FULL-WAVE ANALYSIS OF LOSSY TRANSMISSION LINE INCORPORATING THE METAL MODES

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Abstract

A full-wave mode-matching analysis of a unilateral finline with finite conductivity, metalization thickness, and holding grooves is presented. A new class of metal modes exist in the metalized region for its most part and decay sharply in the air region. It is shown for the first time that without incorporating the metal modes presented here, the mode-matching method for tackling lossy millimeter-wave or microwave transmission lines can not produce accurate results.

I. Introduction

The analysis of conductor losses on integrated millimeter-wave and microwave transmission lines plays an important role on the accurate CAD (computer aided design) modeling required in many demanding applications. Recently, a few methods have been developed for this account, e.g. a combined surface integral solution [1], a modified mode matching method [2], and a phenomenological loss equivalence method [3].

In Fig. 1 a unilateral finline is placed in a waveguide housing with holding grooves. In this case the integral equation method is often not easy to derive. Alternatively, the mode-matching method for treating this problem is adopted here for analyzing a transmission line with finite metalization thickness [2,4,5].

The success of the mode-matching method lies primarily on the eigenfunctions obtained accurately. Apart from the numerical treatment on obtaining accurate eigenfunctions as explained in [2], the mode completeness is paramountly important. In Fig. 1, the eigenvalues obtained for regions 1, 2, and 4 are similar to those described in [5] except for region 3, where there exist a new class of metal modes (eigenfunctions) in addition to the well-known air modes (eigenfunctions). The negligence of the metal modes can cause inaccu-

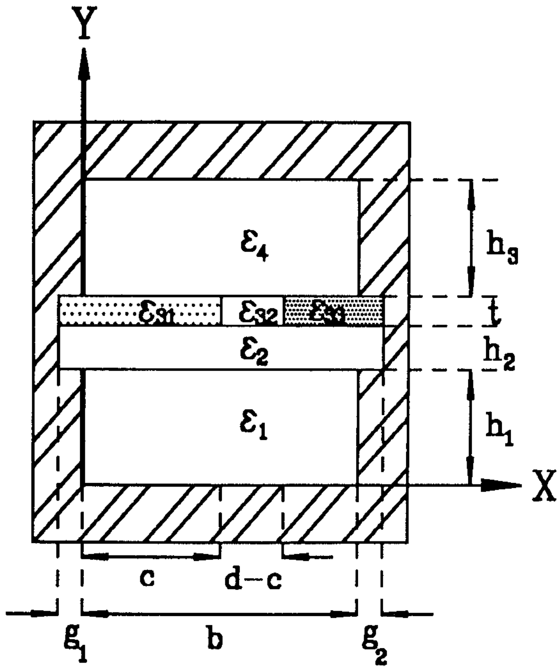

Fig. 1 A unilateral finline with finite conductivity, metalization thickness, and holding grooves. The structural parameters are $c=0.275$mm, $d=1.275$mm, $b=1.55$mm, $g_1=g_2=0.326$mm, $\sigma=3.333\text{x}10^7(\text{ohm-m})^{-1}$, $h_1=1.5$mm, $h_2=0.05$mm, $t=1.\mu$m, $h_3=1.549$mm, $\epsilon_1=\epsilon_{32}=\epsilon_4=1$, $\epsilon_2=3$, and $\epsilon_{31}=\epsilon_{33}=1\text{-}j\sigma/\omega\epsilon_0$.

rate solutions for the complex propagation constant when the metalizations in region 3 have finite conductivities.

Section II discusses the mode-matching method and certain important properties associated with the metal or air modes. Section III gives a brief description on the electromagnetic field distributions of the metal modes and air modes, respectively. Section IV presents and discusses the theoretical results under many test conditions that employ various numbers of metal modes.

II. Formulation: Mode-Matching Method

In Fig. 1, the finline structure is divided into four regions. Regions 1 and 4, which are represented by their relative dielectric constants as ϵ_1 and ϵ_4, respectively, are the air region. Region 2 is for a dielectric substrate with relative dielectric constant ϵ_2. The metalized strips are in the regions denoted by ϵ_{31} and ϵ_{33}, and ϵ_{32} equals to 1 for the air-filled slot region. g_1 and g_2 are the intrusion depths of the substrate into the waveguide housing.

The mode-matching formulation based on the TE-to-x and TM-to-x eigenfunction expansions for all regions is derived. As an example, the eigenfunction expansions in region 3 in terms of the TM-to-x and TE-to-x fields can be listed as,

$$\Psi_3^e=\sum_{n=0}^{N3}\Phi_{3n}^e(x)\left\{E_n^e\,\frac{\cos[\beta_{3n}^e(h_1+h_2+t-y)]}{\cos[\beta_{3n}^e t]}+F_n^e\,\frac{\sin[\beta_{3n}^e(h_1+h_2+t-y)]}{\sin[\beta_{3n}^e t]}\right\} \qquad (1)$$

$$\Psi_3^h=\sum_{n=1}^{N3}\Phi_{3n}^h(x)\left\{E_n^h\,\frac{\cos[\beta_{3n}^h(h_1+h_2+t-y)]}{\cos[\beta_{3n}^h t]}+F_n^h\,\frac{\sin[\beta_{3n}^h(h_1+h_2+t-y)]}{\sin[\beta_{3n}^h t]}\right\} \qquad (2)$$

where N3 denotes the numbers of eigenfunctions for TM-to-x and TE-to-x fields, respectively. It is noted that the summation in Eq. (1) starts from n=0 in order to include the quasi-TEM mode. In the case of finite conductivities at regions denoted by ϵ_{31} and ϵ_{33}, we tend to obtain more eigenvalues than usual as compared to other regions which have the similar form as $n\pi/b$ in region 1.

The side walls of the waveguide housing are assumed to be perfect electric conductors. The coefficients A_n^e, B_n^h (region 1), C_n^e, D_n^e, C_n^h, D_n^h (region 2), E_n^e, F_n^e, E_n^h, F_n^h (region 3), etc., can be eliminated by matching all the necessary tangential boundary conditions at each interface. It should be noted that in the region with lossy conductors, it is desirable to invoke the bi-orthogonal set of eigenfunctions in order to simplify the analysis. Finally a determinantal equation is obtained to determine the propagation constant, $\gamma=\alpha+j\beta$ (the $e^{j\omega t-\gamma z}$ factor is assumed.), of the waveguide structure.

III. The Metal Modes and Air Modes

The existence of the air and metal modes can be best understood by extending region 3 in both positive and negative y directions. In this way, the finline reduces to a parallel-plate waveguide, which has two vertical perfectly conducting sidewalls. The new waveguide is now inserted with two layers of metals with finite conductivities and an air

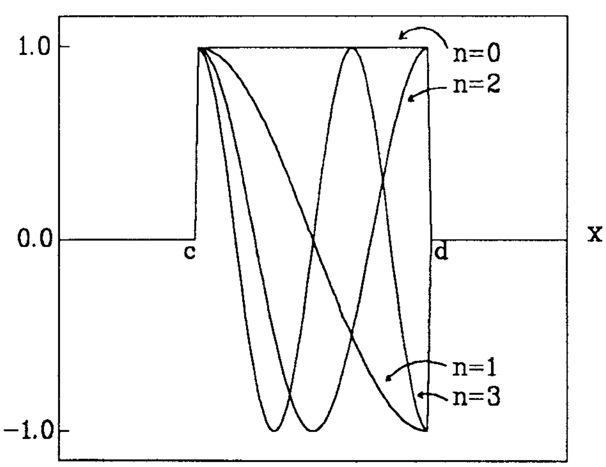

Fig. 2 The first few TM-to-x air modes, $\sigma=3.333\times10^7(\text{ohm-m})^{-1}$.

region between the metal layers. The complete modal description of this particular case is illustrated in Figs. 2 and 3. Fig. 2 is the plots of the first few air modes whereas Fig. 3 plots the first few metal modes. Both air and metal modes have TE-to-x and TM-to-x modes, respectively. Here only TM type is presented. The TE type can be obtained in a similar way. Thus N3 in Eq. (1) (Eq. (2)) is the sum of the numbers of TM-to-x (TE-to-x) air modes (a) and TM-to-x (TE-to-x) metal modes (m) on the opposite sides of the air region, i.e. N3=a+2m for the symmetric case. The existence of the metal modes in addition to the air modes does not change the formulation described in section II. It constitutes, however, the mode completeness required in the mode-matching method.

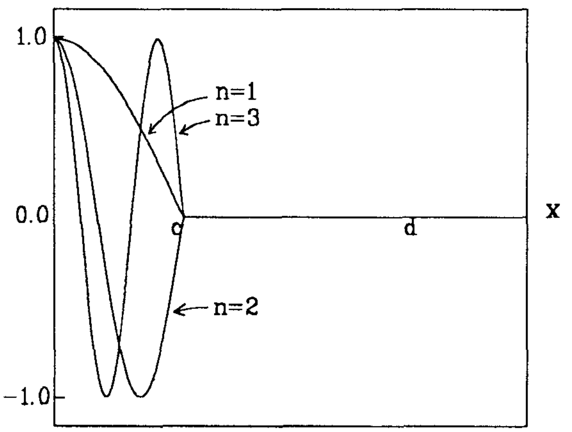

Fig. 3 The first few TM-to-x metal modes in the region denoted by ϵ_{31}, σ=3.333x10^7 (ohm-m)$^{-1}$

IV. Theoretical Results

To analyze a lossless finline in [5] for any modal solution, including the dominant or complex modes, it was found that the relative convergence criterion should be met in any slot-dieletric or slot-air interfaces for good accuracy. In the present study for a lossy finline shown in Fig.1, we denote N1, N2, N3(N3=a+2m), and N4 as the numbers of expansion terms in the constitutive regions, respectively. The theorectical results reported herein are required to satisfy the condition of relative convergence[5,6] by using the number of expansion terms according to the aspect ratios of the finline structure. For the particular case with its structural parameters listed in Fig. 1, the aspect ratios of N1:N2:a:N4 equal to 8:11:5:8. This allows good field matching at locations other than the lossy slot region.

Now we investigate the convergence property at the lossy slot region i.e. region 3. The number of metal modes(m) is increased to investigate the error of field matching as described in Table I, which uses N2=110 for the operating frequency at 65 GHz. It is clear from Table I that, by increasing the number of metal modes, better field matchings are obtained at all interfaces. For the particular case studied, the value of m of 45 is sufficient to yield very good field matching at all interfaces.

Next a sequence of convergence study for the dispersive characteristics of the dominant mode is performed and illustrated in Fig. 4 with the ratio of m to N2 equal to 45/110. When not including any metal mode, i.e. m=0, the value of β/β_0 disagrees with the lossless data and the value of α, the loss term in the propagation constant, is two orders of magnitude smaller than those incorporating metal modes.

Fig. 4 shows that the normalized β/β_0 is insensitive to the variation of the size of matrices if

TABLE I

COMPARISON OF PARAMETERS OBTAINED BY VARIOUS NUMBERS OF METAL MODES

		m=0	m=15	m=30	m=45	m=60
β/β_0		0.71592	0.77322	0.78151	0.79255	0.79267
α(dB/mm)		0.00016	0.00708	0.00273	0.01946	0.01630
Δ^*	$y=h_1$	0.00577	0.00709	0.00734	0.00757	0.00786
	$y=h_1+h_2$	0.16426	0.31259	0.17078	0.03812	0.03651
	$y=h_1+h_2+t$	1.39927	0.62723	0.08638	0.00220	0.00269

* Define the error of field matching at each interface as

$$\Delta = \frac{\sqrt{\int |E_x(y^+) - E_x(y^-)|^2 dx}}{\sqrt{\int |E_x(y^+)|^2 dx}}$$

both relative convergence and metal modes are properly accounted for. When these criteria are satisfied, the solutions for both β/β_0 and α converge to their respective limiting values, as the number of expansion terms is increased. It is interesting to see that the value of the normalized propagation constant(β/β_0) for the lossy finline is slightly higher than the lossless case. In particular, in the high frequency limit, about 1.3% deviation may occur.

Of more importance is the fact that there exist the so-called *metal modes* in each metalized region with finite conductivity. For the particular case studied, the omission of the metal modes results in an inaccurate propagation constant, of which the attenuation constant can be two orders of magnitude smaller, as compared to that obtained by including the metal modes.

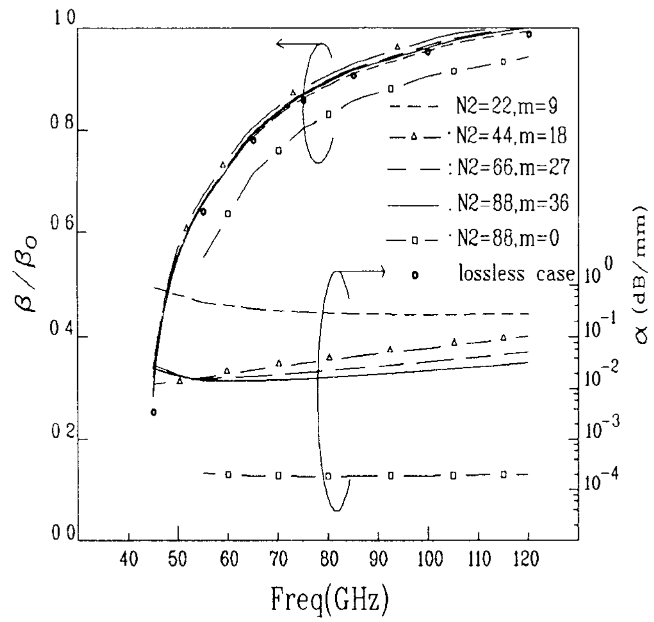

Fig. 4 Dispersive characteristics of the dominat mode for a symmetric unilateral finline with its structural and material parameters listed in Fig. 1.

V. Conclusion

Full-wave theoretical results for a gold-plated unilateral finline are presented. The relative convergence criterion for a lossless waveguide is also observed for the finline with good metal coating. A criterion is given in order to determine the relative numbers of air and metal modes needed in the mode-matching formulation.

References:

[1] T. E. Van Deventer, P. B. Katehi, and A. C. Cangellaris, "High frequency conductor and dielectric losses in shielded microstrip," 1989 IEEE MTT-S Digest, session FF-3, pp. 919-922.

[2] W. Heinrich, "Full-wave analysis of conductor losses on MMIC transmission lines," 1989 IEEE MTT-S Digest, session FF-1, pp. 911-914.

[3] H.- Y. Lee and T. Itoh, "Wideband conductor loss calculation of planar quasi-TEM transmission lines with thin conductors using a phenomenological loss equivalence method," 1989 IEEE MTT-S Digest, session L-8, pp. 367-370.

[4] F. Alessandri, U. Goebel, F. Melai, and R. Sorrentino, "Theoretical and experimental characterization of nonsymmetrically shielded coplanar waveguides for millimeter wave circuits," 1989 IEEE MTT-S Digest, session PP-27, pp.1219-1222.

[5] W.- K. Wang, C.- K. C. Tzuang, C.- Y. Shih, and T.- H. Wang, "Investigations of complex modes in a generalized bilateral finline with mounting grooves and finite conductor thickness," 1989 IEEE MTT-S Digest, session L-40, pp. 491-494.

[6] T. S. Chu, T. Itoh, and Y.- C. Shih, "Comparative study of mode-matching formulations for microstrip discontinuity problems," IEEE Trans. Microwave Theory and Tech., Vol. MTT-33, pp. 1018-1023, Oct. 1985.