT
ENTER 2 TO ENTER Z0(1) AND CALCULATE Z0(1)
1

ENTER Z0(1) (ohm)
83
ENTER Z0(2) (ohm)
26
ENTER Z0(3) (ohm)
26

DO A FREQUENCY SWEEP (Y/N)?
N
ANALYSIS COMPLETE
RESULT IN DATA FILE : M3OUT .DAT
??
344.8000
-117.8000
-117.8000
118.6000
45.9000
-19.8000
-19.8000
20.2000
1455.6000
-1228.5000
-1228.5000
1229.1000
213.8000
-190.3000
-190.3000
193.2000
258.6000
-76.4000
-76.4000
258.6000
33.1000
-13.3000
-13.3000
33.1000
CAPACITANCE MATRICES FOR SECTION 1 IN pF/m
CD(1, 1) = 344.8000
CD(1, 2) = -117.8000
CD(2, 1) = -117.8000
CD(2, 2) = 118.6000
CA(1, 1) = 45.9000
CA(1, 2) = -19.8000
CA(2, 1) = -19.8000
CA(2, 2) = 20.2000

CAPACITANCE MATRICES FOR SECTION 2 IN pF/m
CD(1, 1) = 1455.6000
CD(1, 2) = -1228.5000
CD(2, 1) = -1228.5000
CD(2, 2) = 1229.1000
CA(1, 1) = 213.8000
CA(1, 2) = -190.3000
CA(2, 1) = -190.3000
CA(2, 2) = 193.2000

CAPACITANCE MATRICES FOR SECTION 3 IN pF/m
CD(1, 1) = 258.6000
CD(1, 2) = -76.4000
CD(2, 1) = -76.4000
CD(2, 2) = 258.6000
CA(1, 1) = 33.1000
CA(1, 2) = -13.3000
CA(2, 1) = -13.3000
CA(2, 2) = 33.1000

NORMAL MODE PARAMETERS FOR SECTION 1
Rc , Rpi = 0.9521148 47.68021
Vc , Vpi = 1.0222246E+08 1.2374132E+08
Eeffc , Eeffpi = 8.600996 5.869646
Z1c , Z1pi = 42.05016 -1.532906
Z2c , Z2pi = -1908.951 69.58942

NORMAL MODE PARAMETERS FOR SECTION 2
Rc , Rpi = 0.9450694 4.402442
Vc , Vpi = 1.0177906E+08 1.191193E+08
Eeffc , Eeffpi = 8.676100 6.334770
Z1c , Z1pi = 33.35302 -2.123929
Z2c , Z2pi = -138.7651 8.836864

NORMAL MODE PARAMETERS FOR SECTION 3
Rc , Rpi = 1.000000 -0.9999985
Vc , Vpi = 9.8827784E+07 1.1157252E+08
Eeffc , Eeffpi = 9.202022 7.219829
Z1c , Z1pi = 55.53575 26.75458
Z2c , Z2pi = 55.53573 26.75456

CENTER FREQUENCY f0 = 30.00000 GHz

LENGTH OF SECTION 1 L = 0.9330E-03 METERS
LENGTH OF SECTION 2 L = 0.9147E-03 METERS
LENGTH OF SECTION 3 L = 0.1500E-03 METERS

ELEMENTS OF MATRIX Z

ELEMENTS OF COLUMN# 1
<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000000000E+00</td>
<td>0.1930760956E+02</td>
<td>0.1930760956E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.0000000000E+00</td>
<td>-0.3567679977E+02</td>
<td>0.3567679977E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.0000000000E+00</td>
<td>0.3128817940E+02</td>
<td>0.3128817940E+02</td>
<td>90.00</td>
</tr>
</tbody>
</table>

**ELEMENETS OF COLUMN# 2**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000000000E+00</td>
<td>-0.3567679977E+02</td>
<td>0.3567679977E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.0000000000E+00</td>
<td>-0.5538592529E+02</td>
<td>0.5538592529E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.0000000000E+00</td>
<td>-0.5678274536E+02</td>
<td>0.5678274536E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 3**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000000000E+00</td>
<td>0.3128818130E+02</td>
<td>0.3128818130E+02</td>
<td>90.00</td>
</tr>
<tr>
<td>2</td>
<td>0.0000000000E+00</td>
<td>-0.5678275299E+02</td>
<td>0.5678275299E+02</td>
<td>-90.00</td>
</tr>
<tr>
<td>3</td>
<td>0.0000000000E+00</td>
<td>-0.5556187439E+02</td>
<td>0.5556187439E+02</td>
<td>-90.00</td>
</tr>
</tbody>
</table>

**PORT TERMINATING IMPEDANCES**

- Z0 (1) = 83.0000
- Z0 (2) = 26.0000
- Z0 (3) = 26.0000

**ELEMENTS OF MATRIX S**

**ELEMENTS OF COLUMN# 1**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2574606240E-01</td>
<td>0.8677302301E-01</td>
<td>-0.9051970226E-01</td>
<td>79.47</td>
</tr>
<tr>
<td>2</td>
<td>-0.8794417232E-01</td>
<td>-0.7010679841E+00</td>
<td>0.7065624595E+00</td>
<td>-97.15</td>
</tr>
<tr>
<td>3</td>
<td>0.1073734313E+00</td>
<td>0.6935763359E+00</td>
<td>0.7018384337E+00</td>
<td>81.20</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 2**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.8794414252E-01</td>
<td>-0.7010679245E+00</td>
<td>0.7065623999E+00</td>
<td>-97.15</td>
</tr>
<tr>
<td>2</td>
<td>0.4539710879E+00</td>
<td>-0.2508807182E+00</td>
<td>0.5186818838E+00</td>
<td>-28.93</td>
</tr>
<tr>
<td>3</td>
<td>0.4486482739E+00</td>
<td>-0.1745089889E+00</td>
<td>0.4813924134E+00</td>
<td>-21.25</td>
</tr>
</tbody>
</table>

**ELEMENTS OF COLUMN# 3**

<table>
<thead>
<tr>
<th>ROW#</th>
<th>REALPART</th>
<th>IMAGINARY_PT</th>
<th>MAGNITUDE</th>
<th>DEG.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1073734239E+00</td>
<td>0.6935763359E+00</td>
<td>0.7018384337E+00</td>
<td>81.20</td>
</tr>
<tr>
<td>2</td>
<td>0.4486483037E+00</td>
<td>-0.1745089591E+00</td>
<td>0.4813924433E+00</td>
<td>-21.25</td>
</tr>
<tr>
<td>3</td>
<td>0.4447245598E+00</td>
<td>-0.2791132033E+00</td>
<td>0.5250563025E+00</td>
<td>-32.11</td>
</tr>
</tbody>
</table>

**PORT# | VSWR | ELEMENTS OF S | MATRIX IN dB**

| 1    | 1.1990 | -20.8659 | -3.0170 | -3.0753 |
| 2    | 3.1553 | -3.0170 | -5.7020 | -6.3500 |
| 3    | 3.2110 | -3.0753 | -6.3500 | -5.5959 |