FAST AND ACCURATE COMPUTATION OF DIELECTRIC LOSSES IN MULIT-LAYER, MULTI-CONDUCTOR MICROSTRIP STRUCTURES

James P. K. Gilb and Constantine A. Balanis

Department of Electrical Engineering, Telecommunications Research Center
Arizona State University, Tempe, Arizona 85287-7206

ABSTRACT

Accurate analysis of the dielectric losses in complex microstrip structures is important in the computer-aided design of microwave and millimeter-wave integrated circuits. The proposed approach can be used in lieu of lossy, full-wave solutions to provide accurate and efficient data for the CAD of multi-layer, multi-conductor MIC and MMIC structures. This new application gives results that are as accurate as lossy full-wave techniques over a wide range of frequency, including the dispersive region. In addition to giving accurate results, this method is up to three times faster, depending on the number and type of substrates or superstrates. Results are shown for various symmetric and asymmetric, multi-conductor, multi-layer structures which have good agreement with the lossy, full-wave approach and use significantly less computer time.

INTRODUCTION

One of the most important goals in the computer modeling of MIC's and MMIC's is to provide highly accurate simulations in order to reduce the number of design cycles. Current techniques available for the calculation of the dielectric loss coefficient compromise on either accuracy or speed and many are not suitable for complex structures. We present here a new application of an old formulation which provides accurate results for the dielectric loss coefficient for multi-layer, multi-conductor structures in less time.

Various full-wave methods have been used to compute the dielectric loss in multi-layer, multi-conductor structures. Examples of these include: the Spectral Domain Approach (SDA) , [2], the space-domain, moment method [3], and the Finite-Difference, Time-Domain (FDTD) method [4]. All of these techniques give accurate results for the dielectric loss in a general microstrip structure, but they require a significant amount of computational effort. One of the most widely used formulas for computing the dielectric loss coefficient is the one advanced by Schneider [5]. This formula has long been used with approximate formulas for ϵ_{reff} to compute the dielectric loss coefficient, α_d. It was recently shown that this formula gives results that are as accurate as those obtained with a lossy full-wave approach if the partial derivative of ϵ_{reff} is computed accurately [2].

Although this formula has been verified for single-substrate, single-conductor microstrip structures, there has not yet been a study to determine if this formula can be successfully applied to more general structures. In this paper, the range of frequency and dielectric loss over which the formula advanced by Schneider gives accurate results is studied for multi-layer structures. The numerical efficiency of the method is also analyzed for multi-layer, multi-conductor structures where some or all of the layers are lossy. These results show that using Schneider's formulation is faster than using a full-wave, lossy formulation while giving results that are just as accurate.

THEORY

We consider a general, lossy, multi-layer, multi-conductor structure as shown in Fig. 1. The structure is surrounded on all four sides by perfect electric conductors at $x = \pm a$, $y = 0$, and $y = \sum_{i=1}^{M} h_{L_i} + \sum_{i=1}^{N} h_{U_i}$. For an open structure, $a \rightarrow \infty$ and $h_{U1} \rightarrow \infty$ whereas for a covered structure without sidewalls, $a \rightarrow \infty$ while h_{U1} remains finite. There may be any number of conductors located on any of the dielectric interfaces. Two conductors are shown in Fig. 1 located at $x = x_i$ and $x = x_{i+1}$ with widths w_i and w_{i+1}, respectively. The conductors are separated by a spacing s_i which is always measured between the near edges of adjacent conductors. We define the complex effective dielectric constant as

$$\epsilon_{reff}^{*} = \epsilon_{reff}' - j\epsilon_{reff}'' = \frac{\gamma_z^2}{\omega^2 \mu_0 \epsilon_0} \tag{1}$$

where γ_z is the complex propagation constant of the structure. The formula given by Schneider for the effective loss tangent for this structure is given by [5]

$$(\tan\delta)_{\text{eff}} = \frac{\epsilon_{reff}''}{\epsilon_{reff}'} = \frac{1}{\epsilon_{reff}} \sum_{n=1}^{N} \epsilon_{rn} \frac{\partial \epsilon_{reff}}{\partial \epsilon_{rn}} \tan\delta_n \tag{2}$$

IF1

1992 IEEE MTT-S Digest

where ϵ_{rn} and $\tan\delta_n$ are the relative dielectric constants and loss tangents, respectively, of the nth dielectric substrate and N represents the total number of dielectric layers. In the above formula and throughout this paper, ϵ_{reff} (without primes) represents the effective dielectric constant of the equivalent lossless problem. This formula can also be used in the dispersive region by including the frequency dependence for ϵ_{reff} in the formula and partial derivatives. Since the derivation given in [5] is valid for any mode which can exist in a given structure, we can use a formula similar to (2) to compute effective loss tangent for each of the M independent modes in an M-conductor structure.

For low-loss structures, it has been shown that (2) will give good results if the partial derivative is computed accurately. Since closed-form expressions for the ϵ_{reff} are not available for a wide variety of structures and approximate formulas that are available are not very accurate [2], the partial derivative is computed using a finite difference approximation with ϵ_{reff} determined by full-wave, lossless method, such as the SDA [6]. In this paper, the SDA, as described in [6], is used to compute the lossless ϵ_{reff} used in (2) and in the partial derivatives. However, any other accurate, lossless formulation can be used with (2) to compute the dielectric loss coefficient.

RESULTS

There are two main concerns in using equation (2) to compute the dielectric loss coefficient; the range of parameters of the dielectric layers for which the formula gives accurate results, and the amount of computational effort required to achieve accurate results. To address the first concern, a two-substrate, open microstrip structure, with dimensions given in Fig. 2, is analyzed as a function of the substrate loss tangent. The imaginary part of the complex effective dielectric constant, ϵ''_{reff}, is plotted as a function of the loss tangent of the lower substrate using three methods. The first uses (2) with ϵ_{reff} computed using a lossless SDA and the finite difference approximation for the derivative. The second also uses (2) and the finite difference approximation for the derivative, but with ϵ_{reff} determined from a lossy SDA formulation. The final approach is the full-wave, lossy SDA formulation.

For relatively low-loss, $\tan\delta \ll 1$, all three methods agree very well, as would be expected. As the loss tangent increases, the results using the first method continue to increase linearly since the partial derivative in (2) is constant for a lossless structure. This method eventually fails because it does not take into account the change in ϵ'_{reff} due to high losses. The second method does account for the change in ϵ'_{reff} due to the change in the loss tangent by computing ϵ'_{reff} with the lossy SDA. This method has better agreement with the full-wave method, but it too eventually gives poor results for large loss tangents. In fact, for very large values of $\tan\delta$ this method predicts negative ϵ''_{reff} and hence negative α_d. Note that this method also takes much longer than simply computing the results with the lossy SDA and is only included to show the range of validity for (2) when the value of ϵ'_{reff} and the partial derivatives are computed accurately. Thus, while the second method fully accounts for changes in ϵ'_{reff} due to changing loss tangent, it also fails. This is because (2) was derived with the assumption that the space charge in the dielectric layer was zero, which is not valid for large loss tangents, or high conductivities.

Since (2) can be used for a wide variety of microwave circuit designs, its numerical efficiency is also an important consideration. In Fig. 3, the time used to compute the effective dielectric constant and dielectric loss coefficient are presented for three structures with multiple substrates as a function of the number of substrate layers that have loss. A single center conductor, open microstrip structure is used with $w = 0.6mm$. All computations were done on an IBM 3090 and the times in Fig. 3 are for computing 81 frequency values of ϵ'_{reff} and α_d for the microstrip structure using the same number of spectral components in the integration. The results for ϵ'_{reff} and α_d using (2) agree with the lossy SDA results to within the accuracy of the full-wave method for all values of frequency. Tables 1-3 summarize the substrate parameters used for Fig. 3.

If none of the substrate layers is lossy, then (2) is two to three times faster than the full-wave approach, as shown in Fig. 3. As the number of layers with loss increases, the computation time for the approximate formula increases linearly, since one additional partial derivative must be computed for each additional layer that is lossy. The full-wave method, on the other hand, requires very little additional effort to compute the complex propagation constant for additional lossy layers. Thus, the execution times of the full-wave method are fairly constant as the number of sub-

Table 1: Substrate parameters for 2 substrate case ($h_{L1} =$ 0.335 mm, $h_{L2} = 0.3$ mm, $\epsilon_{L1} = 2.2$, $\epsilon_{L2} = 9.7$).

# of lossy layers	$\tan\delta_{L1}$	$\tan\delta_{L2}$
0	0.0	0.0
1	0.0	0.0001
2	0.0001	0.0001

Table 2: Substrate parameters for 3 substrate case ($h_{L1} =$ 0.335 mm, $h_{L2} = 0.3$ mm, $h_{L3} = 0.3$ mm, $\epsilon_{L1} = 2.2$, $\epsilon_{L2} =$ 4.4, $\epsilon_{L3} = 9.7$).

# of lossy layers	$\tan\delta_{L1}$	$\tan\delta_{L2}$	$\tan\delta_{L3}$
0	0.0	0.0	0.0
1	0.0001	0.0	0.0
2	0.0001	0.0	0.0001
3	0.0001	0.0020	0.0001

Table 3: Substrate parameters for 4 substrate case (h_{L1} = 0.2 mm, h_{L2} = 0.2 mm, h_{L3} = 0.2 mm, h_{L4} = 0.2 mm, $\epsilon_{L1} = 2.2$, $\epsilon_{L2} = 4.4$, $\epsilon_{L3} = 9.7$, $\epsilon_{L4} = 6.8$).

# of lossy layers	$\tan\delta_{L1}$	$\tan\delta_{L2}$	$\tan\delta_{L3}$	$\tan\delta_{L4}$
0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0001
2	0.0	0.0	0.0002	0.0001
3	0.0	0.0001	0.0002	0.0001
4	0.0020	0.0001	0.0002	0.0001

strate layers with loss increases. However, for all cases, using (2) gives results that are just as accurate as the full-wave method, using less time. Using (2) with the lossless ϵ_{reff} gives accurate results as long as the presence of losses do not significantly affect the field structure, usually if $(\tan\delta_i)_{\max} < 0.1$. An additional benefit in using (2) instead of a lossy, full-wave method is that it can isolate the contribution of each dielectric layer to the loss coefficient.

Another advantage in using a full-wave lossless approach when computing ϵ_{reff} and the partial derivatives is that multi-layer, multi-conductor structures can be easily analyzed. In Figs. 4-6, the complex ϵ^*_{reff} for multi-layer, multi-conductor structures is shown for a variety of substrate and conductor configurations. In all of these figures, ϵ'_{reff} is computed using a lossless SDA formulation and ϵ''_{reff} is computed using (2) with a finite-difference approximation for the partial derivative and a lossless formulation for ϵ_{reff}. The computation times are for an IBM 3090 using the same number of spectral components for the lossy and lossless cases and computing 81 values of ϵ^*_{reff} for each mode. As was shown in Fig. 3, using (2) provides a significant advantage in speed over using a lossy, full-wave approach for low-loss structures.

In Fig. 4, the ϵ'_{reff} and ϵ''_{reff} of symmetric coupled microstrips on two substrates are plotted as a function of the ratio of the height of the lower substrate, h_{L1}, to the total height of the substrate, $h_{L1} + h_{L2}$. The lower substrate is RT/duroid 5880 ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$), the upper substrate is RT/duroid 6010.2 ($\epsilon_r = 9.8$, $\tan\delta = 0.0023$). The total substrate height is fixed at 0.635 mm (25 mils) and the frequency is set at 1 GHz. The height ratio is varied from 0, representing a single substrate with $\epsilon_r = 9.8$, to 1, representing a single substrate with $\epsilon_r = 2.2$. The maximum difference in the results for ϵ''_{reff} using the lossy SDA and (2) was only 0.17% for all three cases and all height ratios while the average disagreement between the two methods was 0.056%. The results for ϵ^*_{reff} for all three cases required 48.39 seconds using the lossy SDA and only 28.25 seconds using (2).

The characteristics of lossy, asymmetric coupled microstrips are shown in Fig. 5 for the c and π modes as a function of frequency. The upper substrate is RT/duroid 6010.2 with a height of 0.384 mm (15 mils) and the lower substrate is RT/duroid 5880, with a height of 0.254 mm (10 mils). The maximum disagreement between the lossy SDA and (2) for ϵ''_{reff} for both modes was 0.24% and the average disagreement was 0.046%. The time required to compute ϵ^*_{reff} for both modes was 39.06 seconds for the lossy SDA and only 23.91 seconds using (2).

The final example uses four symmetrically spaced conductors on two substrates with a dielectric cover layer. The results for ϵ''_{reff} for the four independent modes as a function of frequency are shown in Fig. 6. The relative signs of the currents on each of the four conductors is shown in the graph titles in Fig. 6 for each of the four modes. The maximum disagreement between the lossy SDA and (2) was 0.46% for all four modes and the average disagreement was 0.055%. The lossy SDA required 81.65 seconds to compute the ϵ^*_{reff} for all four modes while (2) used only 62.97 seconds.

CONCLUSION

The formula advanced by Schneider offers a quick and easy way to accurately compute the dielectric loss coefficient for multi-layer, multi-conductor structures with relatively low loss. This approach achieves accurate results up to three times faster than a comparable full-wave, lossy technique. Another advantage is that this technique can be used to compute the dielectric loss coefficient of all the modes in multi-layer, multi-conductor structures, also with significant savings in time.

REFERENCES

[1] T.-C. Mu, H. Ogawa, and T. Itoh, "Characteristics of multiconductor, asymmetric, slow-wave microstrip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 1471–1477, Dec. 1986.

[2] J. P. K. Gilb and C. A. Balanis, "Transient analysis of distortion and coupling in lossy coupled microstrips," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1894–1899, Dec. 1990.

[3] T. E. van Deventer, P. B. Katéhi, and A. C. Cangellaris, "High frequency conductor and dielectric losses in shielded microstrip," in *IEEE MTT-S Int. Microwave Symp. Dig.* (Long Beach, CA), 1989, pp. 919–922.

[4] T. Shibata and E. Sano, "Characterization of MIS structure coplanar transmission lines for investigation of signal propagation in integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 881–890, July 1990.

[5] M. V. Schneider, "Dielectric loss in integrated microwave circuits," *Bell Syst. Tech. J.*, vol. 48, pp. 2325–2332, Sept. 1969.

[6] J. P. K. Gilb and C. A. Balanis, "Asymmetric, multi-conductor, low-coupling structures for high-speed, high-density digital interconnects," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, pp. 2100–2106, Dec. 1991.

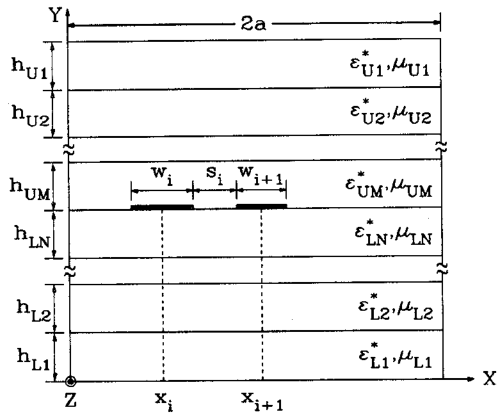

Figure 1: Geometry of an asymmetric multi-layer, multi-conductor interconnect.

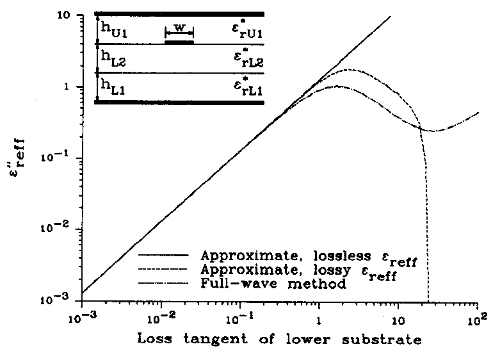

Figure 2: Imaginary part of ϵ^*_{reff} as a function of the loss tangent of the lower substrate, $\tan\delta_{L1}$ ($h_{L1} = 1.6$mm, $h_{L2} = 2.1$mm, $h_{U1} \rightarrow \infty$, $\epsilon_{r1} = \epsilon_{r2} = 8$, $\epsilon_{rU1} = 1.0$, $\tan\delta_{L2} = \tan\delta_{U1} = 0$, $w = 3$mm, $f = 1$GHz).

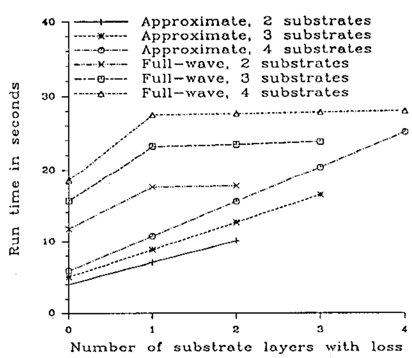

Figure 3: Computation times for various substrate configurations using equation (2) and the lossy SDA.

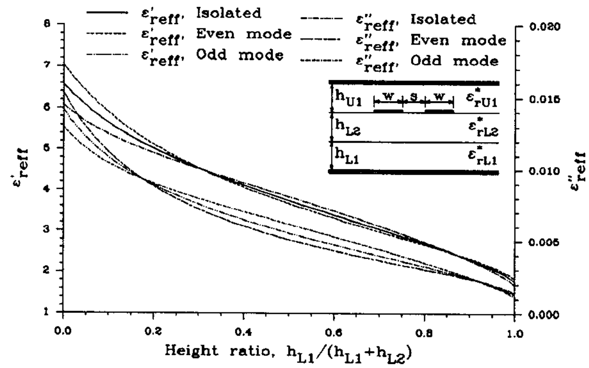

Figure 4: ϵ'_{reff} and ϵ''_{reff} for symmetric, coupled microstrips and a single, isolated microstrip with two substrates as a function of the substrate height ratio ($h_{L1}+h_{L2} = 0.635$mm, $h_{U1} \rightarrow \infty$, $\epsilon_{rL1} = 2.2$, $\epsilon_{rL2} = 9.8$, $\epsilon_{rU1} = 1.0$, $\tan\delta_{L1} = 0.0009$, $\tan\delta_{L2} = 0.0023$, $\tan\delta_{U1} = 0$, $w = 0.6$mm, $s = 1.2$mm, f = 1 GHz).

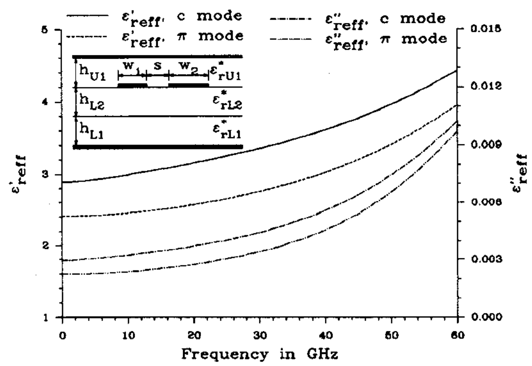

Figure 5: ϵ'_{reff} and ϵ''_{reff} of the c and π modes of asymmetric coupled microstrips with two-substrates as function of frequency ($h_{L1} = 0.381$mm, $h_{L2} = 0.254$mm, $h_{U1} \rightarrow \infty$, $\epsilon_{rL1} = 2.2$, $\epsilon_{rL2} = 9.8$, $\epsilon_{rU1} = 1.0$, $\tan\delta_{L1} = 0.0009$, $\tan\delta_{L2} = 0.0023$, $\tan\delta_{U1} = 0$, $w_1 = 0.6$mm, $w_2 = 1.2$mm, $s = 1.2$mm).

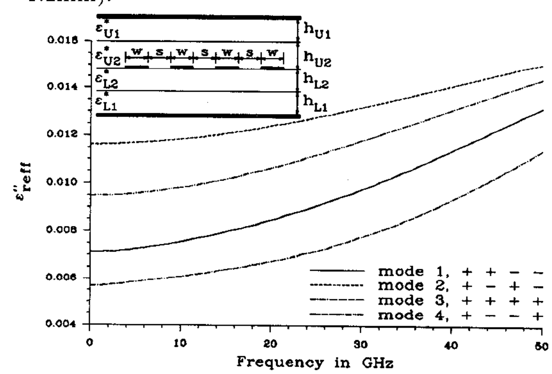

Figure 6: The modal ϵ''_{reff} for four, symmetric coupled microstrips with two substrates and a dielectric cover as a function of frequency. ($h_{L1} = 0.381$mm, $h_{L2} = 0.254$mm, $h_{U2} = 0.254$mm, $h_{U1} \rightarrow \infty$, $\epsilon_{rL1} = 2.2$, $\epsilon_{rL2} = 9.8$, $\epsilon_{rU2} = 6.0$, $\epsilon_{rU1} = 1.0$, $\tan\delta_{L1} = 0.0009$, $\tan\delta_{L2} = 0.0023$, $\tan\delta_{U2} = 0.0019$, $\tan\delta_{U1} = 0$, $w = 0.6$mm, $s = 0.6$mm).