Asymmetrical Three-Line Coupled Striplines with Anisotropic Substrates

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Abstract —**Analytical methods are presented for the general structure of three-line coupled striplines with anisotropic media for the first time. Two approaches are included; one gives variational expressions for the quasistatic parameters of the cases with the uniaxially anisotropic substrates cut with their planar surface at an arbitrary angle to the optical axis, the other gives the rigorous hybrid-mode formulation for the cases with the uniaxially anisotropic substrates cut with their surface perpendicular to the optical axis. Accurate numerical results are presented for the propagation constants as well as the characteristic impedances of various types of three-line coupled striplines with anisotropic media.**

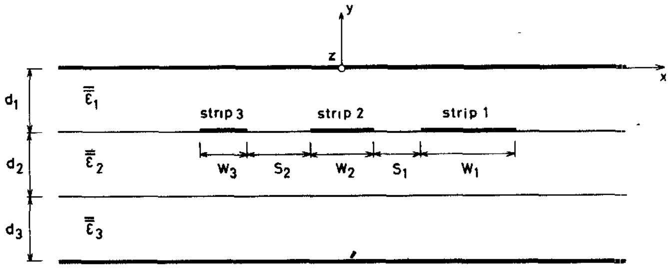

Fig. 1. General structure of asymmetrical three-line coupled striplines with anisotropic substrates.

I. Introduction

PROPAGATION characteristics of various types of two coupled striplines have been investigated by many authors [1]–[8]. The simple structure of coupled microstrips has generally unequal phase velocities, which cause poor coupler isolation. Several attempts have been made to equalize the phase velocities including the use of an anisotropic substrate [4] and the modification of the structure [6], e.g., coupled suspended strips and coupled overlaid strips. Recently, three-line coupled stripline configurations [9]–[15] were introduced for filter and coupler applications. Asymmetrical versions of three-line coupled striplines [11] are especially promising because of the additional flexibilities offered by the asymmetrical configuration and the impedance transform nature. An analytical method of asymmetrical three-line coupled striplines [11] was presented by extending the procedure of two-line coupled lines. However, it dealt with the microstrip structure on an isotropic substrate only and presented results for the propagation constants only. At the present time, there is no analytical method applicable to the various types of three-line coupled striplines with anisotropic substrates and no information about the characteristic impedances of asymmetrical three-line coupled striplines. This paper presents two analytical approaches for the general structure of three-line coupled striplines with anisotropic media (Fig. 1), which includes three-line coupled microstrips, suspended strips, and strips with an overlay. One approach is based on the quasistatic formulation and is applicable to the cases with the uniaxially anisotropic substrates cut with their planar surface at an arbitrary angle to the optical axis. The other, based on the hybrid-mode formulation, gives the rigorous frequency-dependent solutions for the cases with the uniaxially anisotropic substrate cut with its surface perpendicular to the optical axis.

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The quasistatic characteristics of three-line coupled lines can be described in general by three propagation constants and nine characteristic impedances because of three fundamental modes of propagation (Section II-A). Section II-A shows how these propagation parameters can be expressed in terms of the line constants. The variational expressions for the line constants, in turn, are derived in Section II-B. The rigorous hybrid-mode formulation of Section III is an extended version of that for the two-line coupled lines case and is outlined briefly. Numerical examples are presented for the propagation constants as well as the characteristic impedances of various types of three-line coupled striplines in Section IV. Propagation characteristics of the three-line coupled striplines with anisotropic media are presented for the first time.

II. Quasistatic Characteristics

A. Three Conductor Transmission-Line Analysis

The basic equations for three conductor TEM transmission lines can be expressed in general as follows:

$$-\frac{dV_i}{dz}=\sum_{j=1}^{3} z'_{ij}I_j$$
$$-\frac{dI_i}{dz}=\sum_{j=1}^{3} y'_{ij}V_j \qquad (i=1,2,3) \qquad (1)$$

where V_i and I_i are the voltages and currents on the ith conductor, and z'_{ii}, y'_{ii} are self impedances and self admittances per unit length of lines, and z'_{ij}, y'_{ij} $(i \neq j)$ are mutual impedances and mutual admittances per unit length, respectively. For lossless lines with uniaxially an-

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isotropic media, one has

$$z'_{ij} = z'_{ji} = j\omega L_{ij}$$
$$y'_{ij} = y'_{ji} = j\omega C_{ij} \qquad (2)$$

where L_{ii} and C_{ii} are the self inductances and self capacitances per unit length, and L_{ij} and C_{ij} $(i \neq j)$ are the mutual inductances and capacitances per unit length, respectively. Eliminating the currents I_i from (1), we obtain a set of differential equations for voltages V_i only

$$\frac{d^2V_i}{dz^2} - t_{i1}V_1 - t_{i2}V_2 - t_{i3}V_3 = 0 \qquad (i=1,2,3) \qquad (3)$$

where

$$t_{ij} = z'_{i1}y'_{1j} + z'_{i2}y'_{2j} + z'_{i3}y'_{3j} \qquad (i,j=1,2,3). \qquad (4)$$

Assuming a z-variation of the form $V_i(z) = V_{i0}e^{-j\beta z}$ for the voltages, the differential equations (3) reduce to the following eigenvalue equation:

$$\begin{bmatrix} \beta^2 + t_{11} & t_{12} & t_{13} \\ t_{21} & \beta^2 + t_{22} & t_{23} \\ t_{31} & t_{32} & \beta^2 + t_{33} \end{bmatrix} \begin{bmatrix} V_{10} \\ V_{20} \\ V_{30} \end{bmatrix} = 0. \qquad (5)$$

For (5) to yield nontrivial solutions, the determinant of the coefficient matrix must be zero, that is,

$$\beta^6 + a\beta^4 + b\beta^2 + c = 0 \qquad (6)$$

where

$$a = t_{11} + t_{22} + t_{33}$$
$$b = t_{11}t_{22} + t_{22}t_{33} + t_{33}t_{11} - t_{12}t_{21} - t_{23}t_{32} - t_{31}t_{13}$$
$$c = t_{12}t_{23}t_{31} + t_{21}t_{32}t_{13} + t_{11}t_{22}t_{33} - t_{12}t_{21}t_{33} - t_{23}t_{32}t_{11} - t_{31}t_{13}t_{22}. \qquad (7)$$

Equation (6) is the determinantal equation for β, and it gives six roots

$$\beta = \pm\beta_1, \pm\beta_2, \pm\beta_3. \qquad (8)$$

The general solutions for the voltage on line i can be written as

$$V_i = R_{i1}\left(A_1e^{j\beta_1 z} + B_1e^{-j\beta_1 z}\right) + R_{i2}\left(A_2e^{j\beta_2 z} + B_2e^{-j\beta_2 z}\right) + R_{i3}\left(A_3e^{j\beta_3 z} + B_3e^{-j\beta_3 z}\right) \qquad (i=1,2,3) \qquad (9)$$

where A_i, B_i are constants, and R_{ik} are ratios of the voltages V_i and V_1 for the mode k

$$R_{ik} = \frac{V_i}{V_1} \qquad \text{for } \beta = \beta_k \qquad (k=1,2,3). \qquad (10)$$

The currents I_i are obtained by substituting (9) into (1)

$$I_i = Y_{i1}R_{i1}\left(A_1e^{j\beta_1 z} + B_1e^{-j\beta_1 z}\right) + Y_{i2}R_{i2}\left(A_2e^{j\beta_2 z} + B_2e^{-j\beta_2 z}\right) + Y_{i3}R_{i3}\left(A_3e^{j\beta_3 z} + B_3e^{-j\beta_3 z}\right) \qquad (11)$$

where Y_{ik} is the characteristic admittance of line i for mode k and it is given by

$$Y_{ik} = \frac{\beta_k}{R_{ik}} \cdot \frac{R_{1k}\tilde{Z}_{1k} + R_{2k}\tilde{Z}_{2k} + R_{2k}\tilde{Z}_{3k}}{|\bar{\bar{Z}}|} \qquad (12)$$

where $\tilde{Z}_{ij}$ is a cofactor of the impedance matrix $\bar{\bar{Z}}$

$$\bar{\bar{Z}} = \begin{bmatrix} z'_{11} & z'_{12} & z'_{13} \\ z'_{12} & z'_{22} & z'_{23} \\ z'_{13} & z'_{23} & z'_{33} \end{bmatrix} \qquad (13)$$

and $|\bar{\bar{Z}}|$ is the determinant of the impedance matrix.

B. Variational Expressions for the Quasistatic Parameters

According to the preceding discussion, the quasistatic characteristics, that is, the phase constants β_k and characteristic impedances $Z_{ik} = 1/Y_{ik}$ of three-line coupled striplines shown in Fig. 1, can be described in terms of inductances L_{ij} and capacitances C_{ij} (eqs. (6) and (12)), where L_{ij} are obtained by using the self and mutual capacitances C_{ij} of the case without substrates. The capacitances are defined as

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{12} & C_{22} & C_{23} \\ C_{13} & C_{23} & C_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \qquad (14)$$

where Q_i is the total charge on the strip i. However, to authors' knowledge, the expressions of the elements of this capacitance matrix C_{ij} have not been presented for any type of three-line coupled lines. In the following, the compliance matrix, the inverse matrix of the capacitance matrix, is introduced, and the variational expressions for the matrix elements are derived for the general structure of the asymmetrical three-line coupled striplines with uniaxially anisotropic media (Fig. 1). The tensor permittivities of the layered anisotropic media are given as

$$\bar{\bar{\epsilon}}_i = \begin{bmatrix} \epsilon_{ixx} & \epsilon_{ixy} \\ \epsilon_{ixy} & \epsilon_{iyy} \end{bmatrix} \epsilon_0 \qquad (i=1,2,3). \qquad (15)$$

The potential distribution at the strip plane can be obtained by using the extended version of the method in [8]

$$\phi(x) = \int_{-\infty}^{\infty}\int_0^{\infty} G(\alpha; x \mid x')\sigma(x')\,d\alpha\,dx' \qquad (16)$$

where $\sigma(x)$ is the charge distribution on the strips and

$$G(\alpha; x|x') = \frac{1}{\pi\epsilon_0\alpha}F(\alpha)\cos\alpha(x-x') \qquad (17)$$

$$F(\alpha) = \frac{1}{\epsilon_{1e}\coth(p_1d_1\alpha) + \epsilon_{2e}L} \qquad (18)$$

$$L = \frac{\epsilon_{2e} + \epsilon_{3e}\coth(p_2d_2\alpha)\coth(p_3d_3\alpha)}{\epsilon_{2e}\coth(p_2d_2\alpha) + \epsilon_{3e}\coth(p_3d_3\alpha)} \qquad (19)$$

$$\epsilon_{ie} = \sqrt{\epsilon_{ixx}\epsilon_{iyy} - \epsilon_{ixy}^2}$$

$$p_i = \sqrt{\frac{\epsilon_{ixx}}{\epsilon_{iyy}} - \left(\frac{\epsilon_{ixy}}{\epsilon_{iyy}}\right)^2}. \qquad (20)$$

$\phi(x)$ should be constant over the strip conductors

$$\phi(x) = V_i \qquad (i=1,2,3). \tag{21}$$

We will derive the variational expressions for the elements of the compliance matrix, which is defined as

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12} & D_{22} & D_{23} \\ D_{13} & D_{23} & D_{33} \end{bmatrix} \begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix}. \tag{22}$$

We consider the following sets of excitations:

i) $Q_1 \neq 0, \quad Q_2 = Q_3 = 0$ (23a)

ii) $Q_2 \neq 0, \quad Q_3 = Q_1 = 0$ (23b)

iii) $Q_3 \neq 0, \quad Q_1 = Q_2 = 0$ (23c)

iv) $Q_1 = Q_2 \neq 0, \quad Q_3 = 0$ (23d)

v) $Q_2 = Q_3 \neq 0, \quad Q_1 = 0$ (23e)

vi) $Q_3 = Q_1 \neq 0, \quad Q_2 = 0.$ (23f)

From (16), (21), and (23a), we obtain

$$V_1 Q_1 = V_1 \int_{W_1} \sigma(x)\, dx$$
$$= \int_{W_1} \int_{-\infty}^{\infty} \int_0^{\infty} \sigma(x) G(\alpha; x|x') \sigma(x')\, d\alpha\, dx'\, dx \tag{24a}$$
$$0 = V_2 \int_{W_2} \sigma(x)\, dx$$
$$= \int_{W_2} \int_{-\infty}^{\infty} \int_0^{\infty} \sigma(x) G(\alpha; x|x') \sigma(x')\, d\alpha\, dx'\, dx \tag{24b}$$
$$0 = V_3 \int_{W_3} \sigma(x)\, dx$$
$$= \int_{W_3} \int_{-\infty}^{\infty} \int_0^{\infty} \sigma(x) G(\alpha; x|x') \sigma(x')\, d\alpha\, dx' dx \tag{24c}$$

by utilizing

$$Q_1 = \int_{W_1} \sigma(x)\, dx \neq 0$$
$$Q_i = \int_{W_1} \sigma(x)\, dx = 0 \qquad (i=2,3). \tag{25}$$

Therefore, we get

$$D_{11} = \left.\frac{V_1}{Q_1}\right|_{Q_2 = Q_3 = 0}$$
$$= \int\int_{-\infty}^{\infty} \sigma(x) G(\alpha; x|x') \sigma(x')\, d\alpha\, dx'\, dx / Q_1^2. \tag{26}$$

Similar expressions for D_{22}, D_{33}, $D_{11} + 2D_{12} + D_{22}$, $D_{22} + 2D_{23} + D_{33}$, and $D_{33} + 2D_{13} + D_{11}$ can be obtained by using (23b), (23c), (23d), (23e), and (23f), respectively. It can be shown easily that (26) has a stationary property and it gives an upper bound to the exact value.

III. Hybrid-Mode Analysis

Frequency-dependent hybrid-mode solutions are available for the cases of isotropic and/or uniaxially anisotropic substrates cut with their planar surface perpendicular to the optical axis. The method of solution is a straightforward extension of that in [8] and no approximations for simplification are used in the formulation procedure.

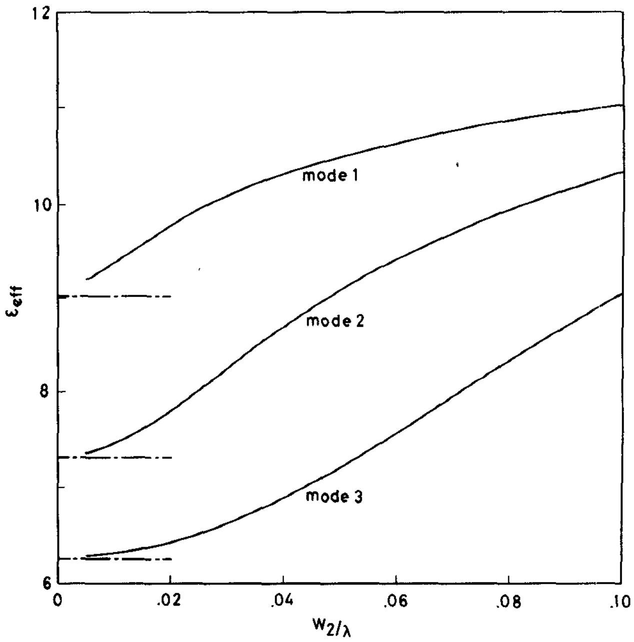

Fig. 2. Dispersion characteristics of three-line coupled microstrips. $\epsilon_{1xx} = \epsilon_{1yy} = 1$, $\epsilon_{2xx} = 9.4$, $\epsilon_{2yy} = 11.6$, $\epsilon_{ixy} = 0$ $(i=1,2,3)$, $d_1 \to \infty$, $d_{2/W_2} = 1$, $d_3 = 0$, $W_{1/W_2} = 1.5$, $W_{3/W_2} = 2.0$, $S_{1/W_2} = 1.0$, $S_{2/W_2} = 0.5$. ——: hybrid-mode, —-—: quasi-static.

The rigorous expression of the electric field for the general structure of three-line coupled striplines with anisotropic media can be obtained as

$$\hat{E}(x, y, z) = -\int_{x'}\int_{y'} \bar{\bar{Z}}(x, y|x', y') \cdot \hat{i}(x') \delta(y' + d_1)\, dy'\, dx' e^{-j\beta z} \tag{27}$$

where $\hat{i}(x)$ and β are the unknown current density on the strips and the propagation constant, respectively, and the dyadic Green's function $\bar{\bar{Z}}$ is obtained by utilizing the procedure in [8]. Applying the boundary condition at the strip conductors leads to the integral equation for $\hat{i}(x)$ and implicitly β. Galerkin's procedure is applied to the integral equation for numerical computations. For the symmetrical structures [6], the even and odd modes can be treated separately, which results in two separate determinantal equations, whereas the present formulation does not utilize any symmetrical property, treats all the propagation modes simultaneously and gives a single determinantal equation. The frequency-dependent hybrid-mode solutions for propagation constants and characteristic impedances are presented in the next section.

IV. Numerical Examples

The Ritz procedure is applied to the variational expressions of the quasistatic parameters obtained in Section II for the numerical computation, whereas Galerkin's procedure is used in the frequency-dependent hybrid-mode calculations. In both procedures, the unknown quantities involved are expanded in terms of the appropriate basis

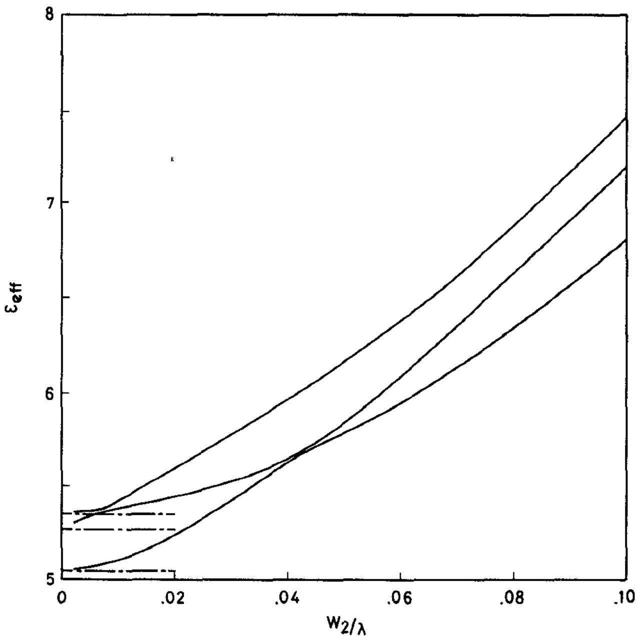

Fig. 3. Dispersion characteristics of three-line coupled suspended strips. $\epsilon_{ixx}=\epsilon_{iyy}=1$ $(i=1,3)$, $\epsilon_{2xx}=9.4$, $\epsilon_{2yy}=11.6$, $\epsilon_{ixy}=0$ $(i=1,2,3)$, $d_1 \rightarrow \infty$, $d_{2/W_2}=1$, $d_{3/W_2}=0.1$, $W_{1/W_2}=1.5$, $W_{3/W_2}=2.0$, $S_{1/W_2}=1.0$, $S_{2/W_2}=0.5$. ——: hybrid-mode, —·—: quasi-static.

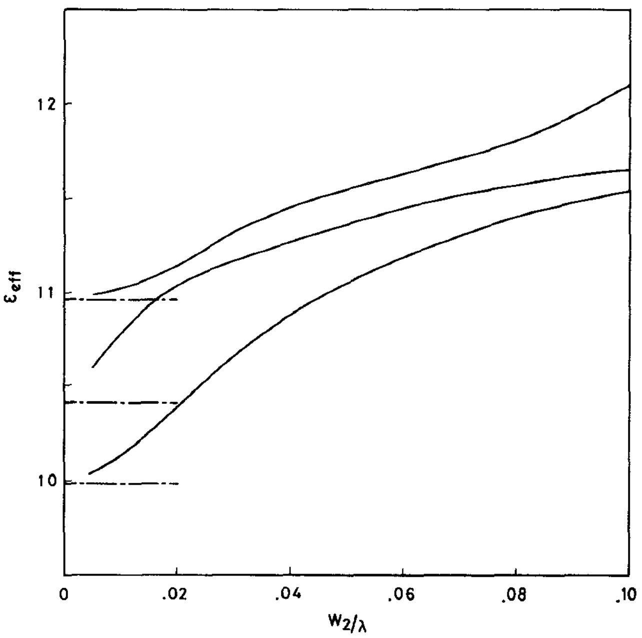

Fig. 4. Dispersion characteristics of three-line coupled overlaid strips. $\epsilon_{1xx}=9.4$, $\epsilon_{1yy}=11.6$, $\epsilon_{2xx}=\epsilon_{2yy}=16$, $\epsilon_{3xx}=\epsilon_{3yy}=1.0$, $\epsilon_{ixy}=0$ $(i=1,2,3)$, $d_{1/W_2}=1$, $d_{2/W_2}=0.5$, $d_3 \rightarrow \infty$, $W_{1/W_2}=1.5$, $W_{3/W_2}=2.0$, $S_{1/W_2}=1.0$, $S_{2/W_2}=0.5$. ——: hybrid-mode, —·— quasi-static.

functions which are similar to those used in [8] and take the edge effect into consideration. Some preliminary computations showed that three basis functions for the quasistatic and two basis functions for the frequency-dependent solutions are sufficient in most cases.

Figs. 2–4 show the effective dielectric constants for different types of three-line coupled striplines with uniaxially anisotropic substrates cut with their planar surface perpendicular to the optical axis. There are three fundamental modes of propagation, and the frequency-dependent hybrid-mode values of the modes converge to the corresponding quasistatic values in lower frequency ranges, which display the accuracy of the computations. We mention that the phase velocities of different modes of three-line coupled suspended striplines have very close values at some frequency but they never coincide, i. e., there is a

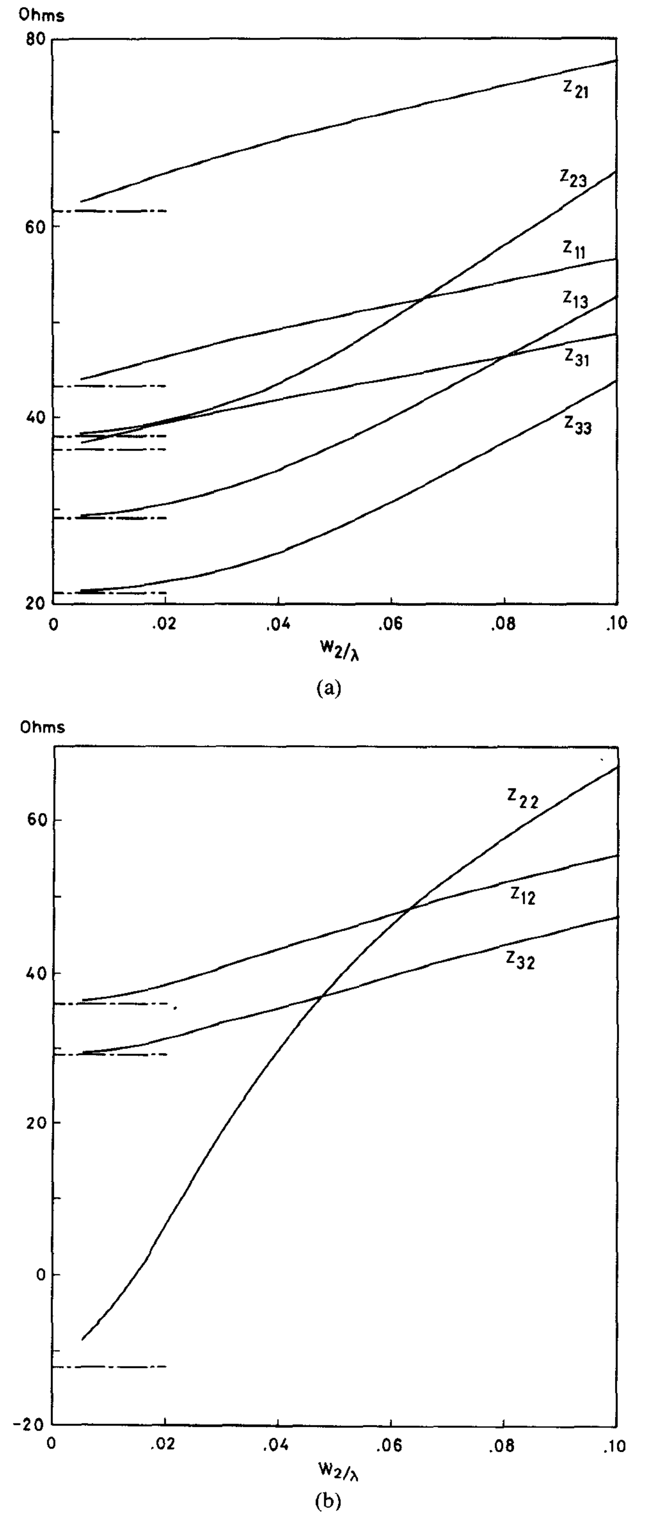

Fig. 5. (a) Characteristic impedances for modes 1 and 3. Dimensions are same as in Fig. 2. (b) Characteristic impedances for mode 2. Dimensions are same as in Fig. 2.

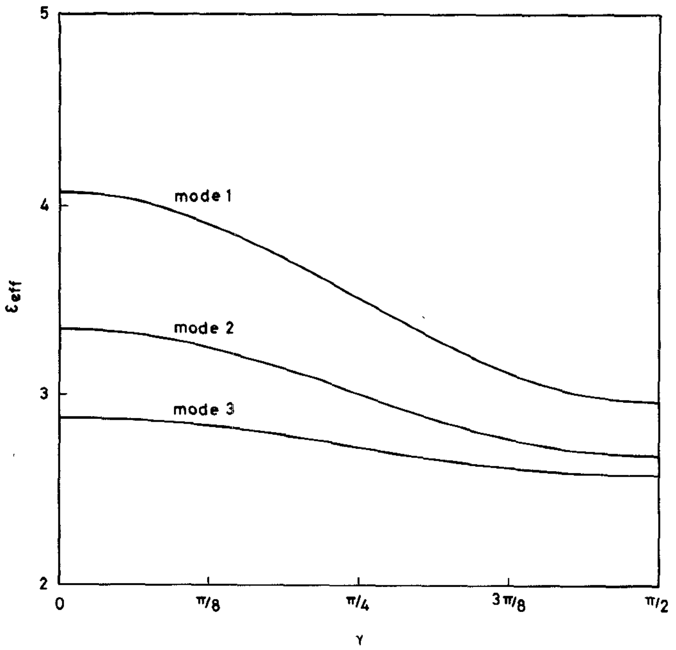

Fig. 6. Effective dielectric constants of three-line coupled microstrips versus γ. $\epsilon_{1xx}=\epsilon_{1yy}=1$, $\epsilon_{1xy}=0$, $\epsilon_{2xx}=3.40$, $\epsilon_{2yy}=5.12$, $\epsilon_{2xy}=0$ when $\gamma=0$, $d_1\rightarrow\infty$, $d_2/w_2=1$, $d_3=0$, $W_1/w_2=1.5$, $W_3/w_2=2.0$, $S_1/w_2=1.0$, $S_2/w_2=0.5$.

small gap between the dispersion curves because of the mode coupling. Examining the voltages and currents of each mode of the three-line coupled microstrips shows that modes 1, 2, and 3 of our theory become the EE-, OE-, and OO-modes in the symmetrical case [9],[16]. Therefore, modes 1, 2, and 3 of the microstrip case (Fig. 2) could be referred as the *cc*-, *πc*-, and *ππ*-modes, respectively. However, for the asymmetrical three-line coupled suspended lines and overlaid configurations considered in Figs. 3 and 4, the modes of propagations cannot be identified for a wide range of frequencies because of the mode coupling, e.g., the lowest dispersion curve of Fig. 3 is similar to that of mode 2 of the microstrip case in lower frequencies, but it is similar to that of mode 3 at higher frequencies. Therefore, mode numbers are not assigned in Figs. 3 and 4. Fig. 5 shows the characteristic impedance of three-line coupled microstrips. The definition for the characteristic impedance is not uniquely specified for the hybrid-mode propagation. The definition chosen here is

$$Z_{ik}=\frac{V_{ik}}{I_{ik}} \tag{28}$$

where V_{ik} and I_{ik} are the voltage at the center of the strip i and the total current on the strip i for the mode k, respectively. Again, the frequency-dependent values of the characteristic impedances converge to the quasistatic values in lower frequency ranges. For the symmetrical case, the voltage of strip 2 for mode 2 (the OE-mode), v_{22}, is always zero. On the contrary, for the asymmetrical case considered here, the voltage V_{22} becomes zero only at some frequency. Therefore, at the frequency the characteristic impedance of strip 2 for mode 2, Z_{22}, becomes zero (Fig. 5(b)).

Fig. 6 shows the effective dielectric constants ϵ_{eff} of asymmetrical three-line coupled microstrips on a uniaxially anisotropic substrate cut with its surface at γ to the optical axis.

V. Conclusions

Two analytical approaches are presented for the general structure of three-line coupled striplines with anisotropic media; one gives variational expressions for the quasistatic parameters, the other gives the rigorous hybrid-mode formulation for the various types of three-line coupled striplines. Accurate numerical computations based on the quasistatic and the frequency-dependent formulation are presented for the progagation constants as well as the characteristic impedances of the cases with anisotropic media, for the first time.

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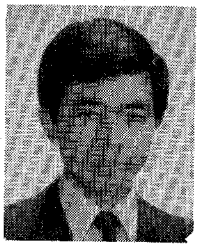

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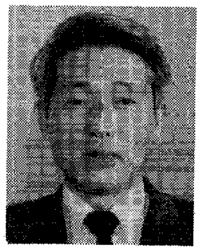

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