ELECTROMAGNETIC COUPLING OF MICROSTRIP LINES AND COPLANAR WAVEGUIDES TO MULTILAYER LOSSY MEDIA

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ABSTRACT

In medical-diagnostic and geophysical applications of electromagnetic (EM) techniques, it is of critical importance to use radiating systems that couple the EM energy efficiently and with minimum external leakage. Experimentally, a family of printed circuit elements including coplanar waveguides has proven to be an ideal surface-wave type coupling system for such applications. To date, no work has been done to describe the coupling characteristics of these structures. In this paper, the spectral domain method is used to provide a detailed analysis of the coupling characteristics of coplanar waveguides to multi-layered lossy dielectric media. The role of a superstrate layer of lossless dielectric in setting up and controlling the surface-wave type coupling to the lossy media is examined. Results for the dispersion characteristics and the various components of the coupled electric field in the lossy medium are presented.

INTRODUCTION

There are many medical application of electromagnetic techniques, including those related to monitoring various physiological parameters such as the blood flow rate and changes in lung water content. In these applications, microstrip devices, including coplanar waveguides, were found to provide superior performance as compared to other kinds of radiating structures [1,2]. They are flat, light, compact, and, most importantly, couple the EM energy efficiently to the human body with minimum external leakage around the surface [3]. This surface wave rather than radiation-type EM coupling, minimizes the sensitivity of the measurements to surroundings, particularly when conducted on continuous bases. Geophysical downhole well logging is another area of application where the coplanar waveguide has proven most efficient for broadband coupling of the electromagnetic energy to the rock formation [4]. The commonly used cavity-backed slot antenna in the commercially available "Electromagnetic Propagation Tools" [5], is narrowband and for size considerations can be used at fairly high frequencies (1 GHz) which severely limits its depth of investigation. Coplanar waveguides with their broadband coupling were found to provide very attractive coupling characteristics that would certainly enhance the utilization of these tools.

The analysis of coplanar waveguides on one or more dielectric substrates has been widely discussed [6-8]. The coupling characteristics to multi-layer lossy dielectric media with complex permittivities as high as those of the human body or geophysical formations, however, have not been investigated. Furthermore, the role of a thin superstrate layer of lossless dielectric between the coplanar waveguide and the lossy medium in setting up and controlling the coupling characteristics has not been previously investigated. These issues, as well as analysis of the actual field configurations coupled to the multi-layer lossy media, will be investigated in this paper using the spectral-domain technique.

ANALYSIS PROCEDURE

The spectral-domain method is used to analyze the coupling characteristics of the coplanar waveguide coupler to multi-layer lossy dielectric media. It will be used further to analyze the role of a thin layer of lossless superstrate in controlling the coupling characteristics. The spectral-domain method provides an elegant procedure for reducing partial differential equations to ordinary ones which often can be further analytically simplified. This method has become by far the most popular method of analyzing the propagation characteristics of many microwave and millimeter-wave integrated circuits. We analyzed the four-layer structure shown in Fig. 1. Layer 2 represents the substrate, while layers 3 and 4 represent the coupling superstrate and the lossy dielectric media, respectively. Assuming $e^{\Gamma z}$ propagating waves, where $\Gamma = \alpha + j\beta$, taking the Fourier transform of the wave function $\varphi(x,y)$ in the x-direction to eliminate the need to analytically express the x-dependence of the function, and applying the boundary conditions at the interfaces between the various dielectric layers, we obtain a set of coupled equations of the form

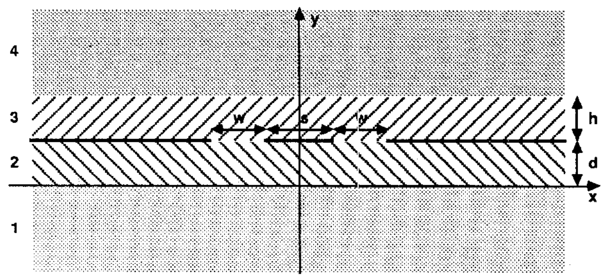

Fig. 1. Four-layered dielectric coplanar waveguide.

$$\begin{bmatrix} G_{11}(\tau,\Gamma) & G_{12}(\tau,\Gamma) \\ G_{21}(\tau,\Gamma) & G_{22}(\tau,\Gamma) \end{bmatrix} \begin{bmatrix} \tilde{E}_x(\tau) \\ \tilde{E}_z(\tau) \end{bmatrix} = \begin{bmatrix} \tilde{J}_z(\tau) \\ \tilde{J}_x(\tau) \end{bmatrix}$$

where $\tilde{E}_x$ and $\tilde{E}_z$ denote the Fourier transform of the x- and z-directed electric field in the slots, while J_x and J_z denote the Fourier transform of the x- and z-directed current density components on the metal. Expanding the electric field in the gaps in terms of a known set of basis functions and applying Galerkin's method we obtain

$$\sum_{n=1}^{\infty} P_{mn}(\Gamma)\, a_n + \sum_{n=1}^{\infty} Q_{mn}(\Gamma)\, b_n = 0 \qquad (1a)$$

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$$\sum_{n=1}^{\infty} R_{mn}(\Gamma)\, a_n + \sum_{n=1}^{\infty} S_{mn}(\Gamma)\, b_n = 0 \qquad (1b)$$

where

$$Q_{mn}(\Gamma) = \int_{-\infty}^{\infty} G_{12}(\tau,\Gamma)\; \eta_m(\tau)\; \zeta_n(\tau)\, d\tau$$

where $\eta_m(\tau)$ and $\zeta_n(\tau)$ are the Fourier transform of the expansion functions used to express the E_x and E_z components of the fields in the coplanar gap. Similar expressions are obtained for P_{mn}, R_{mn}, and S_{mn} in terms of η_m, ζ_n, and the dydic Green's functions $G_{ij}(\tau,\Gamma)$, i = 1,2, and j = 1,2. The propagation constant Γ is obtained by making the determinant of the coefficient matrix (1) be zero. Spatial-domain expressions of the field components are obtained by taking the inverse Fourier transform of the spectral-domain field expansions.

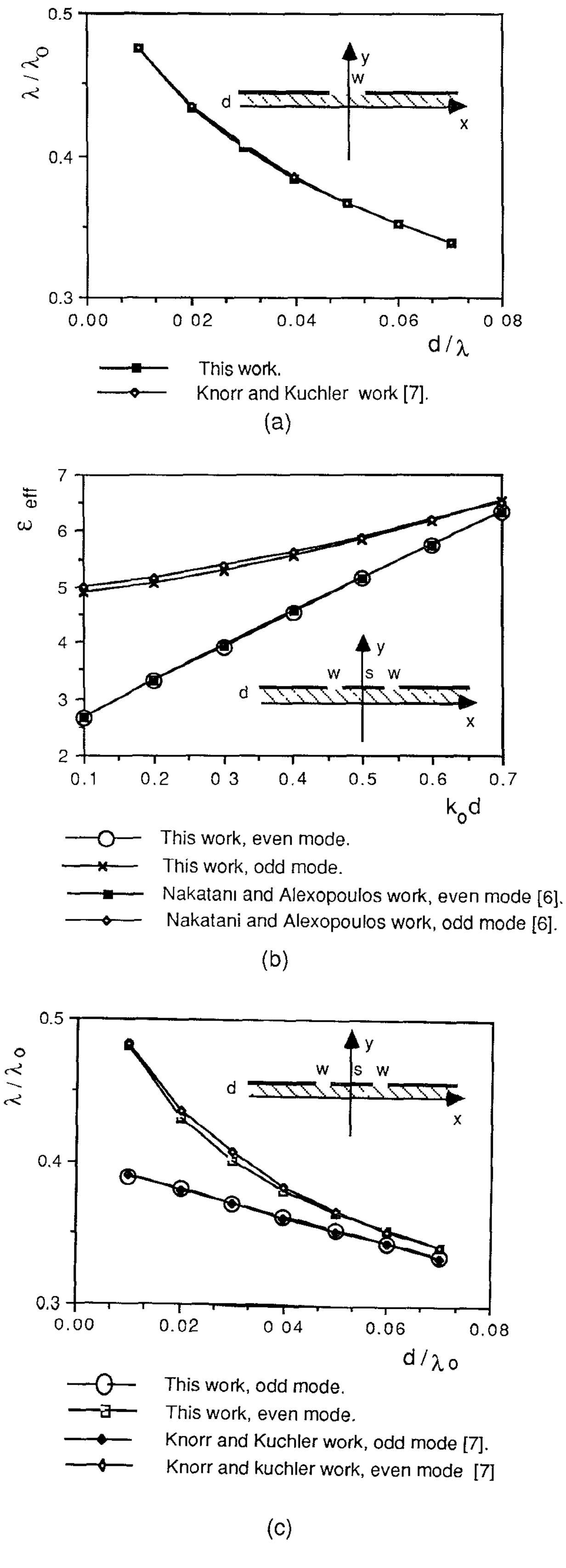
In our calculations, two types of bases functions were used to expand the fields. This includes the often-utilized pulse-basis functions and those that explicitly include the singularity of the E_x-field component at the metallic edges [9].

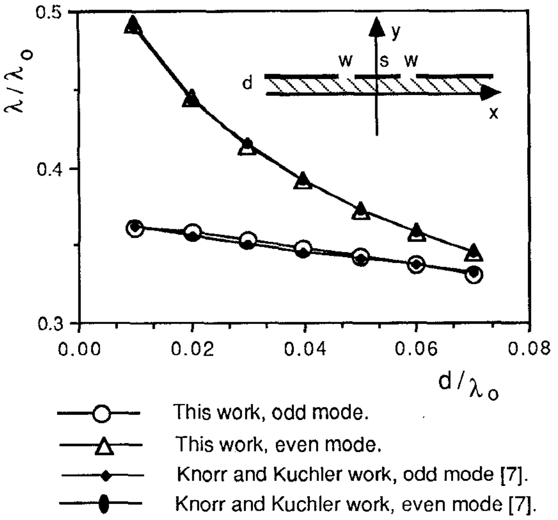
NUMERICAL RESULTS

To check the accuracy and convergence of our numerical calculations, we compared the obtained results with dispersion characteristics data available in the literature for slot lines and coplanar waveguides. No literature data are available for coupling to multi-layer dielectric media and hence the developed code will be validated experimentally. Fields maps using three mutually orthogonal electric-field probes will be conducted [10,11]. Figure 2 shows comparisons of some of the obtained dispersion characteristics with data available in literature [6-8] for both slot lines and coplanar waveguides. Excellent agreements are generally observed even for the simple pulse expansion of the unknown gap fields. Results for even and odd modes in coplanar waveguides are also in excellent agreement with available data.

Results for the spatial distribution of the transverse electric field are shown in Fig 3. It is apparent from Fig. 3 that the transverse electric field components are much stronger when the coplanar waveguide was placed in direct contact with high dielectric constant lossy medium. These stronger transverse fields, thus, have an improved penetration in the high dielectric material. Of particular interest, however, is the role of a superstrate in controlling the coupling characteristics to the high-dielectric lossy medium. Fig. 4 shows the spatial distribution of the coupled electric field when a layer of lossless dielectric superstrate was placed between the coplanar waveguide and the lossy medium. Numerical results generally showed a significant reduction in the magnitude of the transverse field components in the lossy medium. At the same time, however, significant increase in the axial component of the electric field E_z was observed. This, in effect, reduced the TEM type of wave in the lossy medium and instead facilitated a surface wave type coupling to the lossy medium. Fig 5 shows the radial attenuation of the axial electric field component for both cases with and without the superstrate.

There are, however, other factors that control the magnitude of the axial field component in the high-dielectric lossy medium. This includes the width of the gap in the coplanar structure and the dielectric constant of the superstrate material. These, as well as other detailed examination of the coupling characteristics of coplanar wave to lossy dielectric medium, will be described in a future article.

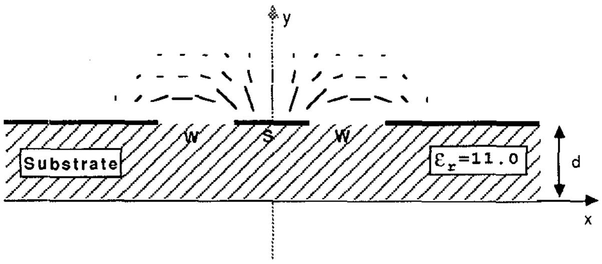




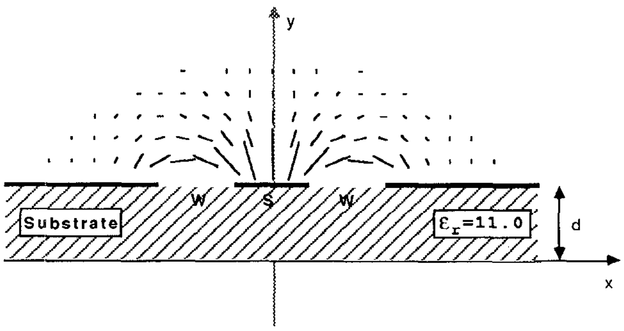
(d)

Fig. 2. Comparison of numerically obtained dispersion characteristics with available data.

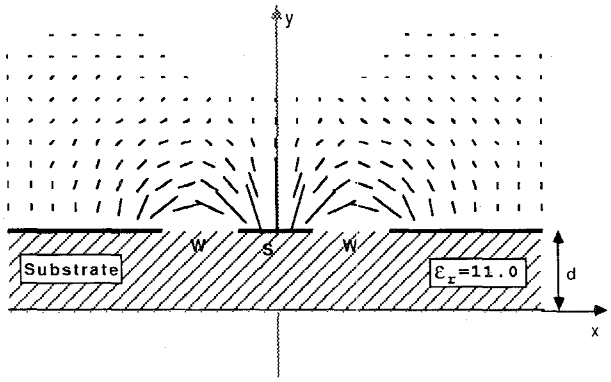
a. Single slot line: ε_r = 16, w/d = 0.
b. Coplanar waveguide: ε_r = 10.2, w/d = 1.0, s/d = 0.5.
c. Coplanar waveguide: ε_r = 16.0, w/d = 0.4, s/d = 0.3.
d. Coplanar waveguide: ε_r = 16.0, w/d = 0.4, s/d = 1.0.



(a)



(b)



(c)

Fig. 3. Spatial distribution of the transverse components of the electric field (a) in air, (b) in lossy dielectric medium of ε_r^* = 30 + j20, and (c) in lossy dielectric medium of ε_r^* = 60 + j20. In all cases the substrate has ε_r = 11, and of thickness d = 1 cm. The widths of the center conductor and the gap are S = 1 cm and W = 1 cm, respectively. Calculations were made at frequency of 1 GHz.

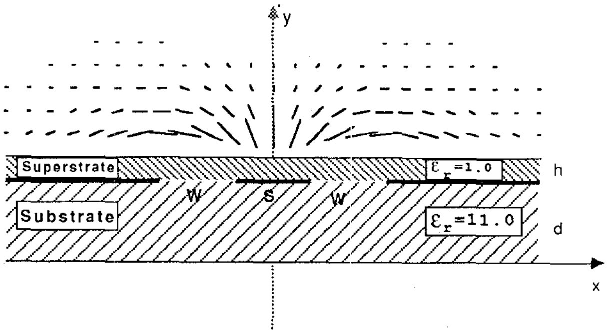


Fig. 4. Spatial distribution of the transverse components of the electric field when a superstrate of thickness 0.292 cm was placed between the coplanar waveguide and the loss dielectric medium of ε_r^* = 60 + j20. All other dimensions and frequency are same as in Fig. 3.

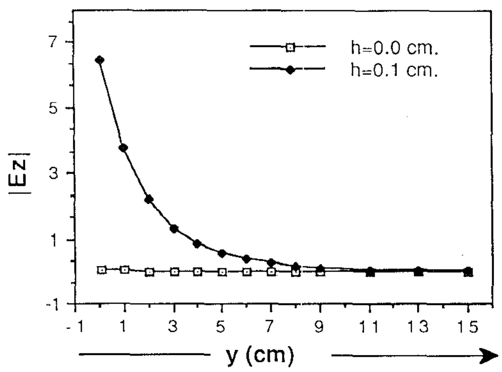


Fig. 5. The magnitude of axial electric field component $|E_z|$ in a lossy dielectric medium of ε_r^* = 60 + j20 when placed in direct contact with a planar waveguide h = 0 cm, and when a superstrate of h = 0.1 cm was placed between the coplanar waveguide and the lossy medium. Calculations were made along the vertical y-axis for x = 0.

CONCLUSIONS

The spectral-domain method is used to analyze the EM surface wave type coupling of microstrip lines and coplanar waveguides to multi-layer lossy dielectric media. Detailed analysis of these coupling characteristics and the role of a thin superstrate layer of lossless material in controlling this coupling are important in fully developing the application of microstrip circuit technology in medical and geophysical applications. Obtained numerical results for the dispersion characteristics were found to be in excellent agreement with published data in special cases of coplanar waveguides and slot lines. Results for the spatial distribution of the various field components in a lossy medium are, however, more involved Specifically it was noticed that the presence of a superstrate of lossless dielectric medium significantly enhances the axial electric field component, thus facilitating a surface-wave type coupling with exponential decay to the lossy medium. Efforts are underway to further quantify these effects and quantify the role of parameters such as the gap width and the dielectric constant of the superstrate on the coupling characteristics of these structures.

REFERENCES

1. M. F. Iskander and C. H. Durney, "Electromagnetic Energy Coupler/Receiver: Apparatus and Method," U.S. Patent No. 4,240,445.
2. M. F. Iskander and C. H. Durney, "Microwave Methods of Measuring Changes in Lung Water," *Journal of Microwave Power*, Vol. 18, 1983, pp. 265-275.
3 M. F. Iskander and C. H. Durney, "Electromagnetic Techniques for Medical Diagnostics: A Review," *Proceedings of the IEEE*, Vol. 68, 1980, pp. 126-132.
4. M. F. Iskander, S. L. Rattlingourd, and J. Oomrigar, "A New Electromagnetic Propagation Tool for Well Logging," *Society of Petroleum Engineers Publication No. 13189*, 1984
5. R. Freedman and J. P Vogiatzis, "Theory of Microwave Dielectric Logging Using the Electromagnetic Wave Propagation Method," *Geophysics*, Vol. 44, 1979, pp. 969-986.
6 A Nakatani and N. G Alexopoulos, "Toward a Generalized Algorithm for Modeling of the Dispersive Properties of Integrated Circuit Structures on Anisotropic Substrates," *IEEE Transactions on Microwave Theory and Techniques*, Vol MTT-33, 1985, pp. 1436-1441.
7. J B. Knorr and K. D. Kuchler, "Analysis of Coupled Slots and Coplanar Strips on Dielectric Substrates, " *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-23, 1975, pp 541-548.
8. R. H. Jansen, "The Spectral-Domain Approach for Microwave Integrated Circuits," *IEEE Transactions on Microwave Theory and Techniques*, Vol MTT-33, 1985, pp. 847-881.
9 M. F Iskander and M. A F. Hamid, "Numerical Solution for the Near-Field Transmission Between Spectral Electromagnetic Horns," *IEEE Transactions on Antennas and Propagation*, Vol. AP-24, 1976, pp. 87-89.
10. M. F Iskander, H. Massoudi, C. H. Durney, and S. J. Allen, "Measurements of the RF Power Absorption in Spheroidal Human and Animal Phantoms Exposed to the Near Field of a Dipole Source," *IEEE Transactions on Biomedical Engineering*, Vol. BME-28, 1981, pp 258-264.
11. M. F. Iskander and A. M. Tumeh, "Optimization of Interstitial Antennas for Hyperthermia Applications," *IEEE Transactions on Biomedical Engineering*, will appear February 1989.