SUSPENDED H-WAVEGUIDE AND ITS MILLIMETER WAVE APPLICATIONS

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ABSTRACT

The propagation and loss characteristics of the suspended H-waveguide, a new dielectric waveguide structure for millimeter-wave applications, are described. Both the mode-matching and the effective dielectric constant techniques are investigated. Some novel applications of the suspended H-waveguide are also presented.

INTRODUCTION

Several types of dielectric waveguide structures are currently available as guiding media for millimeter wave applications, such as image guide[1], insular guide[2] and H-guide.[3] For normal mode of operation, the image guide has high metal loss due to the proximity of the dielectric core to the ground plane. The insular guide has lower metal loss but is more difficult to fabricate. Bonding materials are needed to hold the dielectrics in place. These open structures usually need extra shielding mechanisms to reduce radiation and crosstalk among circuit elements. The H-guide should only be used to carry the TM waves since the metal loss associated with the TE waves is very high.[3]

In this paper, we introduce a new dielectric-based waveguide structure in which the dielectric cores are sandwiched between two insulating dielectric layers. The dielectric arrangement is then shielded to obtain a closed structure as shown in Figure 1a. Since the dielectric cores have higher dielectric constants than those in the substrate regions, most of the electromagnetic energy is concentrated in the cores, and therefore, the structure has lower metal loss. The radiation loss of the suspended H-waveguide is expected to be less than that for other open waveguide structures due to total shielding. For this same reason, crosstalk among circuit elements can be eliminated. The metal enclosure also allows plenty of ground for dc biasing. Bonding materials may not be needed since the metal enclosure will secure all dielectric layers tightly in place. In practice, the two insulating dielectric layers are copper-cladded dielectric sheets which are commercially available. Due to the unique arrangement of the dielectrics and the metal side walls, the suspended H-waveguide can be adapted for many component designs which are described in the text.

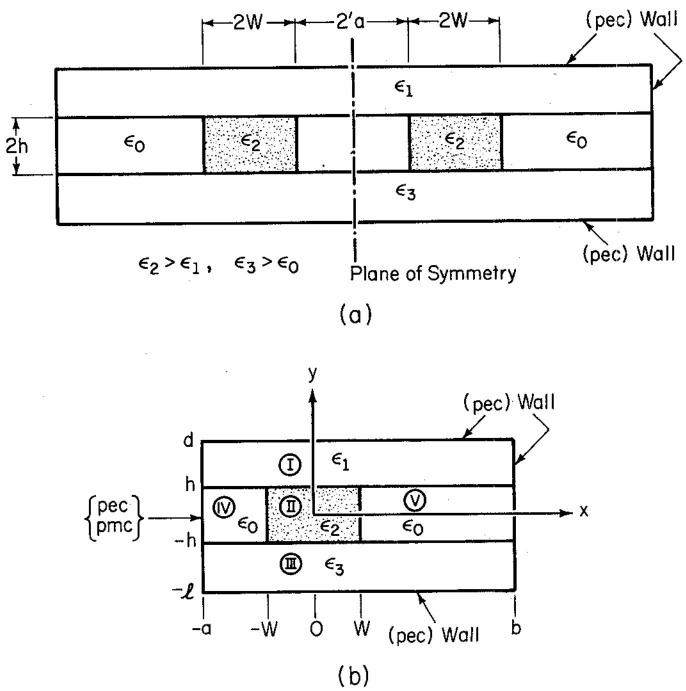

FIGURE 1: (a) CROSS SECTION OF THE COUPLED SUSPENDED H-WAVEGUIDE. (b) STRUCTURE ADOPTED FOR ANALYSIS.

Method Of Analysis

To obtain reliable information for the designs of both active and passive components, accurate theoretical predictions of the field and propagation characteristics must be available. To this end, the rigorous mode-matching technique in which the fields in each subregion of the guide cross section are expanded in terms of regional eigenfunctions is used. This technique has been used to accurately predict the propagation constants of many dielectric waveguide structures.[4-6]

The cross section of a coupled suspended H-waveguide is shown in Figure 1a. Because of the symmetry of the structure about the plane x = -a, even and odd modes can propagate in the coupled structure. The analysis of the coupled line can then be reduced to that shown in Figure 1b where a perfect electric conducting (pec) wall implies odd-mode propagation, and a perfect magnetic conducting (pmc) wall implies even-mode propagation. For a = b, the coupled line reduces to that of a single, uncoupled structure.

The analysis using the mode-matching technique can be applied by separating the cross section of the suspended H-waveguide into five subregions, I-V. The total fields are derived from the Hertzian potentials $\bar{\pi}_e$ and $\bar{\pi}_h$ which have a single x-directed component [7], i.e.,

$$\bar{E} = \nabla \times \nabla \times \bar{\pi}_e - j\omega\epsilon_0 \nabla \times \bar{\pi}_h \quad (1a)$$

$$\bar{H} = j\omega\epsilon_0 \epsilon_i \nabla \times \bar{\pi}_e + \nabla \times \nabla \times \bar{\pi}_h \quad (1b)$$

*Currently at Hughes Aircraft Company, Torrance, CA 90509 where ϵ_i is the relative dielectric constant of each region, and $\bar{\pi}_e$ and $\bar{\pi}_h$ are referred to as longitudinal-section electric (LSE) mode and longitudinal-section magnetic (LSM) mode, respectively. These potentials must be chosen in such a way that the correspondent fields will satisfy all boundary conditions at the metal walls. After matching all the tangential field components across the $y = \pm h$ interfaces and using the orthogonality properties of the eigenfunctions of the top and bottom dielectric layers, a system of homogeneous linear equations with unknown coefficients is obtained. The zeros of the determinant of those equations are the longitudinal propagation constants k_z's of the waveguide structure. For each k_z, a set of amplitude coefficients of the potentials is found within a constant multiplicative factor and, hence, a complete description of the total field in the guide.

In general, the mode-matching technique is quite involved and tedious to derive the characteristic equation for k_z. For many engineering applications, where only approximate values of k_z are necessary, the "effective" permeability or permittivity approximation or a combination of the two is quite useful. These approximations provide reasonably accurate results for the propagation constants of many complex structures.[2,5,6,8] Unlike the mode-matching technique, these approximations consider two types of modal fields, i.e., LSE (H-wave) and LSM (E-wave) modes, independently. The H-wave leads to the effective dielectric constant (or permittivity) method while the E-wave is associated with the effective permeability method.[9] For abbreviation, when we refer to both the effective permittivity and the effective permeability and their mean values, the effective parameter will be used.

Figure 2 shows the dispersion characteristics of the fundamental E_{11}^y and E_{11}^x modes as a function of the normalized free-space wavenumber k_0d. The agreement between theoretical and experimental results of the E_{11}^y mode is very good. A combination of a sliding short along the dielectric core and a reverse coupler at the input of the suspended H-waveguide has been used to record the standing wave pattern in the guide.[10] The dielectric core is made of Alumina ($\epsilon_2 = 9.8$), and the insulating top and bottom dielectric layers are copper clad RT/Duroid with an $\epsilon_r = 2.3$. All measurements were done in the E-band.

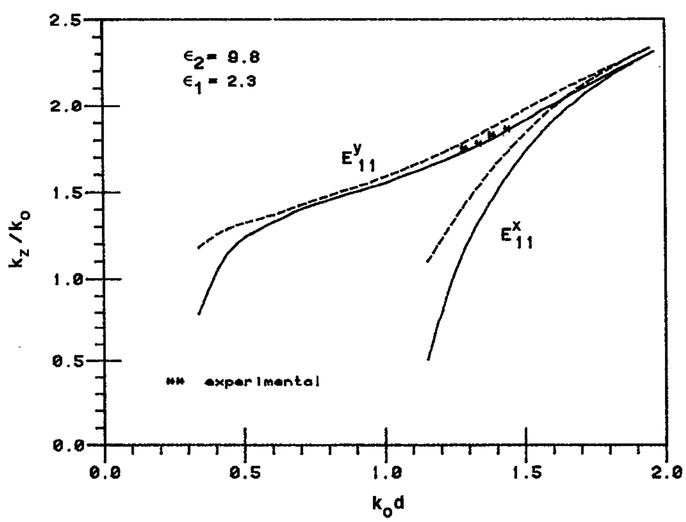

FIGURE 2: NORMALIZED PROPAGATION CONSTANTS OF A SINGLE SUSPENDED H-WAVEGUIDE VS. THE NORMALIZED FREE-SPACE WAVENUMBER. $\epsilon_1 = \epsilon_3$, $\ell = d$, $a = b$. MODE MATCHING: SOLID LINE; EFFECTIVE PARAMETER: DASHED LINE.

Loss Characteristics

The primary contributors to losses in dielectric-based waveguide structures operating at frequencies beyond cutoff are the dielectric loss and the metal loss of the conducting walls. The attenuation α_m in nepers per unit length due to metal loss can be calculated by the conventional power loss method, i.e.

$$\alpha_m = P_L/2P_T \qquad (2)$$

where P_L is the metal loss per unit length, and P_T is the transmitted power in the guide. The field components in all regions are computed by the rigorous mode-matching technique.

Figure 3 shows the attenuation in dB per meter of the E_{11}^y mode in a suspended H-waveguide. It is evident from this figure that the metal loss is much lower when the two dielectric insulating layers are inserted. In the absence of the dielectric layers, i.e., $h/d = 1$, the attenuation of this mode increases as a function of frequency.

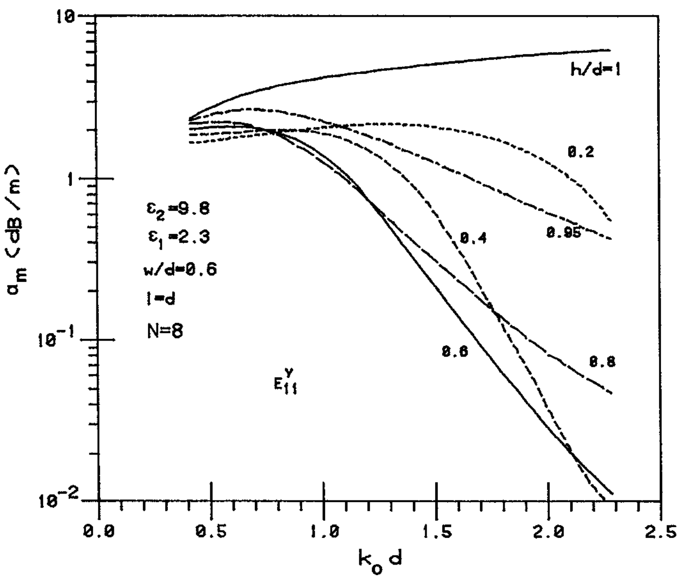

FIGURE 3. ATTENUATION OF THE E_{11}^y MODE IN dB PER METER DUE TO THE METAL LOSS IN A SUSPENDED H-WAVEGUIDE. $\sigma_m = 6.17 \times 10^7$.

The attenuation constant α_d associated with lossy dielectrics can be obtained directly by a perturbation technique, which is based on the solutions of the lossless structure and can be expressed as

$$\alpha_d = -\frac{\sum_{i=1}^{3} \epsilon_i \tan\delta_i \frac{\partial}{\partial \epsilon_i} D(\epsilon_i, k_z, \omega)}{\frac{\partial}{\partial k_z} D(\epsilon_i, k_z, \omega)} \qquad (3)$$

where $\tan\delta_i$, $i = 1,2,3$, is the dielectric loss tangent in the respective region. D is the determinant of a system of linear and homogeneous equations derived from the mode-matching technique. Figure 4 shows the dielectric attenuation constant of the E_{11}^y mode as a function of the normalized free-space

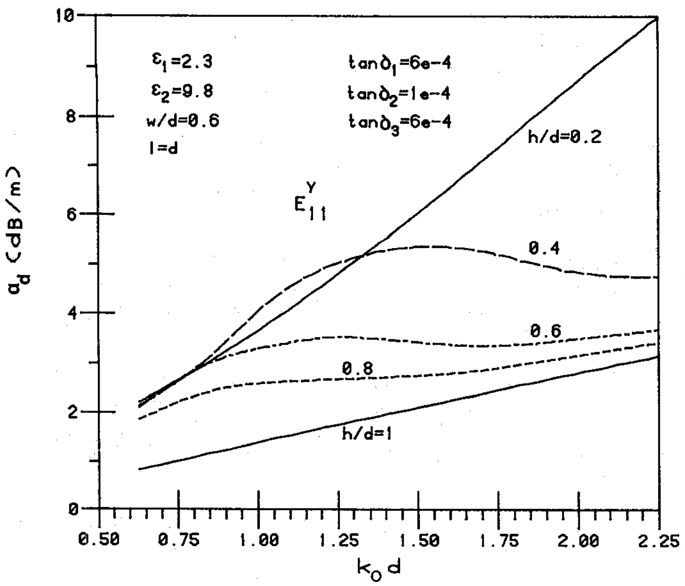

FIGURE 4: ATTENUATION CONSTANT IN dB PER METER OF THE E^Y_{11} MODE IN A SUSPENDED H-WAVEGUIDE.

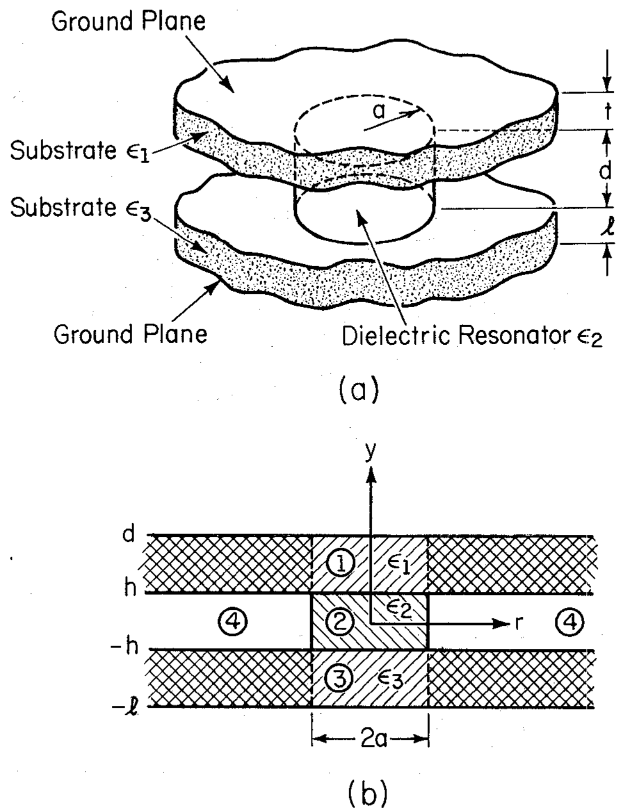

FIGURE 5: (a) CYLINDRICAL DIELECTRIC DISC RESONATOR. (b) STRUCTURE ADOPTED FOR ANALYSIS.

wavenumber. Since the loss tangents of the substrates are much higher than the loss tangent of the dielectric core in this case, e.g., $\tan\delta_1/\tan\delta_2 = 6$, most of the dielectric loss is due to the substrates. If a lower-loss copper-cladded dielectric sheet is available, the dielectric loss of the suspended H-waveguide should be much lower. However, for given waveguide parameters, the total (dielectric and metal) loss of the suspended H-waveguide (h/d = 0.6 and 0.8) is still lower than the total loss of a conventional H-guide (h/d = 1).

Applications

Because of the unique arrangement of the dielectrics in a suspended H-waveguide, a cylindrical disc resonator can be constructed as described in Figure. 5. A circular disc of the same height as of the dielectric core of the suspended H-waveguide is sandwiched between two dielectric insulating layers. The dielectric disc is locked securely in place by the metal enclosure and no bonding material is needed. The dielectric constant of the disc can be different from that of the guiding dielectric core, which allows the use of high-permittivity materials for high-Q applications. A simple analytical technique described by Itoh[11] can be used to analyze this structure. The resonant frequencies are obtained by solving a set of two characteristic equations simultaneously.

Another novel dielectric ring resonator that can be efficiently integrated into a dielectric-based MMW-IC to provide filtering effect is shown in Figure 6. This resonator is particularly useful in a system that employs the suspended H-waveguide as the guiding medium. Figure 6a shows the top view of the resonator, and Figure 6b is the equivalent signal flow graph. From the signal flow graph analysis, the resonances occur when $\ell = n\lambda_g/2$, n = 1,2,... where λ_g is the waveguide wavelength.

Another possible application of the suspended H-waveguide is the leaky-wave antenna (see Figure 7a). The waveguide structure can be converted into a leaky-wave antenna (or a band-reject filter) by edging periodic narrow slots on the top metal surface along the propagation direction. The geometry adopted for analysis is shown in Figure 7b. This antenna is frequency scannable simply by varying the operating frequency, and can be flush mounted.

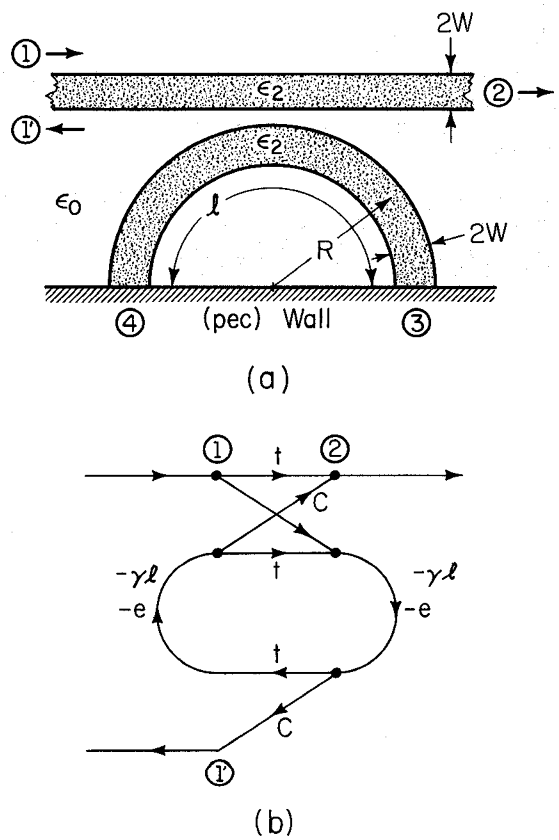

FIGURE 6: (a) DIELECTRIC RING RESONATOR. (b) EQUIVALENT SIGNAL FLOW GRAPH SCHEMATIC.

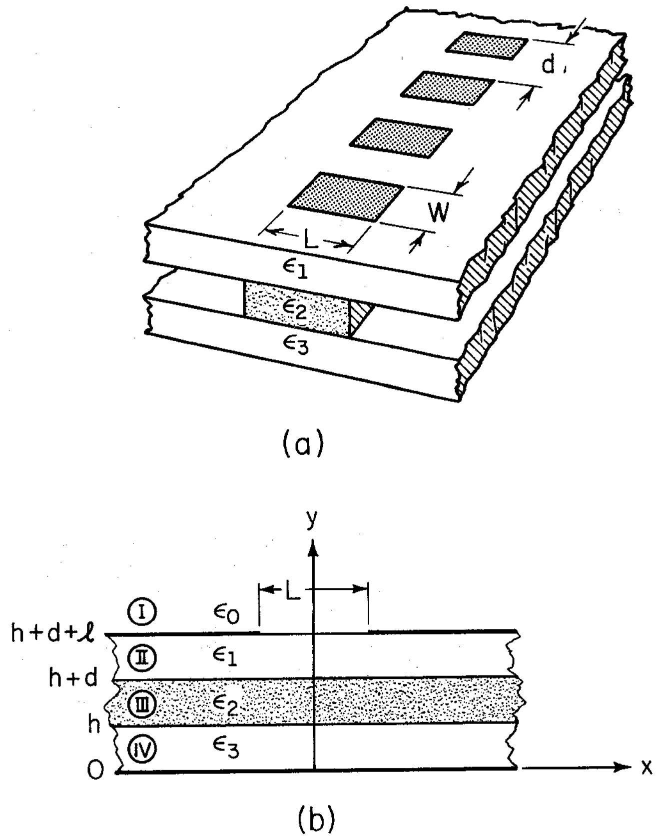

FIGURE 7: (a) LEAKY-WAVE ANTENNA. (b) STRUCTURE ADOPTED FOR ANALYSIS.

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