PLANAR DIELECTRIC STRIP WAVEGUIDE FOR MILLIMETER-WAVE INTEGRATED CIRCUITS

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Abstract

A modal analysis based on the transverse resonance concept is presented for a planar dielectric strip waveguide which exhibits good guiding properties and is particularly applicable to millimeter-wave integrated circuits. Numerical results are given for the dispersion characteristics and modal field distributions for high resistivity silicon substrate.

Introduction

Recent progresses in millimeter-wave active and passive solid-state devices have made feasible many system applications. In order to achieve functional modules for particular system application and to reduce the size and weight of the module, microwave integrated circuit approach at millimeter wavelength has recently received considerable attention. Both conventional microstrip circuit using low dielectric constant substrate[1] scaled from low frequency model and optical dielectric waveguide[2] have been explored in the millimeter-wave region with success. As frequency increases, however, the microstrip technique is eventually limited by technological difficulties. The dielectric waveguide, on the other hand, must be fabricated by chemical etching or machining, and suffers from undesirable diffraction loss and phase distortion due to random waveguide variation introduced by fabrication process. A planar waveguide structure with low loss should therefore have the advantages of simplicity in processing, a lower random diffraction loss and accessibility to monolithic integration techniques.

This paper presents a study of a novel planar waveguide which is suitable for guiding electromagnetic energy in the millimeter-wave and sub-millimeter-wave regions. The cross-section of the waveguide is shown in Fig. 1. By using the Wiener-Hopf technique, the reflection coefficient at the open ends of the guide is first determined. Secondly, a transverse resonance condition is applied to determine the dispersion relation of the modal field. The propagation constant is found to be complex; its imaginary part accounts for the edge diffraction loss of the strip through the open ends of the guide. Thus, using this technique, not only are we able to determine the dispersion characteristics of the guide, but also the small distributed loss inherently associated with an open system.

The planar dielectric waveguide structure under study has a geometry identical to the microstrip transmission line. Unlike the microstripline, however, the transverse dimensions of the guide are relatively large compared to the wavelength and therefore no longer supports the TEM or quasi-TEM mode of propagation as characterized by a zero cut-off frequency.[3-6] The dispersion characteristics and modal fields, on the other hand, are similar to the dielectric waveguide[7,8] which exhibits low frequency cutoff for all propagating modes.

It is to be stressed that the substrate thickness for a dielectric strip guide is considerably greater than for a conventional microstrip. Typically, the thickness is ten to fifteen times larger so that the dominating TEM or quasi-TEM modes in the microstrip are no longer supported in the strip guide. This results from strong radiation caused by the large substrate thickness. The only modes that can still propagate in the dielectric strip guide are similar to those described by Vainshtein[9] for which the propagation constants in the transverse x direction are small and the waves undergo strong reflections at the open ends. The energy is thus trapped in the waveguide and hardly radiates into the free space. Therefore, the strip guide described in this paper is entirely different from the wide microstrip configurations such as the microguide.[10] This substantially larger substrate thickness is advantageous at millimeter and submillimeter wavelengths because of ease in fabrication.

Formulation

With the cross-section of the dielectric strip waveguide shown in Fig. 1, we are interested in the modal fields that are guided along the z direction. It is convenient to classify the fields as $TM^{(y)}$, and $TE^{(y)}$ with y being the transverse direction. For $TM^{(y)}$, all field components are derivable from a scalar potential ψ {with exp $(-i\omega t)$ time convention suppressed}:

$$E_x = \frac{i}{\omega\varepsilon}\frac{\partial^2\psi}{\partial x\partial y} \qquad H_x = -\frac{\partial\psi}{\partial z}$$

$$E_y = \frac{i}{\omega\varepsilon}\left(\frac{\partial^2}{\partial y^2} + k_o{}^2\varepsilon_r\right)\psi \qquad H_y = 0 \qquad (1)$$

$$E_z = \frac{i}{\omega\varepsilon}\frac{\partial^2\psi}{\partial y\partial z} \qquad H_z = \frac{\partial\psi}{\partial x}$$

where $k_o = \omega\sqrt{\mu\varepsilon_o} = 2\pi/\lambda_o$ is the wave number in free space. A similar set of equations exist for $TE^{(y)}$ modes. Since the derivation of $TE^{(y)}$ modes is identical to that of $TM^{(y)}$ modes, we shall only outline the procedure for attacking $TM^{(y)}$ modes. Let us first consider a parallel plate waveguide filled with dielectric medium ε_r. The potential for $TM^{(y)}_{mn}$ modes is given by

$$\psi_{mn} = e^{i\alpha_m x}\cos\left(\frac{n\pi}{b}y\right)e^{i\beta_{mn}z} \qquad (2)$$

where α_m and β_{mn} respectively are the propagation constants along x and z directions, and they satisfy the dispersion relation

$$\alpha_m^2 + \left(\frac{n\pi}{b}\right)^2 + \beta_{mn}^2 = k_o^2 \varepsilon_r \qquad (3)$$

For a finite strip width a, instead of a traveling wave, there should be a standing wave along x direction, namely

$$\psi_{mn} = \left(e^{i\alpha_m x} + R_{mn}\, e^{i2\alpha_m a}\, e^{-i\alpha_m x}\right) \cos\frac{n\pi}{b} y \; e^{i\beta_{mn} z} \qquad (4)$$

where R_{mn} is the reflection coefficient of the $TM_{mn}^{(y)}$ mode at the open ends at x = ±a. In order for a modal solution to exist in the present open structure, the transverse resonance condition requires[9]

$$R_{mn}\, e^{i2\alpha_m a} = e^{i(m+1)\pi}, \quad m = 1,2,3,\ldots \qquad (5)$$

Following (4) and (5), the formal solution for $TM_{mn}^{(y)}$ mode is found to be

$$\psi_{mn} = \begin{Bmatrix} \cos \alpha_m x \\ \\ \sin \alpha_m x \end{Bmatrix} \cos \frac{n\pi}{b} y \; e^{i\beta_{mn} z}, \quad \begin{matrix} m = 1,3,5\ldots \\ \\ m = 2,4,6\ldots \end{matrix} \qquad (6)$$

It therefore follows that once the reflection coefficient R_{mn} is found, the propagation constants α_m and β_{mn} can be determined from (5) and (3) respectively and the formal field solution is then determined by (6). In our analysis, the determination of R_{mn} requires the Wiener-Hopf technique which is too lengthy to be outlined here, but the procedure is standard and the solutions to similar problems can be found in the literature.[9,11,12] It can be shown, for the present open structure, the reflection coefficient of $TM_{mn}^{(y)}$ mode assumes the form

$$R_{mn} = (-1) \exp\left[i \sqrt{4\pi P_m}\,(1+i)\, 0.824\, g_o \right] \qquad (7)$$

P_m is a complex parameter related to the propagation constants α_m and β_{mn} and to the small distributed loss along the open ends of the waveguide. g_o can be regarded as the filling factor due to the dielectric medium and is given by

$$g_o = 1 + \frac{(1+i)}{0.824\sqrt{4\pi P_m}} \left[U(c, P_m) - \frac{1}{2}\, \ell n(1-c) \right] \qquad (8)$$

where

$$U(c, P_m) = \frac{1}{2\pi i} \cdot \int_{-\infty}^{\infty} \frac{\ell n \left\{ 1 - \exp\left[i2\pi P_m + \ell n \;\; c/\sqrt{1-c} \;\; - t^2/2 \right] \right\}}{t - \sqrt{4\pi P_m}\, \exp(i\pi/4)}\, dt \;.$$

The parameter c in (8) is a constant related to the waveguide dimension (a,b) and dielectric constant ε_r, and is given by

$$c = \frac{1 - \varepsilon_r \sqrt{(k_o b/n\pi)^2\,(1-\varepsilon_r) + 1}}{1 + \varepsilon_r \sqrt{(k_o b/n\pi)\;\;(1-\varepsilon_r) + 1}} \qquad (9)$$

Numerical Results and Discussion

Based on equations (5) through (9), the propagation constants β_{mn} and α_m can be determined explicitly through numerical iteration. Figure 2a and 2b present an example of the typical results obtained. The calculated propagation constant (Re β_{mn}) and attenuation constant (Im β_{mn}) along the z direction are plotted as functions of b/λ_o for aspect ratio (a/b) = 1 and ε_r = 11.8 (high resistivity silicon). It is seen that the dispersion characteristics calculated for the present structure are similar to those of the dielectric waveguide which shows a low frequency cutoff for all $TM_{mn}^{(y)}$ modes; as the transverse dimension b increases, the propagation constant for all modes approach $\sqrt{\varepsilon_r} k_o$ asymtotically.

Figure 2b shows the distributed loss through the open ends of the waveguide in terms of radiation caused by diffraction at x = ±a, y = b. Such a loss though generally small in quantity is important in terms of waveguide design. It is seen from Fig. 2b that the radiation loss decreases as the aspect ratio (a/b) or dielectric constant ε_r increases. Secondly, the radiation loss increases as Re β_{mn} decreases. At Re β_{mn} = k_o, the major portion of the modal energy is no longer confined in the waveguide and radiation loss increases sharply.

In order to gain some insight on the transverse field distribution for $TM^{(y)}$ modes, we have also plotted the calculated field distributions along x direction according to (6) for two lowest order $TM^{(y)}$ modes (Fig. 3 and 4). It is seen that the field distributions in the strip guide are similar to those of laser resonators.[9,11] The non-zero value of the field at x = ±a is related to the radiation loss; the higher field value generally results in a higher radiation loss. It is interesting to note that at higher radiation loss, the field distribution deviates from an ideal sine or cosine distribution as normally assumed in typical dielectric waveguide analyses.

Conclusion

An analysis of a dielectric strip waveguide has been presented. The strip waveguide has shown well-defined propagating mode structures and is particularly applicable for millimeter-wave integrated circuits. The dispersion characteristics are very similar to that of the dielectric waveguide which has been widely used in integrated optics.

References

1. M.V. Schneider, "Millimeter-Wave Integrated Circuits," presented at the IEEE GMTT International Microwave Symposium, Denver, Colorado, June 1973.

2. H. Jacobs and M.M. Chrepta, "Semiconductor Dielectric Waveguide for Millimeter-Wave Functional Circuits," presented at the IEEE GMTT International Microwave Symposium, Denver, Colorado, June 1973.

3. P. Daly, "Hybrid-Mode Analysis of Microstrip by Finite-Element Methods," IEEE Transaction Microwave Theory Tech., Vol MTT-19, pp 19-25, January 1971.

4. E. J. Denlinger, "A Frequency Dependent Solution of Microstrip Transmission Lines," IEEE Transaction Microwave Theory Tech., Vol MTT-19, pp 30-39, January 1971.

5. R. Mittra and T. Itoh, "A New Technique for the Analysis of the Dispersion Characteristics of Microstrip Lines," IEEE Transaction Microwave Theory Tech., Vol MTT-19, pp 47-56, January 1971.

6. T. Itoh and R. Mittra, "Spectral-Domaine Approach for Calculating the Dispersion Characteristics of Microstrip Lines," IEEE Transaction Microwave Theory Tech., Vol MTT-21, pp 496-499, July 1973.

7. E.A.J. Marcatili, "Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics," Bell Systems Tech., Vol. 48, pp 2071-2102, September 1969.

8. J.E. Goell, "A Circular-Harmonic Computer Analysis of Rectangular Dielectric Waveguide," Bell Systems Tech. Journal, Vol 48, pp 2133-2160, September 1969.

9. L.A. Vainshtein, "Open Resonators for Lasers," Sov. Physics-JETP, Vol 17, pp 709-719, September 1963.

10. E.G. Cristal, A.F. Podell and D. Parker, "Microguide, A New Microwave Integrated Circuit Transmission Line," presented at the IEEE GMTT International Microwave Symposium, Arlington Heights, May 1972.

11. T.T. Fong and S.W. Lee, "Theory of Fabry-Perot Resonators with Dielectric Medium," IEEE J. Quant. Electr., Vol QE-7, pp 1-11, January 1971.

12. R. Mittra and S.W. Lee, Analytical Techniques in the Theory of Guided Waves, New York: MacMillan, 1971, Chapter 3.

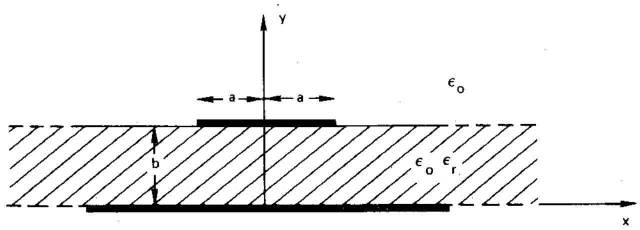

Fig. 1 Cross-section of a dielectric strip guide.

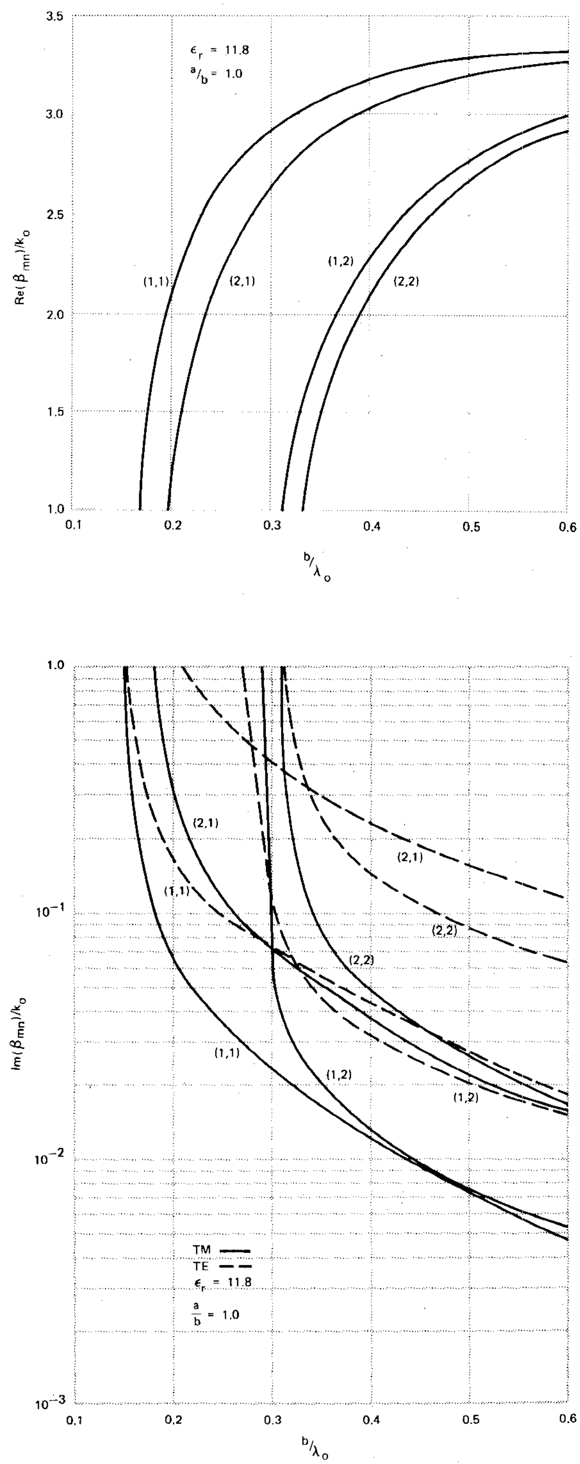

Fig. 2 Normalized propagation and attenuation constants of four lowest order modes for high resistivity silicon substrate with $\varepsilon_r = 11.8$, a/b = 1.0.

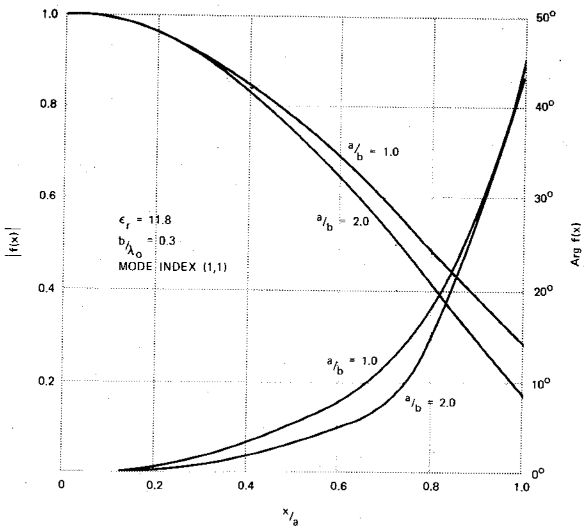

Fig. 3 Field distribution along x direction $f(x) = \cos \alpha_1 x$ for $TM_{11}^{(y)}$ with $\varepsilon_r = 11.8$, $b/\lambda_o = 0.3$.

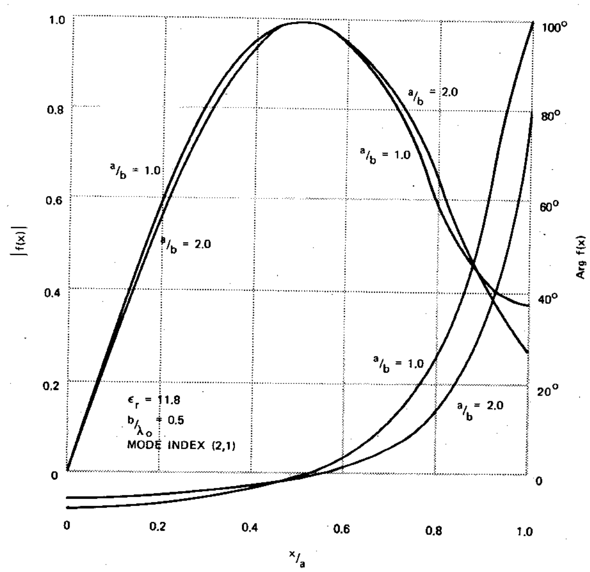

Fig. 4 Field distribution along x direction $f(x) = \sin \alpha_2 x$ for $TM_{21}^{(y)}$ with $\varepsilon_r = 11.8$, $b/\lambda_o = 0.5$.