Dynamic Analysis of Microstrip Lines and Finlines on Uniaxial Anisotropic Substrates

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Abstract —Dyadic Green's functions in the Fourier transform spectral domain are obtained for open microstrip lines and bilateral finlines on uniaxial anisotropic substrates. These functions are written in an impedance matrix form by expressing the electric and magnetic fields in terms of Hertz vector potentials oriented along the optical axis. In combination with Galerkin's method, they are used to obtain the propagation characteristics of single and parallel coupled microstrip lines on uniaxial anisotropic substrates having the optical axis in an arbitrary direction in a transverse plane and of bilateral finlines with the three optical axis orientations of the uniaxial anisotropic substrate that result in the diagonal permittivity tensor.

I. Introduction

MICROSTRIP LINES have been of fundamental importance for the development of microwave integrated circuits. However, the analysis of these structures presents difficulties due to their nonhomogeneity, which does not allow the propagation of a purely TEM mode. At low microwave frequencies, only small deviations from the TEM waves are observed, so that a quasi-static analysis is possible. At higher frequencies, of the order of 10 GHz and above, when the line dimensions are not negligible in comparison with the guided wavelength, the dispersion effects can no longer be neglected and the hybrid nature of the propagating modes has to be taken into account through a dynamic analysis.

The use of anisotropic substrates has become very attractive in the last few years [1]–[7] due to their advantages over other substrates in the development of a variety of devices, particularly directional couplers.

Proposed by Meier [8] in 1973, finlines are a very attractive alternative for use in microwave integrated circuits due to their wide operating band in the main waveguide mode. In addition, in some applications at frequencies from 15 GHz to 50 GHz, they display a better behavior than the conventional microstrip lines.

A variety of finline structures have been used, such as unilateral, bilateral, antipodal, and trilateral. Various methods have been developed for the analysis of their characteristics, all of them for isotropic dielectric substrates [8]–[13]. However, to the authors' knowledge, there has been no analysis developed for these structures with anisotropic dielectric substrates.

The Hertz potential in the Fourier transform spectral domain, proposed by Lee and Tripathi [3] for the analysis of microstrip lines and generalized in [7], is used here for the calculation of the dyadic Green's function in a form of an impedance matrix. This function, in combination with Galerkin's method, is used for the evaluation of the main characteristics of the structure. However, a more general case is considered here, in which the optical axis has an arbitrary orientation in a transverse plane. As a result, the permittivity tensor is no longer diagonal, requiring a much more complicated mathematical manipulation for obtaining the spectral-dyadic Green's function of the structure.

The dyadic Green's functions obtained in impedance matrices form converge to those given by Lee and Tripathi [3] for particular optical axis orientations.

Curves of the frequency dependence of single (Fig. 1) and coupled (Fig. 2) microstrip lines on anisotropic substrates with the optical axis oriented perpendicular to the ground plane of these lines are presented. The results for coupled microstrip line structures (Fig. 2) include those for symmetric ($W_1 = W_2$) and asymmetric ($W_1 \neq W_2$) configurations.

For the case of finlines, while the method is general and may be used for a variety of structures, the analysis here will be restricted to bilateral finlines with uniaxial anisotropic dielectric substrate as shown in Fig. 3.

The analysis is developed for the three optical axis orientations that result in the diagonal permittivity tensor, i.e., with the optical axis along the x, y, and z directions shown in Fig. 3.

The dyadic Green's functions obtained for these three orientations converge to that of Schmidt and Itoh [9] obtained for the isotropic substrate. Curves of the effective permittivity of bilateral finlines with an anisotropic dielectric layer for the dominant mode were obtained. For the particular case of finlines with an isotropic layer, agreement was observed with results from other authors for the dominant and first higher order modes [9], [13].

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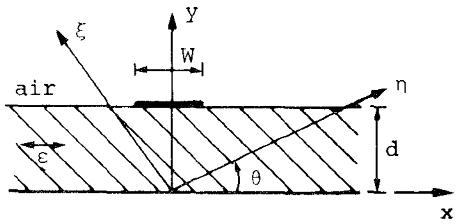

Fig. 1. Cross section of open microstrip line Also shown are the optical axis ξ, the material coordinates (η, ξ), and the geometry coordinates (x, y).

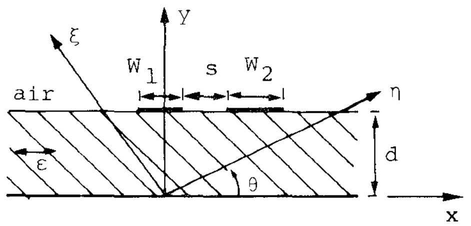

Fig. 2. Cross-sectional view of asymmetric parallel-coupled microstrip lines on arbitrary anisotropic substrates; (η, ξ) are the crystal axes and (x, y) are the microstrip axes.

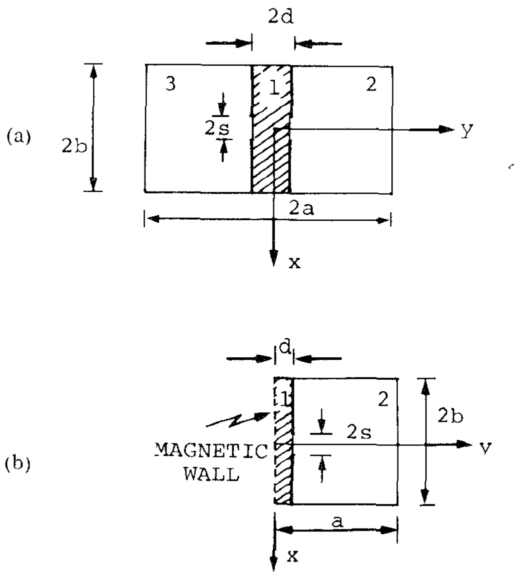

Fig. 3. Bilateral finline. (a) Transverse cross section. (b) Equivalent structure.

II. Theoretical Formulation

A. Open Microstrip Line

The dielectric substrate of Fig. 1 is assumed to be uniaxial, linear, and homogeneous. Losses in the dielectrics and in the conductors as well as the metal thickness are neglected.

The dielectric permittivity tensor is diagonal in the material coordinate system (η, ξ, ζ) and is given by

$$\bar{\bar{\epsilon}} = \begin{vmatrix} \epsilon_{\eta\eta} & 0 & 0 \\ 0 & \epsilon_{\xi\xi} & 0 \\ 0 & 0 & \epsilon_{\zeta\zeta} \end{vmatrix} = \begin{vmatrix} \epsilon_2 & 0 & 0 \\ 0 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_2 \end{vmatrix}. \tag{1}$$

In the microstrip line coordinate system (x, y, z), this tensor is given by

$$\bar{\bar{\epsilon}} = \begin{vmatrix} \epsilon_{xx} & \epsilon_{xy} & 0 \\ \epsilon_{yx} & \epsilon_{yy} & 0 \\ 0 & 0 & \epsilon_{zz} \end{vmatrix}. \tag{2}$$

The tensor components given in (1) and (2) are related as

$$\epsilon_{xx} = \epsilon_1 \sin^2\theta + \epsilon_2 \cos^2\theta \tag{3}$$

$$\epsilon_{yy} = \epsilon_1 \cos^2\theta + \epsilon_2 \sin^2\theta \tag{4}$$

$$\epsilon_{xy} = \epsilon_{yx} = (\epsilon_2 - \epsilon_1)\sin\theta\cos\theta \tag{5}$$

$$\epsilon_{zz} = \epsilon_2 \tag{6}$$

where θ is the angle shown in Fig. 1. As shown in this figure, $y > d$ is free space and the subscript 0 will be used to indicate quantities associated with it while the subscript d will be used to indicate quantities associated with the dielectric anisotropic substrate located in the region $0 \leqslant y \leqslant d$.

The fields are assumed to have a harmonic time dependence of the type $\exp(j\omega t)$. These fields may be obtained from the Hertz vector potentials oriented along the optical axis ξ:

$$\bar{\pi}_{hd} = \pi_{hd}\hat{\xi} \tag{7}$$

$$\bar{\pi}_{ed} = \pi_{ed}\hat{\xi} \tag{8}$$

that satisfy the wave equation [14]

$$\nabla^2\bar{\pi}_{hd} + k_2^2\bar{\pi}_{hd} = 0 \tag{9}$$

$$\nabla^2\bar{\pi}_{ed} + k_1^2\bar{\pi}_{ed} + \frac{\epsilon_1 - \epsilon_2}{\epsilon_2}\frac{\partial^2}{\partial\xi^2}\bar{\pi}_{ed} = 0 \tag{10}$$

and are given by

$$\bar{e}_d = -j\omega\mu_0\nabla \times \bar{\pi}_{hd} + k_0^2\bar{\pi}_{ed} + \frac{\epsilon_0}{\epsilon_2}\nabla\nabla\cdot\bar{\pi}_{ed} \tag{11}$$

$$\bar{h}_d = \nabla \times \nabla \times \bar{\pi}_{hd} + j\omega\epsilon_0\nabla \times \bar{\pi}_{ed} \tag{12}$$

where ϵ_0 and μ_0 are the permittivity and permeability of free space, ω is the angular frequency, and k_0, k_1 and k_2 are given by

$$k_0^2 = \omega^2\mu_0\epsilon_0 \tag{13}$$

$$k_1^2 = \omega^2\epsilon_1\mu_0 \tag{14}$$

$$k_2^2 = \omega^2\epsilon_2\mu_0. \tag{15}$$

The portion of the fields resulting from the Hertz magnetic potential is commonly known as ordinary wave since its behavior is similar to that of plane waves in isotropic media [14]. The portion resulting from the Hertz electric potential is known as extraordinary wave. Note that along the optical axis there is no electric or magnetic field component for the ordinary or extraordinary wave, respectively. Thus, the complete solution may be considered as a superposition of TE and TM modes with respect to the optical axis.

The structure is uniform along the z direction, so the z dependence of the potential and electromagnetic fields may be taken as $\exp(-j\beta z)$.

The electric and magnetic fields that are functions only of x and y may be written in the spectral domain by means of a Fourier transformation:

$$\tilde{\Omega}(\alpha, y) = \int_{-\infty}^{\infty} \Omega(x, y) e^{-j\alpha x} dx \tag{16}$$

$$\Omega(x, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{\Omega}(\alpha, y) e^{j\alpha x} d\alpha. \tag{17}$$

After the Fourier transformation (16), the field components are written in the spectral domain. The wave equations are integrated and the constants of integration are obtained from the boundary conditions to be satisfied by the fields at the $y = 0$ and $y = d$:

$$\hat{y} \times \overline{E}_d(x, 0) = 0 \tag{18}$$

$$\hat{y} \times [\overline{E}_d(x, d) - \overline{E}_0(x, d)] = 0 \qquad \text{for } |x| > \frac{W}{2} \tag{19}$$

$$\hat{y} \times [\overline{H}_0(x, d) - \overline{H}_d(x, d)] = \bar{J}_s(x, d) \qquad \text{for } |x| < \frac{W}{2} \tag{20}$$

where W is the conducting strip width and $\bar{J}_s$ is the surface current density in the strip.

After using these boundary conditions in the spectral domain, a system of six equations for the calculation of the six constants of integration is obtained. With these constants of integration in the expressions of the fields $\tilde{E}_{dx}(\alpha, d)$ and $\tilde{E}_{dz}(\alpha, d)$ or $\tilde{E}_{0x}(\alpha, d)$ and $\tilde{E}_{0z}(\alpha, d)$ will allow the evaluation of $\tilde{E}_x(\alpha, d)$ and $\tilde{E}_z(\alpha, d)$ as follows:

$$\tilde{E}_x(\alpha, d) = \tilde{Z}_{xx}(\alpha, \beta, d)\tilde{J}_x(\alpha, d) + \tilde{Z}_{xz}(\alpha, \beta, d)\tilde{J}_z(\alpha, d) \tag{21}$$

$$\tilde{E}_z(\alpha, d) = \tilde{Z}_{zx}(\alpha, \beta, d)\tilde{J}_x(\alpha, d) + \tilde{Z}_{zz}(\alpha, \beta, d)\tilde{J}_z(\alpha, d). \tag{22}$$

The impedance functions $\tilde{Z}_{xx}(\alpha, \beta, d)$, $\tilde{Z}_{xz}(\alpha, \beta, d)$, $\tilde{Z}_{zx}(\alpha, \beta, d)$, and $\tilde{Z}_{zz}(\alpha, \beta, d)$ that appear in (21) and (22) were obtained for the general optical axis orientation. They reduce to those obtained by Lee and Tripathi [3] for the particular cases of the optical axis coinciding with the x axis ($\theta = 270°$) and y axis ($\theta = 0°$). In addition, for the isotropic case ($\epsilon_1 = \epsilon_2 = \epsilon_r\epsilon_0$) these expressions agree with those obtained by Itoh [15].

Applying Galerkin's method, the Fourier transforms of the electric current densities $\tilde{J}_x(\alpha)$ and $\tilde{J}_z(\alpha)$ on the metal strips of the single and coupled microstrip lines are expanded in terms of basis functions with unknown coefficients. These expressions are then used in conjunction with (21) and (22) such that a homogeneous matrix equation for the unknown expansion coefficients is obtained [7], [16]. The propagation constants are the roots of the equation obtained by setting the determinant of the coefficient matrix equal to zero. Single and coupled structures are analyzed.

B. Bilateral Finline

Following a procedure similar to that shown for the case of open microstrip lines, the electric field components at the interface of the two media are written as

$$\tilde{E}_x(\alpha) = \tilde{Z}_{xx}(\alpha, \beta)\tilde{J}_x(\alpha) + \tilde{Z}_{xz}(\alpha, \beta)\tilde{J}_z(\alpha) \tag{23}$$

$$\tilde{E}_z(\alpha) = \tilde{Z}_{zx}(\alpha, \beta)\tilde{J}_x(\alpha) + \tilde{Z}_{zz}(\alpha, \beta)\tilde{J}_z(\alpha) \tag{24}$$

where $\tilde{J}_x$ and $\tilde{J}_z$ are the electric current density components on the metal fins, and $\tilde{Z}_{xx}$, $\tilde{Z}_{xz}$, $\tilde{Z}_{zx}$, and $\tilde{Z}_{zz}$ are the desired dyadic Green's function components.

Due to the symmetry existing in the structure of Fig. 3(a), the boundary value problem is solved by placing a magnetic wall along the plane $y = 0$ and considering only half of the structure, as shown in Fig. 3(b).

Losses in the dielectric and in the conductors are neglected. Also neglected is the metal fin thickness. The subscript 0 will be used to specify quantities existing in the region $d < y < a$, filled with air, and the subscript d for the anisotropic dielectric substrate in the region $0 < y < d$. Thus, the boundary conditions to be satisfied by the fields are

a) for $|x| < b$:

$$E_{0x}(x, a) = 0 \tag{25}$$

$$E_{0z}(x, a) = 0 \tag{26}$$

$$H_{dx}(x, 0) = 0 \tag{27}$$

$$H_{dz}(x, 0) = 0 \tag{28}$$

b) for $|x| < s$:

$$E_{dx}(x, d) = E_{0x}(x, d) \tag{29}$$

$$E_{dz}(x, d) = E_{0z}(x, d) \tag{30}$$

c) for $s < |x| < b$:

$$H_{0z}(x, d) - H_{dz}(x, d) = J_x(x, d) \tag{31}$$

$$H_{0x}(x, d) - H_{dx}(x, d) = -J_z(x, d). \tag{32}$$

In addition, at the conducting wall located at $x = \pm b$ the fields should be zero:

$$E_{dy}(\pm b, y) = E_{dz}(\pm b, y) = H_{dx}(\pm b, y) = 0 \tag{33}$$

$$E_{0y}(\pm b, y) = E_{0z}(\pm b, y) = H_{0x}(\pm b, y) = 0. \tag{34}$$

Due to (33) and (34), the spectral variable α may assume only discrete values, α_n. Thus, the algebraic equations in the spectral domain that relate the transverse components of the electric field in $y = d$ to the electric current density components on the metal fins are the discrete Fourier transforms of the coupled integral equations obtained in the space domain [9]. As a result,

$$\alpha_n = \left(n + \frac{1}{2}\right)\frac{\pi}{b}, \qquad n = 0, \pm 1, \pm 2, \cdots \tag{35}$$

or

$$\alpha_n = \frac{n\pi}{b}, \qquad n = 0, \pm 1, \pm 2, \cdots \tag{36}$$

for the odd and even modes, respectively in the E_y (optical axis in the y direction), the H_x (optical axis in the x direction), or the E_z (optical axis in the z direction).

The Hertz potentials may be written as

$$\tilde{\pi}_{hi}(\alpha_n, y, z) = \tilde{f}_i(\alpha_n, y)\exp(-j\beta z) \quad (37)$$

$$\tilde{\pi}_{ei}(\alpha_n, y, z) = \tilde{g}_i(\alpha_n, y)\exp(-j\beta z) \quad (38)$$

where $i = d$ or 0, and

$$\tilde{f}_d(\alpha_n, y) = A(\alpha_n)\sinh(\gamma y) + A'(\alpha_n)\cosh(\gamma y) \quad (39)$$

$$\tilde{g}_d(\alpha_n, y) = C(\alpha_n)\cosh(\gamma_1 y) + C'(\alpha_n)\sinh(\gamma_1 y) \quad (40)$$

$$\tilde{f}_0(\alpha_n, y) = B(\alpha_n)\sinh[\gamma_0(a-y)] + B'(\alpha_n)\cosh[\gamma_0(a-y)] \quad (41)$$

$$\tilde{g}_0(\alpha_n, y) = D(\alpha_n)\cosh[\gamma_0(a-y)] + D'(\alpha_n)\sinh[\gamma_0(a-y)] \quad (42)$$

$$\gamma_0^2 = \alpha_n^2 + \beta^2 - k_0^2 \quad (43)$$

$$\gamma_1^2 = \frac{\epsilon_2}{\epsilon_1}(\alpha_n^2 + \beta^2 - k_1^2), \quad \text{optical axis in } y \text{ direction} \quad (44)$$

$$\gamma_1^2 = \frac{\epsilon_1}{\epsilon_2}\alpha_n^2 + \beta^2 - k_1^2, \quad \text{optical axis in } x \text{ direction} \quad (45)$$

$$\gamma_1^2 = \alpha_n^2 + \frac{\epsilon_1}{\epsilon_2}\beta^2 - k_1^2, \quad \text{optical axis in } z \text{ direction} \quad (46)$$

$$\gamma_2^2 = \alpha_n^2 + \beta^2 - k_2^2. \quad (47)$$

The parameters A, A', B, B', C, and C' are obtained from boundary conditions applied to each of the three optical axis orientations considered.

For the case of the optical axis perpendicular to the dielectric–air interface ($\hat{\xi}$, $\hat{y}$), the parameters may be obtained as follows:

$$A = B' = C = D' = 0 \quad (48)$$

$$A' = \frac{-j\eta(\beta\tilde{J}_x + \alpha_n\tilde{J}_z)}{T\phi_1} \quad (49)$$

$$B = \frac{-j\phi'(\beta\tilde{J}_x + \alpha_n\tilde{J}_z)}{T\phi_1} \quad (50)$$

$$C' = \frac{\omega\mu_0\epsilon_2\gamma_0\eta(\alpha_n\tilde{J}_x - \beta\tilde{J}_z)}{\epsilon_0 T\tau_1} \quad (51)$$

$$D = \frac{\omega\mu_0\gamma_1\tau'(-\alpha_n\tilde{J}_x + \beta\tilde{J}_z)}{T\tau_1} \quad (52)$$

where

$$\phi_1 = \gamma_2\eta\phi + \gamma_0\eta'\phi' \quad (53)$$

$$\tau_1 = k_2^2\gamma_0\eta\tau + k_0^2\gamma_1\eta'\tau' \quad (54)$$

with

$$\phi = \sinh(\gamma_2 d) \quad \phi' = \cosh(\gamma_2 d) \quad \tau = \sinh(\gamma_1 d)$$
$$\tau' = \cosh(\gamma_1 d) \quad \eta = \sinh[\gamma_0(a-d)]$$
$$\eta' = \cosh[\gamma_0(a-d)] \quad T = \alpha_n^2 + \beta^2$$
$$S = \alpha_n^2 - k_0^2. \quad (55)$$

With these parameters the dyadic Green's function components of (23) and (24) are obtained as

$$\tilde{Z}_{xx}(\alpha_n, \beta) = \frac{j\omega\mu_0\eta\tau_2}{T\phi_1\tau_1} \quad (56)$$

$$\tilde{Z}_{xz}(\alpha_n, \beta) = \tilde{Z}_{zx}(\alpha_n, \beta) = \frac{-j\omega\mu_0\eta\alpha_n\beta\tau_3}{T\phi_1\tau_1} \quad (57)$$

$$\tilde{Z}_{zz}(\alpha_n, \beta) = \frac{j\omega\mu_0\eta\tau_4}{T\phi_1\tau_1} \quad (58)$$

where

$$\tau_2 = \gamma_1\tau'[\alpha_n^2\gamma_2\gamma_0\eta\phi + ST\eta'\phi'] - k_2^2\beta^2\gamma_0\eta\phi'\tau \quad (59)$$

$$\tau_3 = \gamma_1\tau'[\gamma_2\gamma_0\eta\phi + T\eta'\phi'] + k_2^2\gamma_0\eta\phi'\tau \quad (60)$$

$$\tau_4 = \gamma_1\tau'[\beta^2\gamma_2\gamma_0\eta\phi + (\beta^2 - k_0^2)T\eta'\phi'] - k_2^2\alpha_n^2\gamma_0\eta\phi'\tau. \quad (61)$$

A similar procedure was followed to obtain the dyadic Green's function components for the other two optical axis orientations: 1) optical axis in the transverse direction and parallel to the dielectric–air interface ($\hat{\xi} = \hat{x}$) and 2) optical axis in the longitudinal direction ($\hat{\xi} = \hat{z}$).

It is important to note that the expressions obtained for the three optical axis orientations considered here reduce to that obtained by Schmidt and Itoh [9] for isotropic dielectric substrate by making $\epsilon_1 = \epsilon_2 = \epsilon_r\epsilon_0$.

Using Galerkin's method, the Fourier transforms of the unknown tangential electric fields in the gap between the fins, $\tilde{E}_x(\alpha)$ and $\tilde{E}_z(\alpha)$, are expanded in terms of basis functions with unknown coefficients. Then they are substituted in (23) and (24), and a homogeneous matrix equation for the unknown expansion coefficients is obtained [7], [9]. The propagation constants are the roots of the equation obtained by setting the determinant of the coefficient matrix equal to zero.

III. Numerical Results

A. Open Microstrip Lines

The effective permittivities of single microstrip lines on sapphire ($\epsilon_{xx} = \epsilon_{zz} = 9.4$ and $\epsilon_{yy} = 11.6$ for $\theta = 0°$) and boron nitride ($\epsilon_{xx} = \epsilon_{zz} = 5.12$ and $\epsilon_{yy} = 3.4$ for $\theta = 0°$) are shown in Fig. 4 as functions of frequency. Results using another method [1] for microstrip lines on sapphire are included and a good agreement is observed.

The frequency behavior of the effective permittivity of the even and odd modes of parallel-coupled microstrip lines for the symmetric case ($W_1 = W_2$) is shown in Fig. 5. A good agreement is observed with the results obtained from another method [2] and for the case of parallel-coupled microstrip lines on sapphire. The optical axis was considered oriented perpendicular to the ground plane of the lines (Fig. 2).

In Fig. 6 the results obtained for the propagating c and π modes in asymmetric coupled microstrip lines on sapphire ($\epsilon_{xx} = \epsilon_{zz} = 9.4$ and $\epsilon_{yy} = 11.6$ for $\theta = 0°$) are presented. Of particular interest is that these results agree

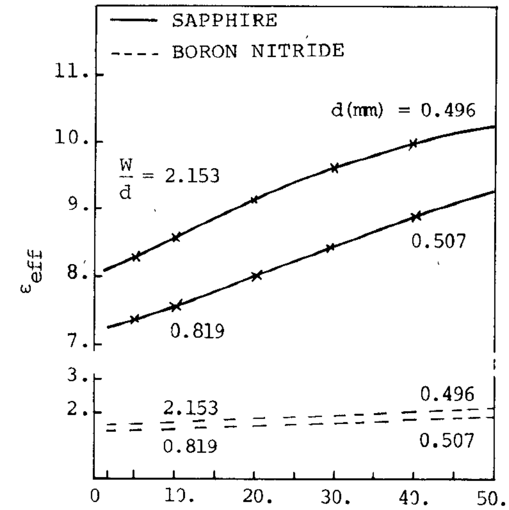

Fig. 4. Frequency dependence of the effective permittivity of single microstrip lines on anisotropic substrates for boron nitride (---) and sapphire (——). Results from [1] (× × × ×) are included for comparison.

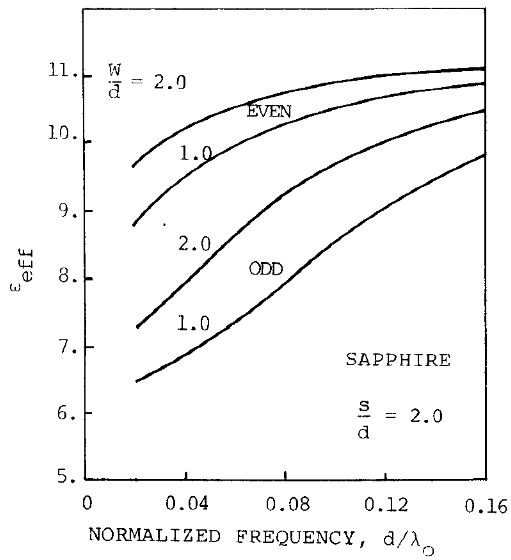

Fig. 5. Even- and odd-mode effective permittivities as a function of the normalized frequency of coupled microstrip lines on sapphire. The optical axis is assumed to be in the y direction and $W_1 = W_2 = W$.

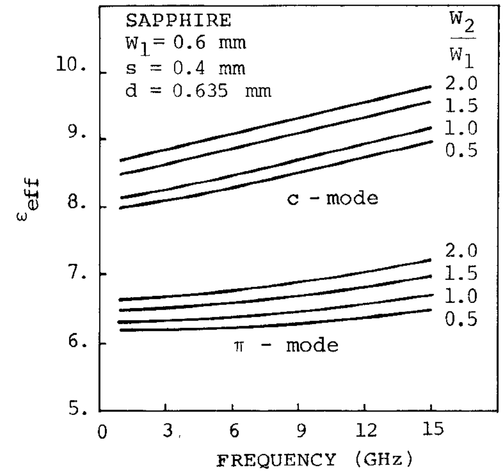

Fig. 6. Dispersive behavior of the effective permittivities of asymmetric coupled microstrip lines on sapphire. The optical axes are in the y direction.

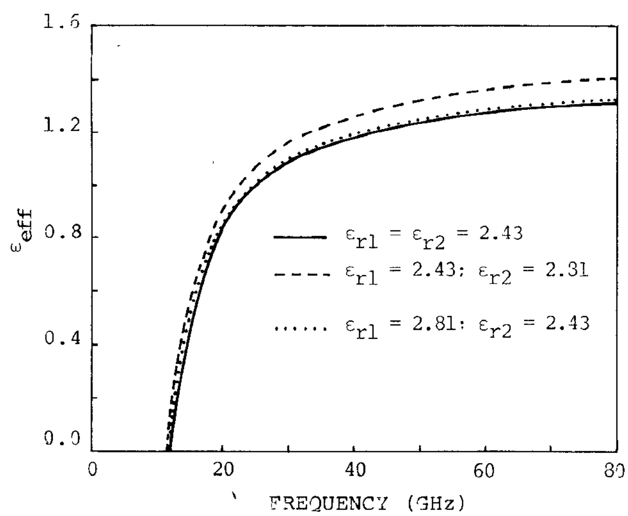

Fig. 7. Dispersion on the effective permittivity of dominant mode in bilateral finlines. The relative permittivity component ϵ_{r1} of the anisotropic dielectric is along the optical axis, which is assumed to be in the y direction. Three different dielectrics are considered.

with those obtained by other authors for the special case of microstrip lines on isotropic substrates ($\epsilon_r = 9.7$) [16], [17].

B. Bilateral Finlines

For obtaining the numerical results, basis functions that could represent the Bessel functions of the first kind in the Fourier transform domain with the possibility of satisfying the boundary conditions and having some numerical convergence criteria were chosen [9], [13]. The dimensions of the conducting shielding surface were chosen as those from a WR-28 rectangular waveguide.

In Fig. 7 the frequency dependence of the effective permittivity of bilateral finlines with three dielectrics is shown. One of the dielectrics has a negative anisotropy ratio ($\epsilon_{r1} = 2.43$; $\epsilon_{r2} = 2.81$), the second has a positive anisotropy ratio ($\epsilon_{r1} = 2.81$; $\epsilon_{r2} = 2.43$), and the third is isotropic ($\epsilon_{r1} = \epsilon_{r2} = 2.43$). The optical axes of both anisotropic dielectrics were chosen perpendicular to the air–dielectric interface ($\hat{\xi} = \hat{y}$). Thus, (56)–(58) were used. For the particular cases of bilateral finlines with isotropic dielectrics, good agreement with results obtained by other authors [9], [13] was observed.

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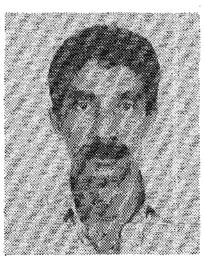

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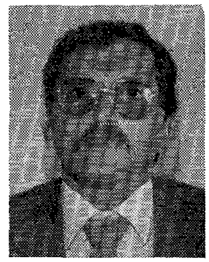

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