

COORDINATED SCIENCE LABORATORY

College of Engineering

**ASYMMETRICAL COUPLED
COPLANAR-TYPE
TRANSMISSION LINES
WITH ANISOTROPIC
SUBSTRATES**

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ASYMMETRICAL COUPLED COPLANAR-TYPE TRANSMISSION LINES
WITH ANISOTROPIC SUBSTRATES

Toshihide Kitazawa, Yoshio Hayashi and Raj Mittra

ABSTRACT

In this paper the asymmetrical coupled coplanar-type transmission line (C-CTL) with an anisotropic substrate is investigated using both the quasistatic method and the hybrid-mode formulations. The line characteristics of interest, e.g., the propagation constant and the characteristic impedances of the various types of C-CTLs with anisotropic substrate, are presented.

I. INTRODUCTION

Various types of transmission lines with anisotropic substrates have been investigated for use in microwave- and millimeter-wave integrated circuits [1]. These include single and coupled striplines [2] - [7], slot lines [8], and coplanar-type transmission lines [9] - [11]. The coplanar-type transmission lines (CTLs) are promising because of their easy adaptation to shunt element connections [12], [13]. The application of coupled coplanar-type transmission lines to filters and couplers was proposed by C. P. Wen [14]. The propagation characteristics of coupled coplanar-type transmission lines (C-CTL) have been studied based on the quasistatic [14], [15] and hybrid-mode formulations [16], [17], and accurate numerical values are available for the cases with isotropic and/or anisotropic substrates. However, most of them assume the structural symmetry. The theoretical approach for the asymmetrical version is available only for the propagation constant of the case with a single isotropic substrate [16]. There is no information available for the characteristic impedances of asymmetrical C-CTLs, even for the simplest case with an isotropic substrate, although it is required to utilize the advantages of the asymmetrical structure, the impedance transform nature and the additional flexibility.

In this paper, we present the analytical method for the general structure of asymmetrical coupled coplanar-type transmission lines with an anisotropic substrate. This method includes both the hybrid-mode and the quasistatic formulations and is useful for accurately computing the characteristic impedances as well as propagation constants of various types of asymmetrical coupled coplanar-type transmission lines.

II. THEORY

A. Variational Expressions for the Elements of the Capacitance Matrix of a C-CTL

The variational method will be described for the quasistatic characteristics of the general structure for asymmetrical, coupled coplanar-type transmission lines (C-CTLs; Fig. 1) with uniaxially anisotropic substrates, whose permittivities are given by the following dyadic:

$$\epsilon_i = \begin{bmatrix} \epsilon_{i,xx} & \epsilon_{i,xy} \\ \epsilon_{i,xy} & \epsilon_{i,yy} \end{bmatrix} \epsilon_0 \quad (1)$$

The quasistatic characteristics of the symmetrical C-CTL can be expressed in terms of the scalar line capacitance [15], whereas, for the asymmetrical C-CTL case considered here, they are described by the capacitance matrix which is defined as:

$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} C_1 & -C_m \\ -C_m & C_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad (2)$$

where V_1 and Q_1 are the potential and the total charge on the right strip, and V_2 and Q_2 are those on the left strip, respectively. The variational expressions of the self and mutual capacitances C_1 , C_2 , and C_m will be derived in the following.

The charge distribution on the conductors can be expressed in terms of the aperture field $e_x(x)$ [15];

$$\sigma(x) = \iint_{-\infty}^{\infty} G(\alpha; x | x') e_{\alpha}(x') d\alpha dx' \quad (3)$$

with

$$G(\alpha; x | x') = -j \frac{\alpha}{2} F(\alpha) e^{j\alpha(x-x')} \quad (4)$$

$$F(\alpha) = \frac{\epsilon_0}{\pi |\alpha|} (Y_U(\alpha) + Y_L(\alpha)) \quad (5)$$

where Y_U and Y_L can be obtained by utilizing the simple recurrent relation (Appendix). The total charge located between x_1 and x_2 is given by

$$Q(x_1, x_2) = \int_{x_2}^{x_1} \sigma(x) dx \quad (6)$$

When x_1 and x_2 lie in slots, $Q(x_1, x_2)$ should be constant, that is,

$$\begin{aligned} Q(x_1, x_2) &= Q_1(|x_2| < a \text{ and } b_1 < x_1 < c_1) \\ &= Q_2(-c_2 < x_2 < -b_2 \text{ and } |x_1| < a) \end{aligned} \quad (7)$$

We consider the following sets of excitations to determine the capacitances:

$$\text{i) } V_1 \neq 0, \quad V_2 = 0 \quad (8a)$$

$$\text{ii) } V_1 = 0, \quad V_2 \neq 0 \quad (8b)$$

$$\text{iii) } V_1 = -V_2 \quad (8c)$$

Multiplying (6) by $e_x(x_1)$ and integrating over the right slot
 $(b_1 < x_1 < c_1)$, we obtain

$$\begin{aligned}
 Q_1 V_1 &= \int_{b_1}^{c_1} e_x(x_1) Q(x_1, x_2) dx_1 \\
 &= \frac{1}{2} \iint_{-\infty}^{\infty} F(\alpha) e_x(x') e^{j\alpha x'} \left\{ \int_{b_1}^{c_1} e_x(x_1) e^{-j\alpha x_1} dx_1 - V_1 e^{-j\alpha x_2} \right\} d\alpha dx' \\
 &\quad (|x_2| < a)
 \end{aligned} \tag{9}$$

by utilizing

$$V_1 = \int_{b_1}^{c_1} e_x(x) dx = - \int_{-a}^a e_x(x) dx \tag{10}$$

Then, multiplying Eq. (9) by $e_x(x_2)$ and integrating over the left slot, we obtain

$$\begin{aligned}
 -Q_1 V_1^2 &= \iint e_x(x_1) Q(x_1, x_2) e_x(x_2) dx_1 dx_2 \\
 &= \frac{1}{2} \iint_{-\infty}^{\infty} F(\alpha) e_x(x') e^{j\alpha x'} \left\{ -V_1 \int_{b_1}^{c_1} e_x(x_1) e^{-j\alpha x_1} dx_1 \right. \\
 &\quad \left. - V_1 \int_{-c_2}^{-b_2} e_x(x_2) e^{-j\alpha x_2} dx_2 \right\} d\alpha dx'
 \end{aligned} \tag{11}$$

That is,

$$Q_1 V_1 = \int_0^{\infty} \iint_{-\infty}^{\infty} F(\alpha) e_x(x') \cos \alpha(x - x') e_x(x) dx' dx d\alpha \tag{12}$$

Therefore, we obtain the stationary expression of C_1 as follows:

$$C_1 = \frac{Q_1}{V_1} \bigg|_{V_2 = 0}$$

$$= \frac{\int_{-\infty}^{\infty} \int_0^{\infty} e_x(x) F(\alpha) \cos \alpha(x - x') e_x(x') d\alpha dx' dx}{\left\{ \int e_x(x) dx \right\}^2} \quad (13)$$

Equation (13) gives an upper bound to the exact value. Similar expressions for C_2 and $C_1 + 2C_m + C_2$ can be obtained by using (8b) and (8c), respectively. The Ritz procedure will be applied to the variational expressions (13) for the numerical computation.

There are two fundamental modes of propagation in asymmetrical coupled coplanar-type transmission lines (C-CTL), that is, c- and π -modes, which become even and odd modes in the symmetrical case, respectively. The propagation characteristics of an asymmetrical C-CTL can be expressed in terms of two propagation constants, β_c , β_π , and four characteristic impedances, $Z_{i,c}$, $Z_{i,\pi}$ ($i = 1, 2$), where $i = 1$ and 2 stand for the right and left strips, respectively. The quasistatic values of the propagation constants and the characteristic impedances for two fundamental modes can be calculated by [6], [18]

$$\beta_{c,\pi} = \frac{\omega}{\sqrt{2}} \{L_1 C_1 + L_2 C_2 - 2L_m C_m \pm U\}^2$$

$$Z_{1,c} = \frac{\omega}{\beta_c} (L_1 - L_m/R_\pi)$$

$$Z_{1,\pi} = \frac{\omega}{\beta_{\pi}} (L_1 - L_m/R_c)$$

$$Z_{2,c} = -R_c R_{\pi} Z_{1,c}$$

$$Z_{2,\pi} = -R_c R_{\pi} Z_{1,\pi}$$

$$R_{c,\pi} = \frac{L_2 C_2 - L_1 C_1 \pm U}{2(L_m C_2 - L_1 C_m)}$$

$$U = \{(L_2 C_2 - L_1 C_1)^2 + 4(L_m C_1 - L_2 C_m)(L_m C_2 - L_1 C_m)\}^{1/2} \quad (14)$$

where L_1 , L_2 , and L_m are the self and mutual inductances, which can be obtained from C_1 , C_2 , and C_m for the case without a substrate.

B. Hybrid-mode Analysis

The network analytical method of electromagnetic fields has been successfully applied to analyze the propagation characteristics of various types of planar transmission lines with isotropic and/or uniaxially anisotropic substrates whose optical axis is coincident with one of the coordinate axes [5], [9], [10]. This method is based on the hybrid-mode formulation, and no approximations for simplification are used in the formulation procedure. The propagation constants of an asymmetrical C-CTL can be obtained easily by using the extended version of this method and applying the Galerkin's procedure. The characteristic impedance is not uniquely specified because of the hybrid mode of propagation. The definition chosen here is

$$Z_{i,j} = \frac{V_{i,j}}{I_{i,j}} \quad (i = 1, 2; \quad j = c, \pi) \quad (15)$$

where $I_{1,j}$ and $V_{1,j}$ are the total current on the right strip and the voltage difference between the right strip and the ground conductor, respectively, and $I_{2,j}$ and $V_{2,j}$ are those for the left strip. The frequency-dependent hybrid-mode solutions for propagation constants and characteristic impedances are presented in Section III.

C. Coplanar-type Transmission Line

The quasistatic and hybrid-mode formulations described above are quite general and applicable to various configurations, e.g., coupled coplanar waveguide (C-CPW; Fig. 2(a)), coupled CPW with double-layered substrate (Fig. 2(b)), coupled sandwich CPW (Fig. 2(c)) and coupled coplanar three strips (Fig. 2(d)). In the coplanar-strip case of Fig. 2(d), the charge and current distribution on the strips are the basic quantities as opposed to the aperture fields in the CPW cases of Figs. 2(a) - (c). Numerical results for these coplanar-type transmission lines are included in the next section.

III. NUMERICAL EXAMPLES

Figure 3 shows the quasistatic characteristics of an asymmetrical coupled coplanar waveguide with an isotropic substrate. Figures 3(a) and (b) depict the effective dielectric constants $\epsilon_{\text{eff},j}$ and the characteristic impedances $Z_{i,j}$ ($j = c, \pi$) as a function of the strip width ratio S_2/S_1 . $\epsilon_{\text{eff},j}$ is obtained by

$$\epsilon_{\text{eff},j} = (\beta_j / \omega \sqrt{\epsilon_0 \mu_0})^2 \quad (16)$$

The values for the symmetrical case ($S_2/S_1 = 1$) are in good agreement with those of [15]. Another check on the results can be made by investigating the limiting case as S_2/S_1 becomes very large, where the left slot is decoupled and $\epsilon_{\text{eff},\pi}$ converges to that of the asymmetrical coplanar waveguide (ACPW) [15] shown in Fig. 4(a). As S_2/S_1 becomes very small, $\epsilon_{\text{eff},c}$ converges to that of ACPW shown in Fig. 4(b), which can be considered as the limiting case of $S_2/S_1 = 0$. Figures 5 and 6 show the quasistatic characteristics of asymmetrical coupled double-layered (Fig. 2(b)) and sandwich (Fig. 2(c)) coplanar waveguides, respectively. They depict $\epsilon_{\text{eff},j}$ and $Z_{i,j}$ ($j = c, \pi$) as functions of the ratio of the thickness of the upper to the lower layer d/h . Figure 7 shows the frequency dependence of the effective dielectric constants for various types of a coupled coplanar waveguide with uniaxially anisotropic substrates cut with their planar surface perpendicular to the optical axis. The frequency-dependent hybrid-mode values of each mode converge precisely to the corresponding quasistatic values in lower frequency ranges for all cases. The phase velocities of two fundamental modes of the case with double-layered substrates have close values in the higher-frequency range, but they never coincide because of the mode coupling.

The mode of propagation can not be identified as the c - or π -mode by investigating the voltage and current. Figure 8 shows the frequency dependence of the characteristic impedances of a coupled coplanar waveguide. Figure 9 shows the effective dielectric constants and the characteristic impedances of coupled coplanar three strips (Fig. 2(d)) with a uniaxially anisotropic substrate. The definition for the characteristic impedance of coupled coplanar strips is chosen as

$$Z_{i,j} = \frac{V_{i,j}}{I_{i,j}} \quad (17)$$

where $I_{1,j}$ and $V_{1,j}$ are the total current on the right strip and the voltage between the right and the center strips, and $I_{2,j}$ and $V_{2,j}$ are those for the left strip. Again, the frequency-dependent values converge to the quasistatic values in the lower-frequency ranges.

Figure 10 shows $\epsilon_{\text{eff},i}$ and $Z_{i,j}$ of an asymmetrical coupled coplanar waveguide on a uniaxially anisotropic substrate cut with its surface at γ to the optical axis.

V. CONCLUSIONS

This paper describes the analytical method for the general structure of asymmetrical coupled coplanar-type transmission lines (C-CTLs) with anisotropic media. It consists of the quasistatic and the hybrid-mode formulations. The former gives variational expressions for the line parameters of the cases with the uniaxially anisotropic substrate cut with its planar surface at an arbitrary angle to the optical axis; the latter gives the rigorous frequency-dependent characteristics for the cases with the anisotropic substrate cut with its surface perpendicular to the optical axis. Some numerical examples showed the accuracy of the method and presented the propagation characteristics, the propagation constants as well as the characteristic impedances of the various types of C-CTL with anisotropic media, for the first time.

APPENDIX: RECURRENT RELATIONS

The Fourier transform of the electric field E_x and the electric flux density D_y in the layer $i(y_{i+1} > y > y_i)$ can be expressed as:

$$\begin{aligned}\hat{E}_x(\alpha; x) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E_x(x, y) e^{-j\alpha x} dx \\ &= \exp(-b_i y) [A_i \cosh(p_i y) + B_i \sinh(p_i y)]\end{aligned}\quad (A1)$$

$$\begin{aligned}\hat{D}_y(\alpha; x) &= \epsilon_{i,xy} \epsilon_0 \hat{E}_x + \epsilon_{i,yy} \epsilon_0 \hat{E}_y \\ &= -\epsilon_{i,yy} \epsilon_0 p_i \exp(-b_i y) [A_i \sinh(p_i y) + B_i \cosh(p_i y)]\end{aligned}\quad (A2)$$

where A_i , B_i are unknown constants and

$$b_i = j \frac{\epsilon_{i,xy}}{\epsilon_{i,yy}} \alpha \quad (A3)$$

$$p_i = \frac{\epsilon_{i,e}}{\epsilon_{i,yy}} |\alpha| \quad (A4)$$

$$\epsilon_{i,e} = \sqrt{\epsilon_{i,xx} \epsilon_{i,yy} - \epsilon_{i,xy}^2} \quad (A5)$$

We will derive the recurrent relation in the upper region $y > 0$. Define the following quantity at the lower surface of the layer i (Fig. 11):

$$Y_i = \frac{j\alpha}{\epsilon_{i,e}\epsilon_0|\alpha|} \cdot \frac{\tilde{D}_y}{\tilde{E}_x} \Big|_{y=y_i+0} \quad (A6)$$

Considering the continuity conditions at the $y = y_{i+1}$ plane, we obtain the following recurrent relation with respect to Y_i

$$Y_i = \frac{\frac{\epsilon_{i+1,e}}{\epsilon_{i,e}} Y_{i+1} - \tanh(p_i d_i)}{1 - \frac{\epsilon_{i+1,e}}{\epsilon_{i,e}} Y_{i+1} \tanh(p_i d_i)} \quad (A7)$$

The electric flux density at the $y = +0$ plane (the slot plane) can be obtained as

$$\tilde{D}_y(\alpha; y = +0) = \frac{\epsilon_{N,e}\epsilon_0|\alpha|}{j\alpha} Y_N \tilde{e}_x \quad (A8)$$

where \tilde{e}_x is the Fourier transform of the aperture field $e_x(x)$. Then, Y_U in Eq. (5) can be obtained as

$$Y_u = \epsilon_{N,e} Y_N \quad (A9)$$

A similar recurrent relation holds in the lower region $y < 0$, and Y_L can be determined.

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LIST OF ILLUSTRATIONS

Fig. 1. General structure of asymmetrical coupled coplanar-type transmission lines with anisotropic substrates.

Fig. 2. (a) Asymmetrical coupled coplanar waveguide (C-CPW).

Fig. 2. (b) Asymmetrical coupled coplanar waveguide with double-layered substrate.

Fig. 2. (c) Asymmetrical coupled sandwich coplanar waveguide.

Fig. 2. (d) Asymmetrical coupled coplanar three strips.

Fig. 3. Quasistatic characteristics of asymmetrical coupled coplanar waveguide versus strip-width ratio S_2/S_1 .

(a) Effective dielectric constants

(b) Characteristic impedances

$$\epsilon_{1xx} = \epsilon_{1yy} = 9.6, \epsilon_{1xy} = 0$$

$$2a/h = 1, S_1/h = 2, W_1/h = 2, W_2/h = 2.$$

Fig. 4. Asymmetrical coplanar waveguide (ACPW).

Fig. 5. Quasistatic characteristics of asymmetrical coupled coplanar waveguide with double-layered substrate.

$$\epsilon_{1xx} = 9.4, \epsilon_{1yy} = 11.6, \epsilon_{2xx} = \epsilon_{2yy} = 2.6, \epsilon_{ixy} = 0 \quad (i = 1, 2)$$

$$S_1/h = 1.0, S_2/h = 0.5, W_1/h = 1.5, W_2/h = 2.0.$$

Fig. 6. Quasistatic characteristics of asymmetrical coupled sandwich coplanar waveguide.

$$\epsilon_{1xx} = \epsilon_{2xx} = 9.4, \epsilon_{1yy} = \epsilon_{2yy} = 11.6, \epsilon_{ixy} = 0 \quad (i = 1, 2)$$

$$S_1/h = 1.0, S_2/h = 0.5, W_1/h = 1.5, W_2/h = 2.0.$$

Fig. 7. Dispersion characteristics of various types of coupled coplanar waveguides.

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

(a) Asymmetrical coupled coplanar waveguide (C-CPW).

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{1xy} = 0.$$

(b) Asymmetrical coupled coplanar waveguide with double-layered substrate.

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{2xx} = \epsilon_{2yy} = 2.6,$$

$$\epsilon_{ixy} = 0 \quad (i = 1, 2), \quad d/h = 0.1.$$

(c) Asymmetrical coupled sandwich coplanar waveguide.

$$\epsilon_{1xx} = \epsilon_{2xx} = 9.4, \quad \epsilon_{1yy} = \epsilon_{2yy} = 11.6,$$

$$\epsilon_{ixy} = 0 \quad (i = 1, 2), \quad d/h = 1.0.$$

————— : Hybrid-mode, ——— - ——— : Quasistatic

Fig. 8. Frequency dependence of the characteristic impedances of coupled coplanar waveguides.

Dimensions are the same as in Fig. 7(a).

Fig. 9. Frequency dependence of the effective dielectric constants and the characteristic impedances of coupled coplanar three strips

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{1xy} = 0$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0.$$

————— : Hybrid-mode, ——— - ——— : Quasistatic

Fig. 10. Effective dielectric constants of coupled coplanar waveguide versus γ .

$$\epsilon_{1xx} = 3.40, \quad \epsilon_{1yy} = 5.12, \quad \epsilon_{1xy} = 0 \quad \text{when} \quad \gamma = 0$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0.$$

Fig. 11. The i -th layer of stratified anisotropic substrates.

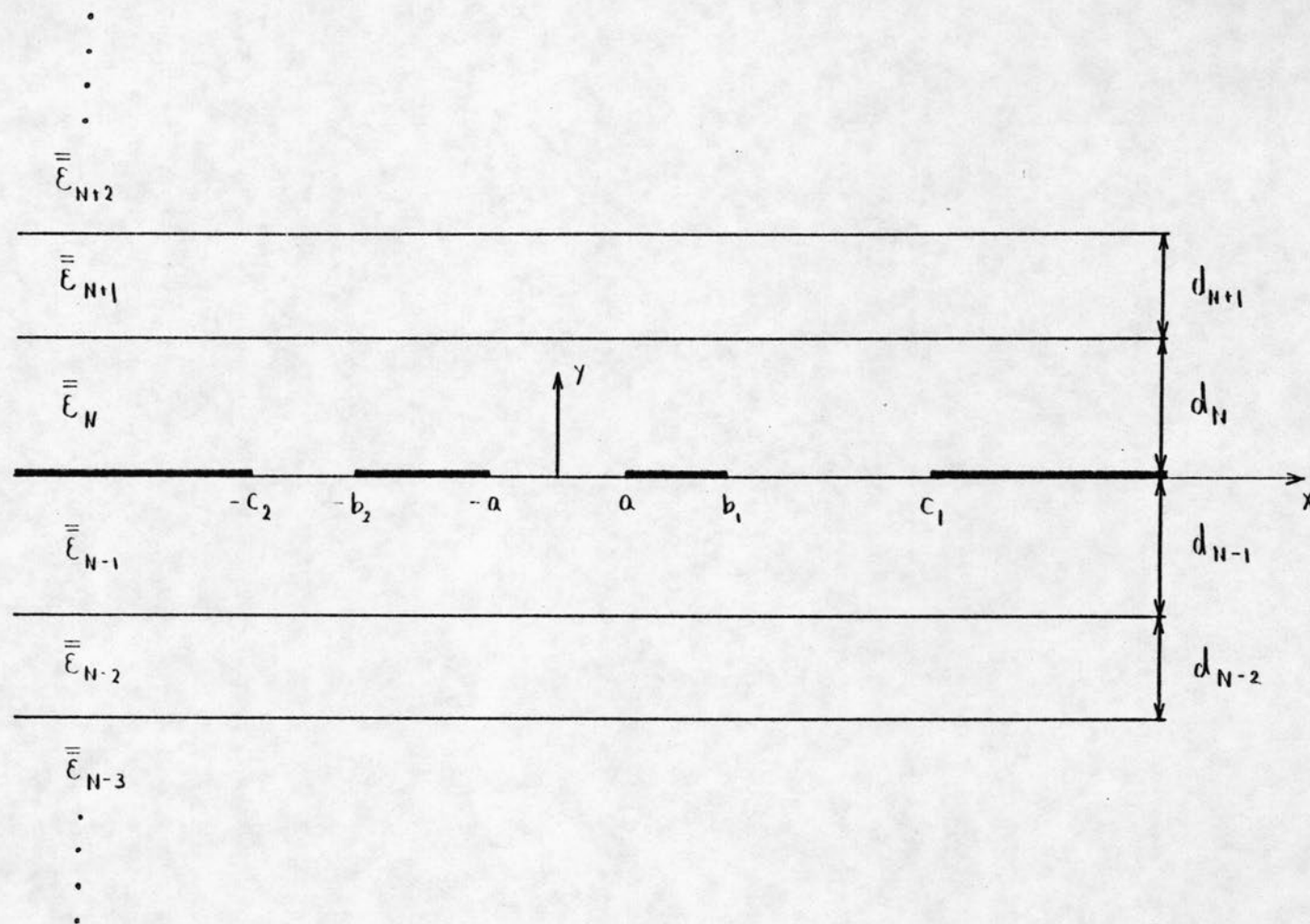


Fig.1 General structure of asymmetrical coupled coplanar-type transmission lines with anisotropic substrates.

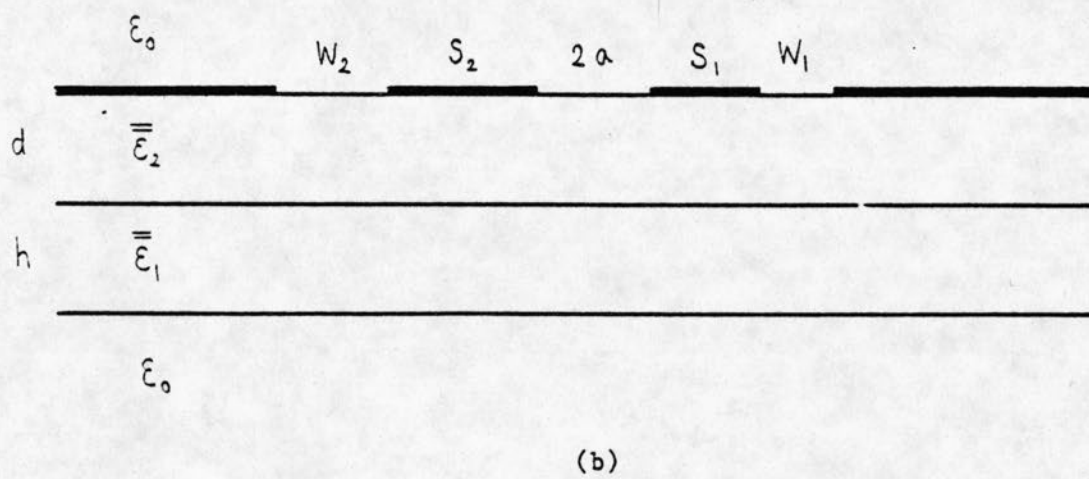
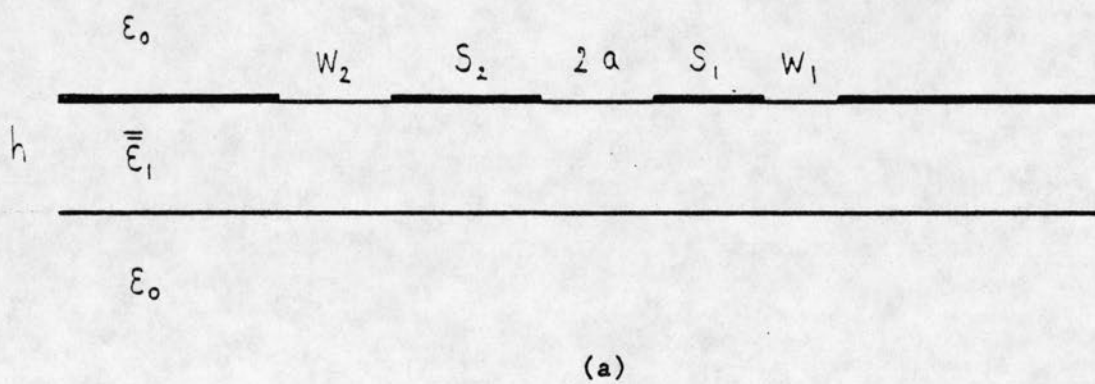


Fig.2

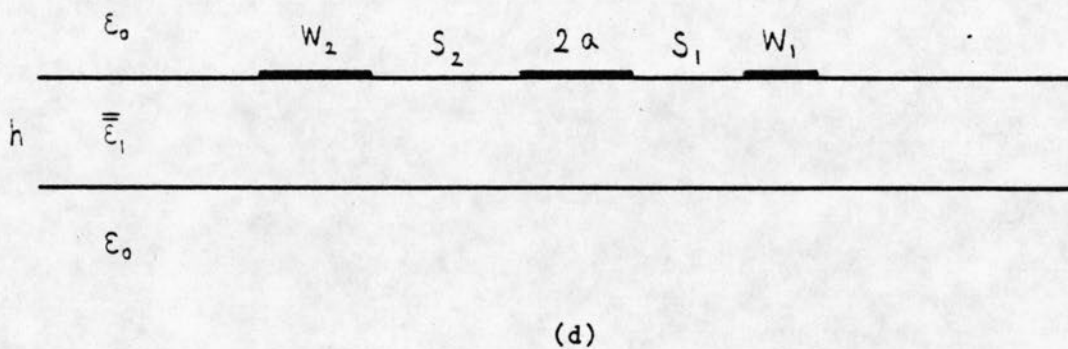
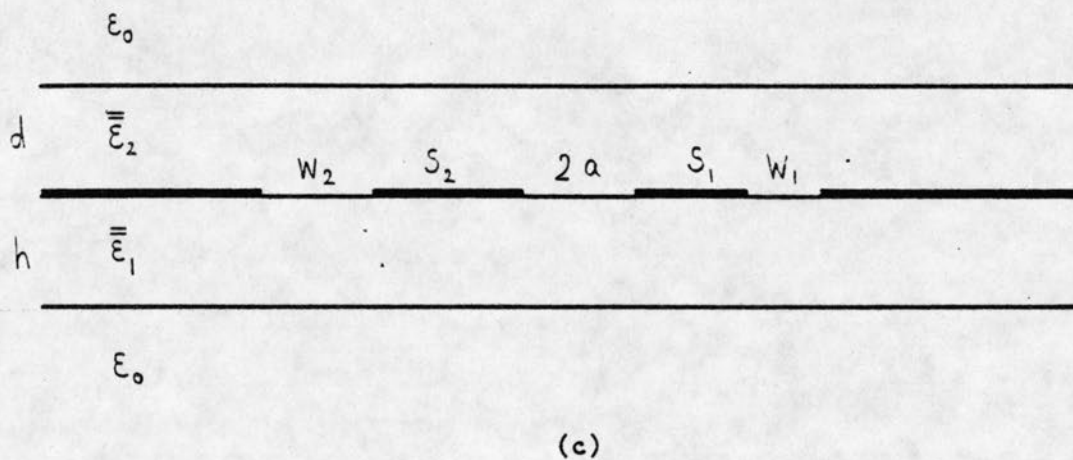


Fig.2 (a) Asymmetrical coupled coplanar waveguide (C-CPW).

Fig.2 (b) Asymmetrical coupled coplanar waveguide with double-layer substrate .

Fig.2 (c) Asymmetrical coupled sandwich coplanar waveguide.

Fig.2 (d) Asymmetrical coupled coplanar three-strips.

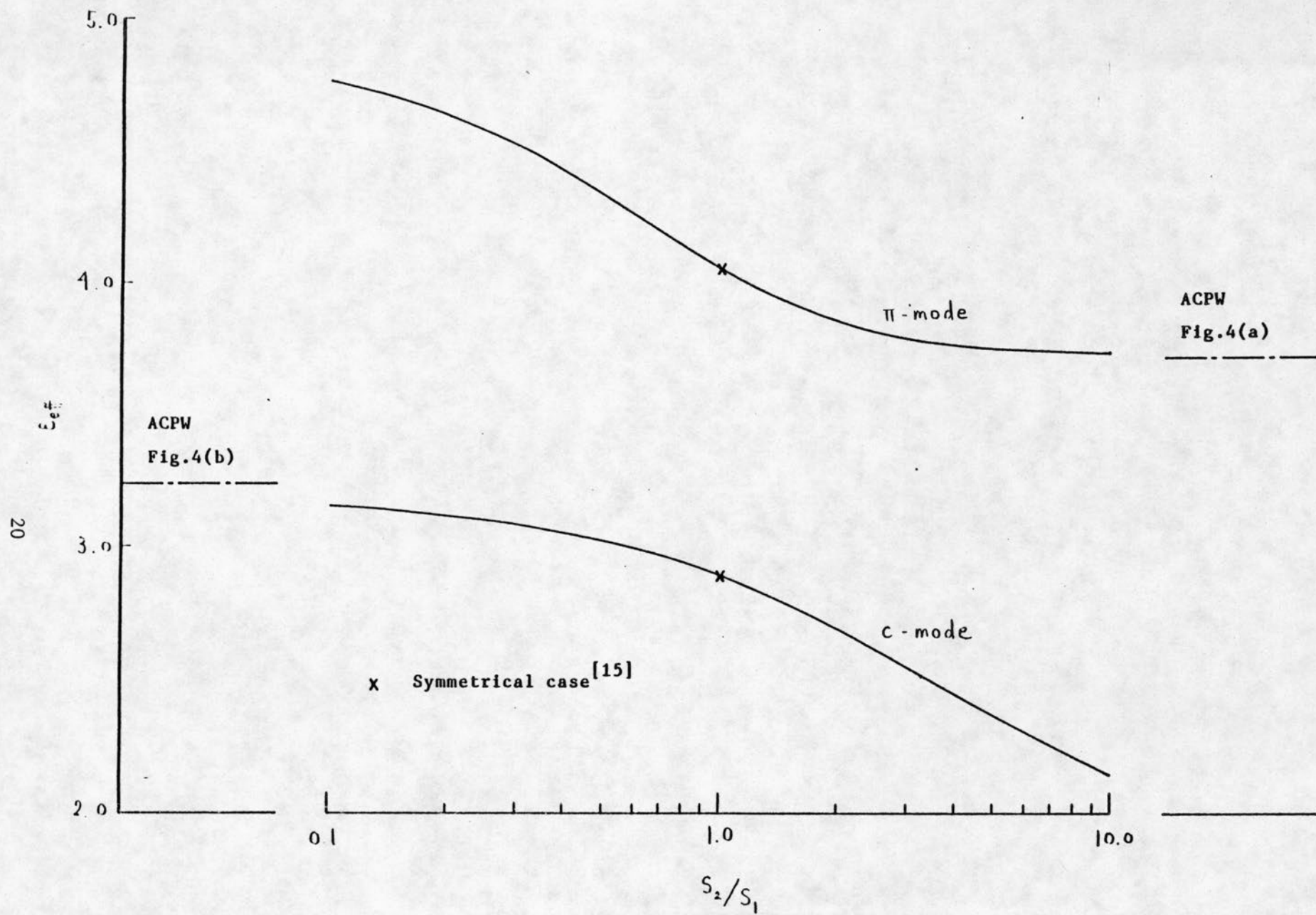


Fig.3 (a)

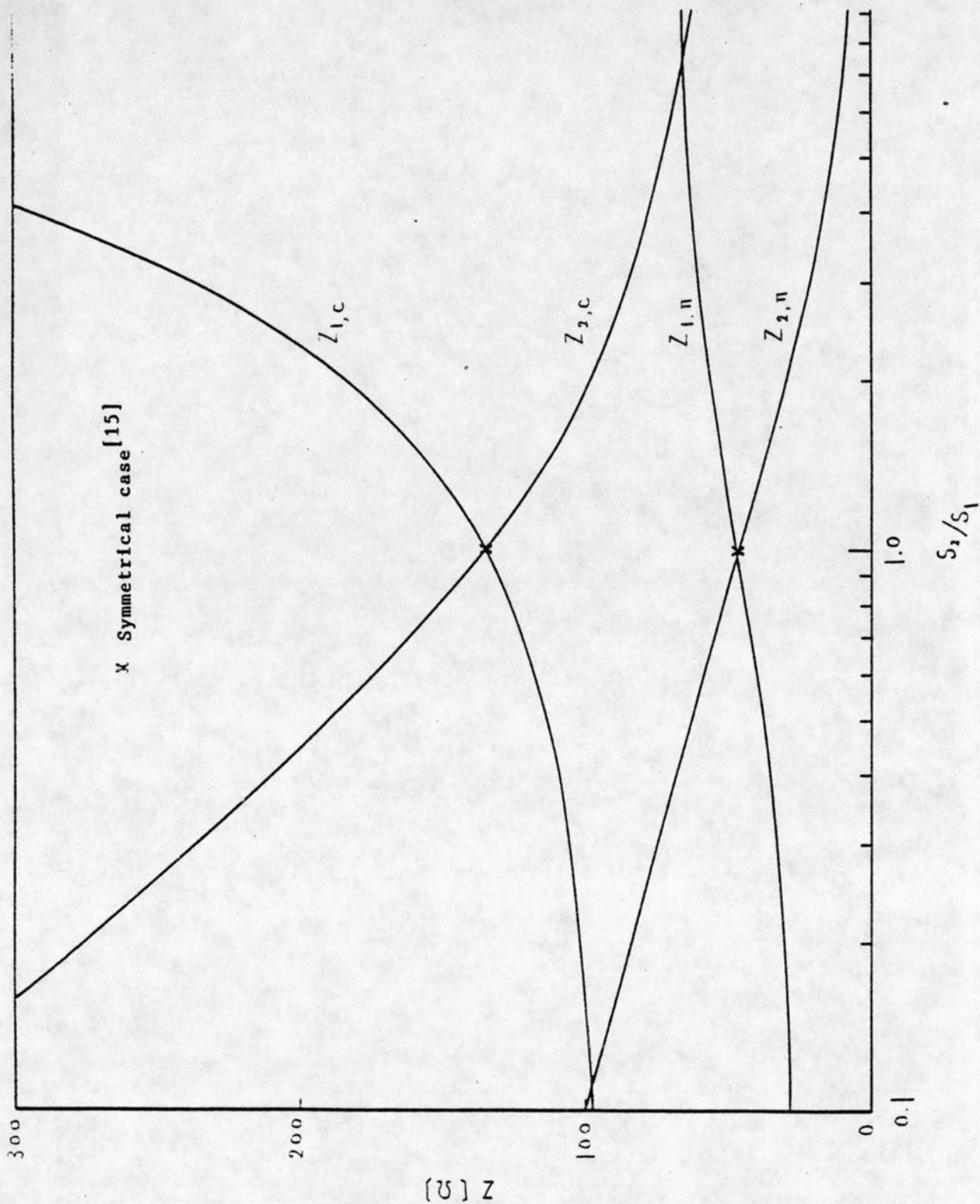


Fig.3 (b)

Fig.3 Quasistatic characteristics of asymmetrical coupled coplanar waveguide versus strip-width ratio S_2/S_1 .

(a) Effective dielectric constants

(b) Characteristic impedances

$$\epsilon_{1xx} = \epsilon_{1yy} = 9.6, \quad \epsilon_{1xy} = 0$$

$$2a/h = 1, \quad S_1/h = 2, \quad W_1/h = 2, \quad W_2/h = 2$$

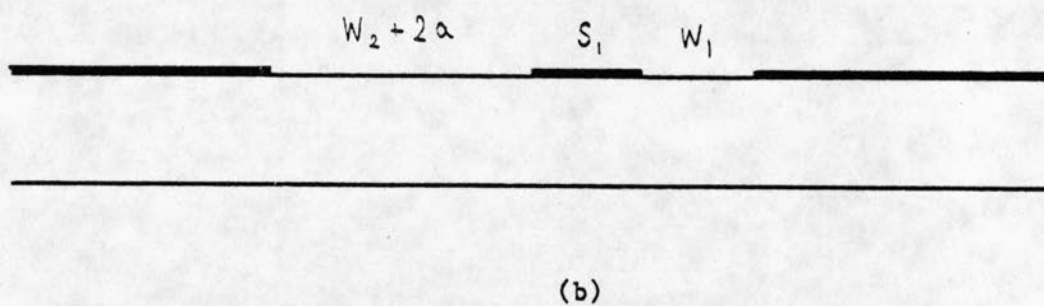
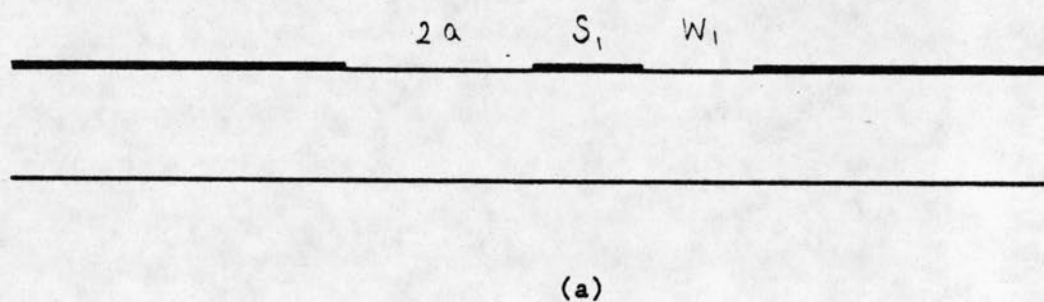


Fig.4 Asymmetrical coplanar waveguide (ACPW).

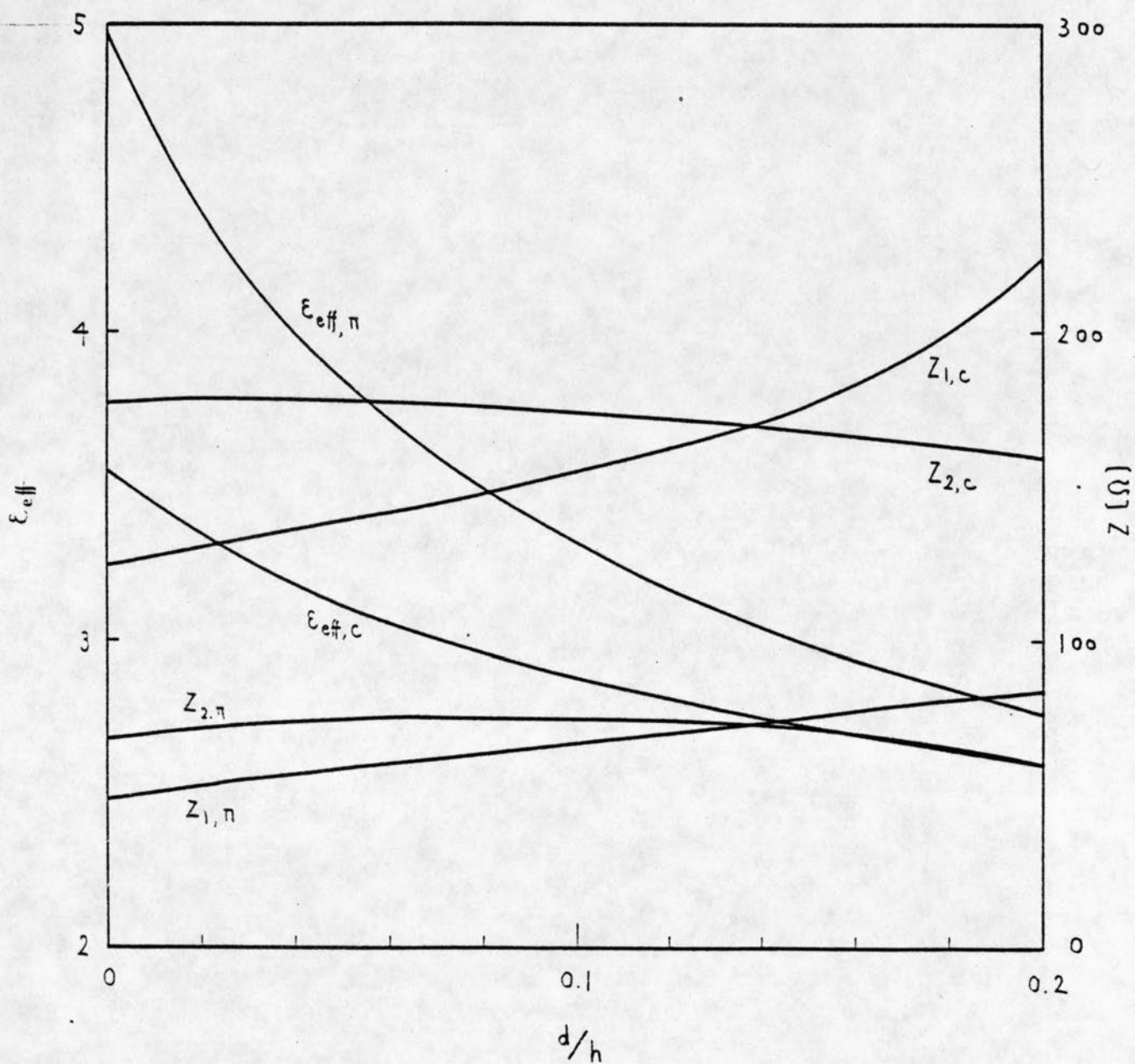


Fig.5 Quasistatic characteristics of asymmetrical coupled coplanar waveguide with double-layer substrate.

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{2xx} = \epsilon_{2yy} = 2.6, \\ \epsilon_{ixy} = 0 \quad (i = 1, 2)$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

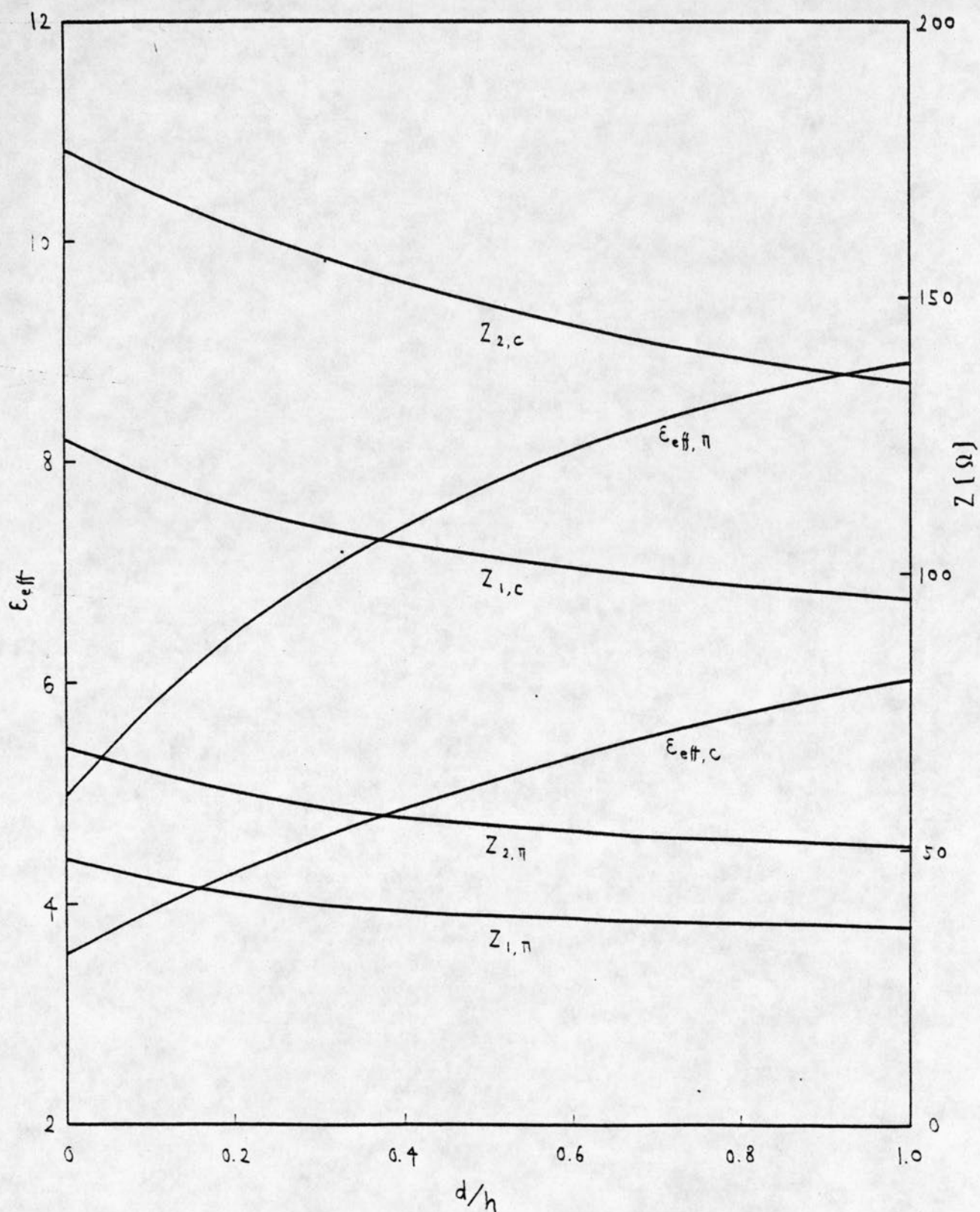


Fig.6 Quasistatic characteristics of asymmetrical coupled sandwich coplanar waveguide.

$$\epsilon_{1xx} = \epsilon_{2xx} = 9.4, \quad \epsilon_{1yy} = \epsilon_{2yy} = 11.6, \quad \epsilon_{ixy} = 0 \quad (i = 1, 2)$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

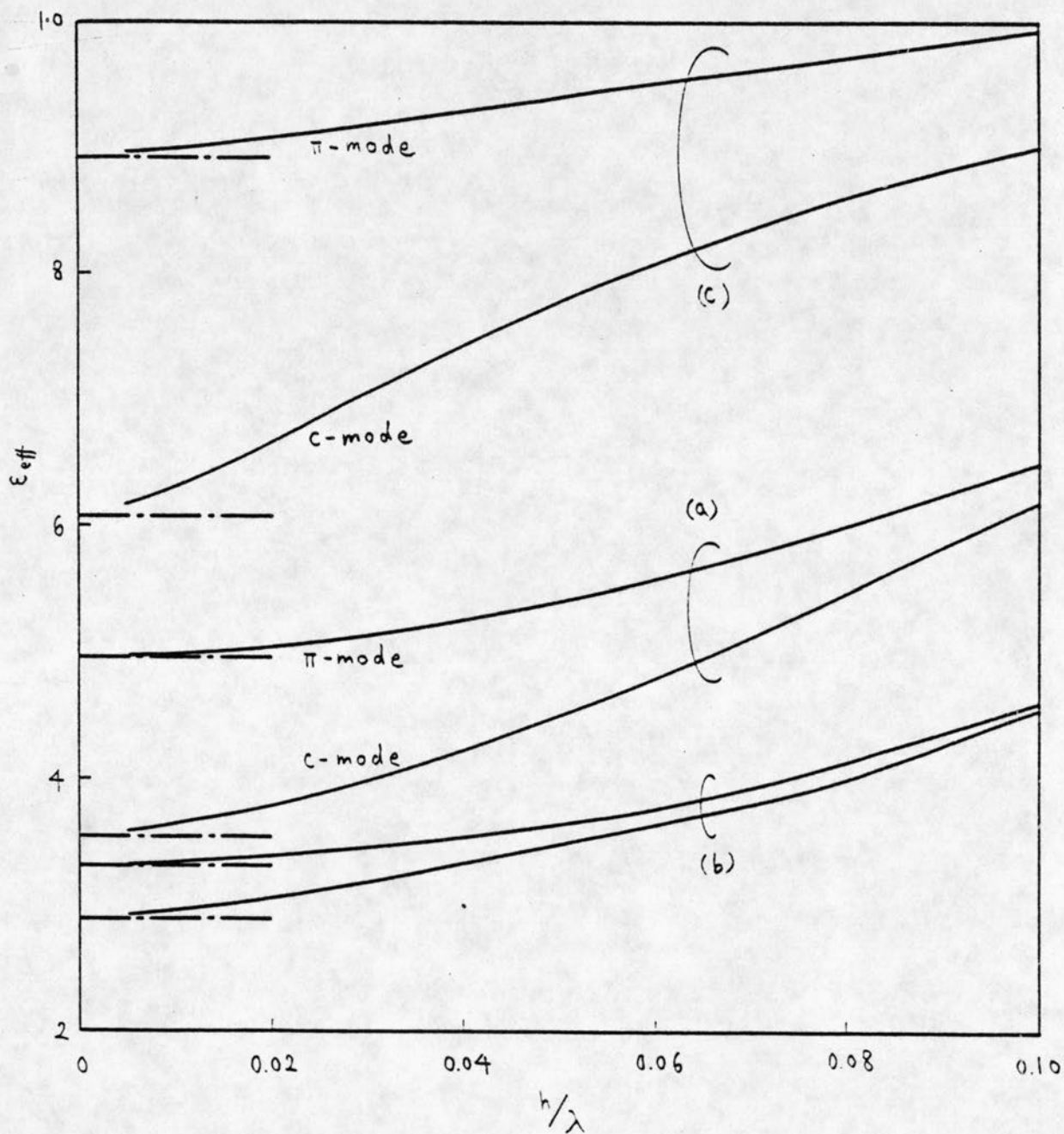


Fig.7

Fig.7 Dispersion characteristics of various types of coupled coplanar waveguide.

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

(a) Asymmetrical coupled coplanar waveguide (C-CPW).

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{1xy} = 0$$

(b) Asymmetrical coupled coplanar waveguide with double-layer substrate .

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{2xx} = \epsilon_{2yy} = 2.6,$$

$$\epsilon_{ixy} = 0 \quad (i = 1, 2), \quad d/h = 0.1$$

(c) Asymmetrical coupled sandwich coplanar waveguide.

$$\epsilon_{1xx} = \epsilon_{2xx} = 9.4, \quad \epsilon_{1yy} = \epsilon_{2yy} = 11.6,$$

$$\epsilon_{ixy} = 0 \quad (i = 1, 2), \quad d/h = 1.0$$

————— : Hybrid-mode, - - - - - : Quasistatic

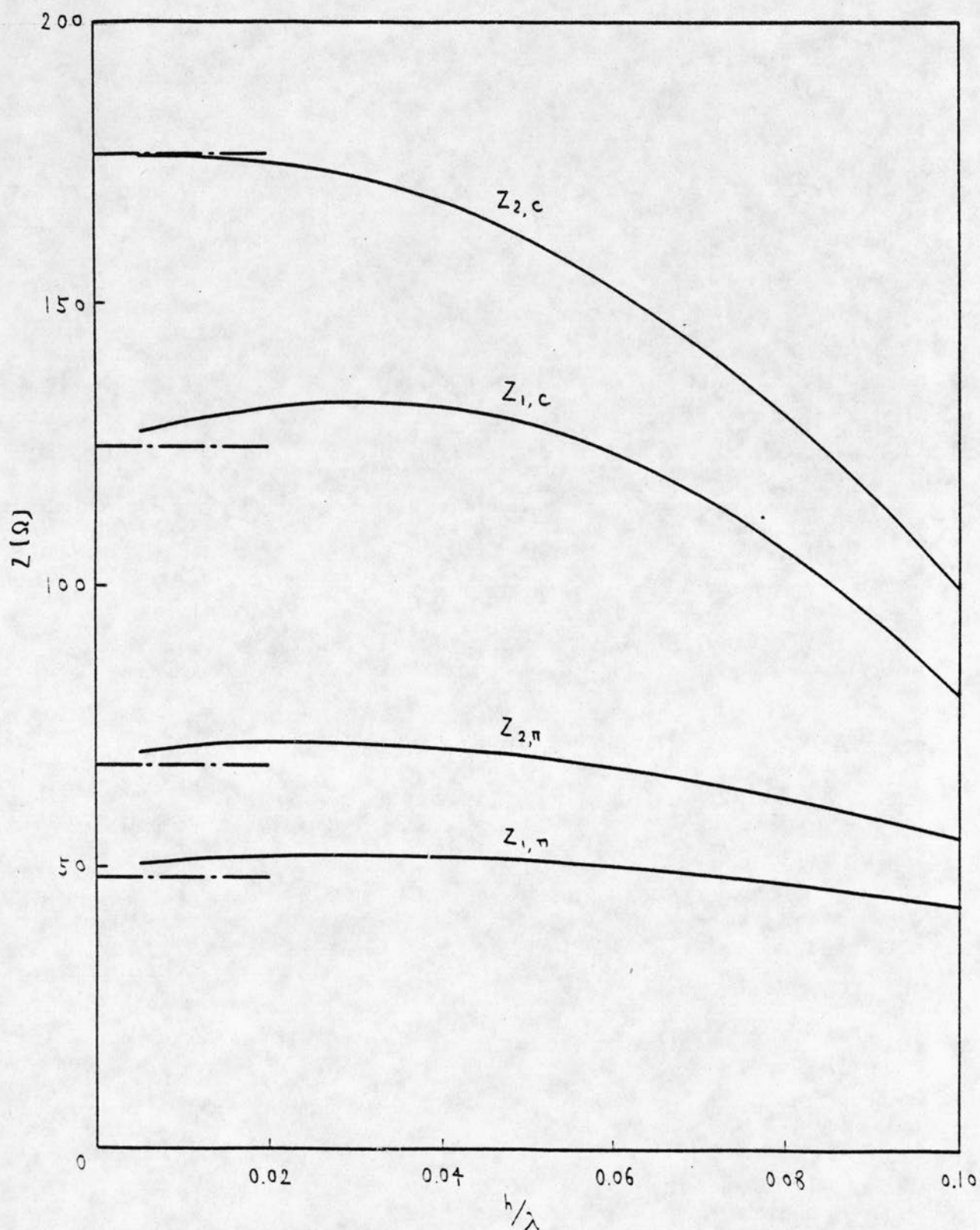


Fig.8 Frequency dependence of the characteristic impedances of coupled coplanar waveguide

Dimensions are same as in Fig.7(a).

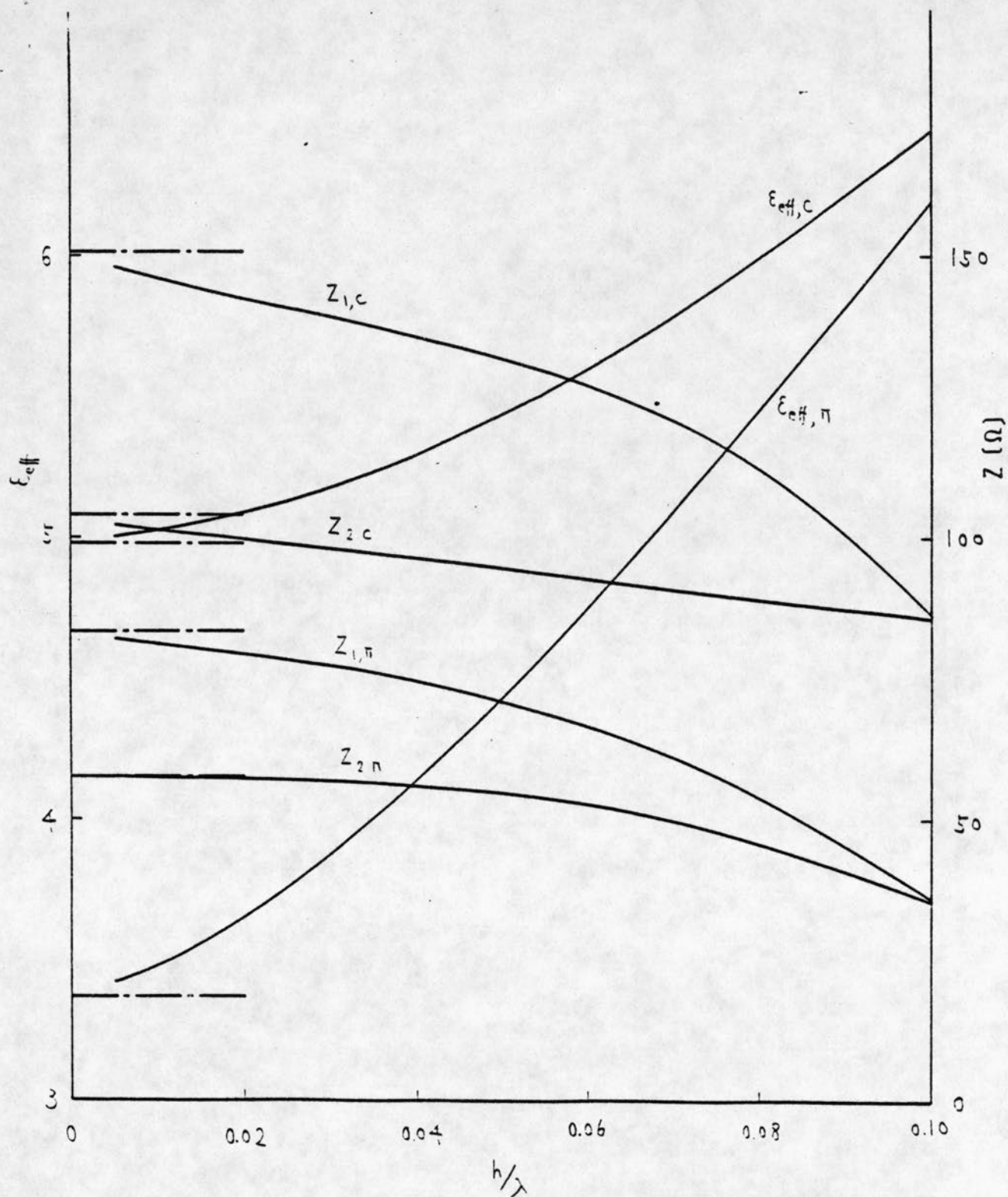


Fig.9 Frequency dependence of the effective dielectric constants and the characteristic impedances of coupled coplanar three-strips

$$\epsilon_{1xx} = 9.4, \quad \epsilon_{1yy} = 11.6, \quad \epsilon_{1xy} = 0$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

————— : Hybrid-mode, - - - - - : Quasistatic

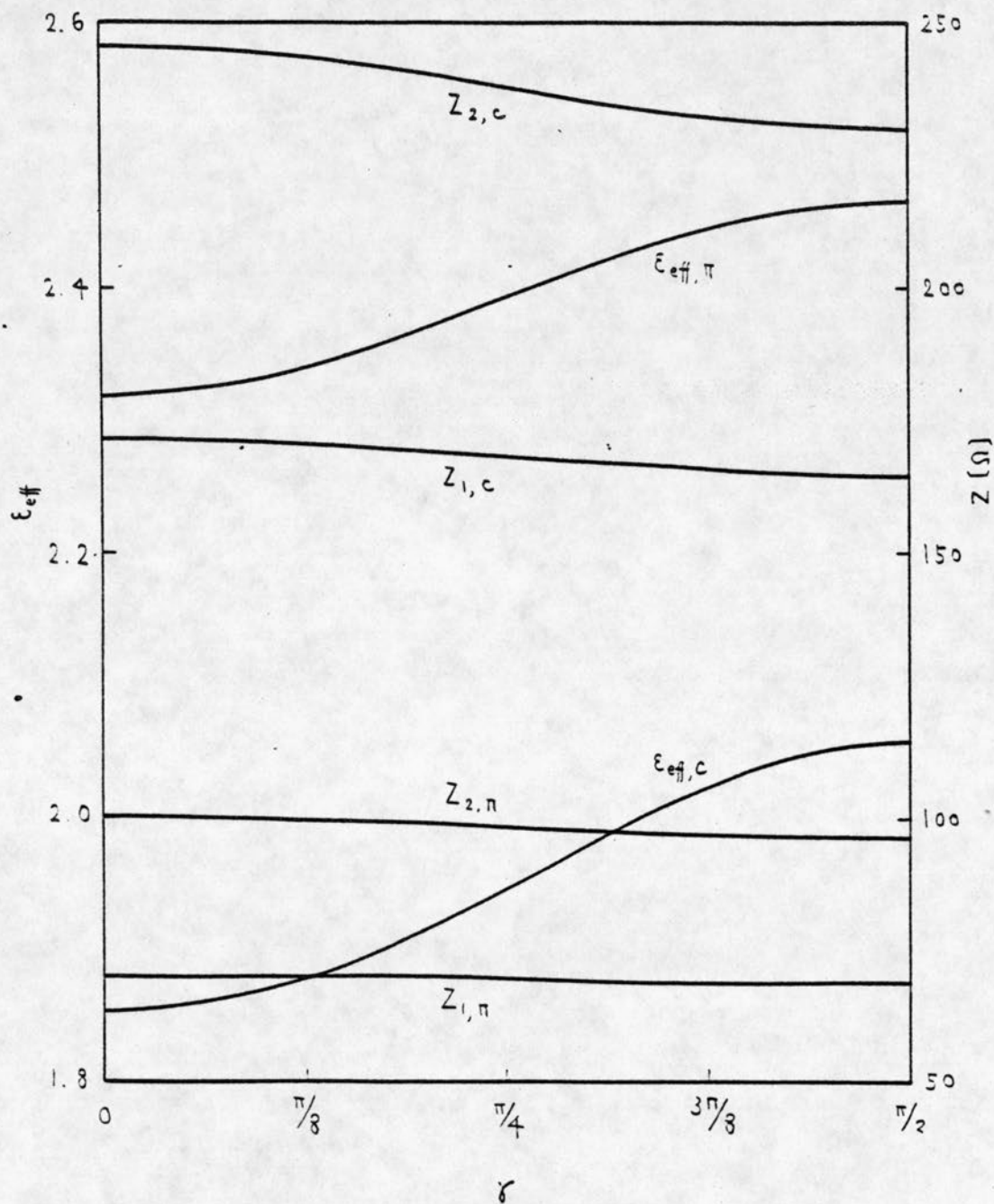


Fig.10 Effective dielectric constants of coupled coplanar waveguide versus γ ,

$$\epsilon_{1xx} = 3.40, \quad \epsilon_{1yy} = 5.12, \quad \epsilon_{1xy} = 0 \quad \text{when } \gamma = 0$$

$$S_{1/h} = 1.0, \quad S_{2/h} = 0.5, \quad W_{1/h} = 1.5, \quad W_{2/h} = 2.0$$

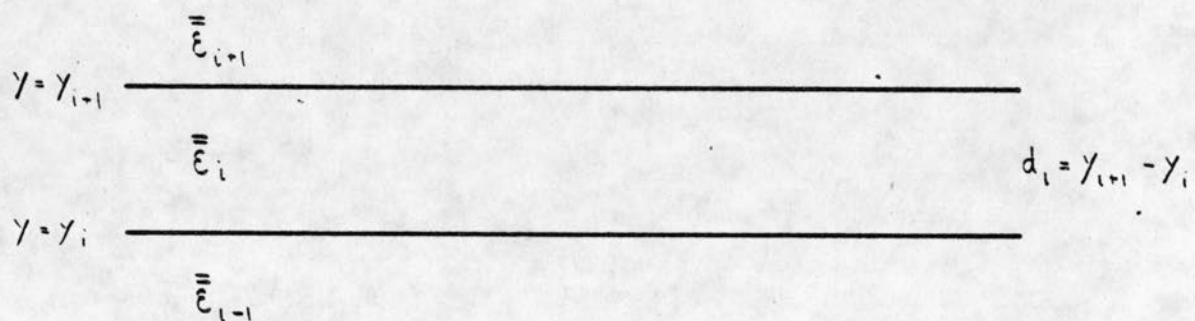


Fig.11 The i -th layer of stratified anisotropic substrates