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TRANSIENT ANALYSIS OF DISTORTION AND COUPLING IN LOSSY COUPLED MICROSTRIPS*

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ABSTRACT

The transient response of lossy coupled microstrips is studied using the Spectral Domain Approach (SDA) to rigorously compute the dielectric losses. Transient coupling is formulated in the frequency domain using an even/odd mode approach. Results for pulse distortion on a semiconducting substrate are presented showing how losses reduce the signal amplitude without significantly distorting the shape.

INTRODUCTION

Since many MMIC circuits are realized on semiconducting substrates, which are inherently lossy, it is essential to be able to characterize the effects of the dielectric losses on transient signals. An accurate and versatile closed form expression for the dielectric losses was derived by Schneider [1], and it is the most widely used approximation for the dielectric attenuation constant. Although this method can be used for multi-layer structures, it is based on a TEM assumption and requires closed form expressions for the partial derivative of the effective dielectric constant with respect to the dielectric constants of each of the layers. Dielectric losses have also been considered using full-wave soultions for multi-layer, multi-conductor microstrip structures [2,3,4]. Transient analysis of lossy microstrips has been done for single microstrips using approximate formulas for the attenuation constant [5]. Transient signal distortion on lossless, coupled microstrip lines has also been presented, [6] showing how differences in the modal propagation constants cause additional distortion and coupling. Although some attention has been focused on the steady state effects of losses and the transient response of single transmission lines, a rigorous analysis of transient signals on lossy, coupled microstrips has not been accomplished.

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This paper uses a variation of the Spectral Domain Approach (SDA) [6] along with a complex permittivity to accurately characterize the frequency dependent complex propagation constant of lossy, coupled microstrips over a wide range of frequencies. The transient response of the coupled lines is derived using the even/odd mode formulation and equations are presented showing how differences in the modal attenuation constants can degrade the signal and cause a spurious response on the adjacent line. Using this formulation along with data from the SDA, resuslts for pulse distortion on single and coupled lossy microstrips are given.

THEORY

The geometry of a general, multi-layer, multi-conductor microstrip structure is shown in Fig. 1. The structure is surrounded on all four sides by perfect electric conductors at $x = \pm a$, $y = 0$ and $y = h_{L1} + h_{L2} + \ldots + h_{U2} + h_{U1}$. If an open structure is to be considered, then $a \rightarrow \infty$ and $h_{U1} \rightarrow \infty$. For a covered microstrip without sidewalls, then $a \rightarrow \infty$ with h_{U1} remaining finite.

For any planar structure, e.g. microstrip, slot-line, or coplanar waveguide, the tangential electric fields on the center conductor interface can be expressed as [7]

$$\tilde{E}_z = \frac{j}{\omega\epsilon_0}\left[\tilde{J}_z\,\tilde{G}_{zz} + \tilde{J}_x\,\tilde{G}_{xz}\right] \quad (1)$$

$$\tilde{E}_x = \frac{j}{\omega\epsilon_0}\left[\tilde{J}_z\,\tilde{G}_{zx} + \tilde{J}_x\,\tilde{G}_{xz}\right] \quad (2)$$

where $\tilde{G}_{xx}$, $\tilde{G}_{xz}$, and $\tilde{G}_{zz}$ are the dyadic Green's functions of the structure which can be determined using a recurrence relation [6], and are functions of frequency and the material parameters of the dielectric layers.

To consider lossy structures, a complex permittivity is defined for the i^{th} dielectric layer as:

$$\epsilon = \epsilon_i' + j\epsilon_i'' = \epsilon_i' - j\frac{\sigma_i}{\omega} \quad (3)$$

and

$$\tan\delta_i = \frac{\epsilon_i''}{\epsilon_i'} = \frac{\sigma_i}{\epsilon_i'\omega} \quad (4)$$

Using this permitivity, the intrinsic wavenumbers of the lossy dielectric layers, $\gamma_i = \omega\sqrt{\mu_i\epsilon_i}$, become complex, as do the z and y directed propagation constants, γ_z and γ_{yi}. However, it can be shown that for any planar dielectric structure, the x directed wavenumber, β_x, is real and so the use of the Fourier transform with the SDA in the x direction is justified. Thus the dyadic Green's functions in (1,2) become complex for lossy media. When Galerkin's method is applied to (1,2) and the determinant is set to zero, the result is two equations; the real and imaginary parts, which can be solved numerically for the two unknowns; the real (α_z) and imaginary (β_z) parts of the complex propagation constant (γ_z).

To compute the degradation of a transient signal due to dispersion, attenuation, and modal coupling, a Fourier transform approach with an even/odd mode formulation is used. If the complex propagation constants for the even and odd modes are given by

$$\gamma_{ze} = \alpha_{ze} + j\beta_{ze} \quad \text{(even mode)} \quad (5)$$

$$\gamma_{zo} = \alpha_{zo} + j\beta_{zo} \quad \text{(odd mode)} \quad (6)$$

then the voltage response at a position z and at a time t to an input signal whose Fourier transform is $\tilde{V}(\omega, z)$ can be expressed as

$$v_1(t,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{V}(\omega,z)e^{j\omega t-\gamma_{zav}z}\cosh\left[\Delta\gamma_z z\right]\,d\omega \quad (7)$$

$$v_2(t,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{V}(\omega,z)e^{j\omega t-\gamma_{zav}z}\sinh\left[\Delta\gamma_z z\right]\,d\omega \quad (8)$$

where

$$\Delta\gamma_z = \frac{\gamma_{zo} - \gamma_{ze}}{2} \quad (9)$$

$$\gamma_{zav} = \frac{\gamma_{zo} + \gamma_{ze}}{2} \quad (10)$$

Since the complex propagation constants for the even and odd mode, are not always the same for all frequencies, then $\Delta\gamma_z$ is non-zero and so the integrand in (8) is also non-zero, producing a spurious response on the adjacent line. Even if the phase constants of the two modes are equal, differences in the modal attenuation constants will create a signal on line 2. Thus the attenuation constants of the even and odd modes degrade the intended signal as well as creating an extra response on the adjacent line.

RESULTS

To illustrate how this method is used to compute the transient response of lossy, coupled microstrip lines, a single substrate, open structure is considered. A GaAs substrate ($\epsilon_r = 12.2$) that is 25 mils thick is chosen along with a center conductor width of 0.5 mm, representing a 50 Ω line. The effective dielectric constant of the even and odd modes for a spacing of 1.0 mm is shown in Fig. 2 along with the corresponding values for a single isolated microstrip over a wide frequency range. Even though the substrate is lossy, the effective dielectric constant is essentially unchanged since the losses are relatively small. The dielectric attenuation constant, α_d, for the same structure is shown in Fig. 3 as a function of the substrate conductivity at a frequency of 1 GHz. As the conductivity increases, the attenuation constant increases almost linearly. However, at higher conductivities, α_d does not increase as rapidly with increasing conductivity. Also, α_d is relatively constant with frequency, increasing slightly as the frequency increases.

Using these results, the transient response of both isolated and coupled lines on this structures can be computed. A Gaussian pulse is chosen, with a half width, half maximum of $\tau = 15$ picoseconds. In Fig. 4, the response at a distance $\ell = 40$ mm for a single isolated line is graphed for different values of the conductivity and the undistorted pulse is included for comparison. This graph includes only the effects of dispersion and losses on the propagation of the signal. The signal shape is distorted due to the effects of dispersion, while losses attenuate the signal without significantly distorting its shape.

If another microstrip conductor is placed adjacent to the original, then there will be additional distortion of the signal due to transient coupling. The time domain responses of the signal line (the line with the impressed signal) and the sense line (the line adjacent) are shown in Figs. 5 and 6 along with the geometry of the structure. At $\ell = 40$ mm, the signal line response, shown in Fig. 5, has been severely degraded in amplitude and the pulse has widened due to the even/odd mode coupling. As the conductivity of the substrate is increased, the signal line response is further decreased in amplitude, although the shape is not significantly distorted.

The sense line response is shown in Fig. 6 and it indicates the level of cross-talk between the lines. At this distance, the response on the sense line is very high, again due to the large difference in the even and odd mode effective dielectric constants. Also, like the isolated case and the signal line response, the presence of losses attenuates the signal without noticeably altering its shape.

CONCLUSIONS

Using a rigorous formulation for the dielectric losses, pulse distortion was studied for isolated and coupled microstrip lines on a semiconducting substrate. As expected, the addition of losses reduced the amplitude of the resulting signal. However, the shape of the pulse was not significantly modified since the dielectric attenuation constant was relatively constant with respect to frequency for this structure. In addition, distortion due to even/odd mode coupling was the dominant distortion mechanism, while coupling due to differences in the modal attenuation constants had a secondary effect.

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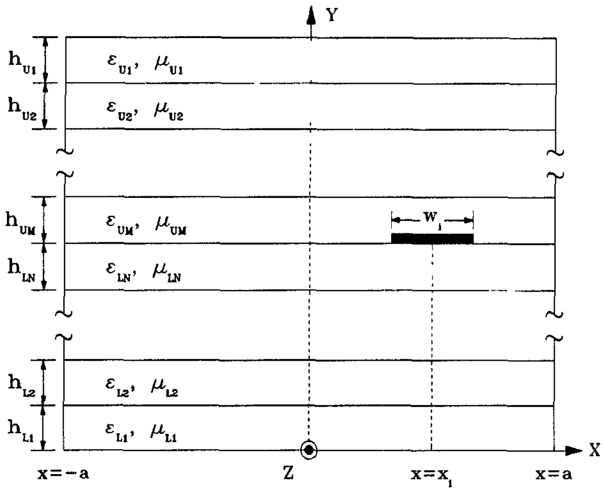

Figure 1: Geometry of multilayer microstrip structure.

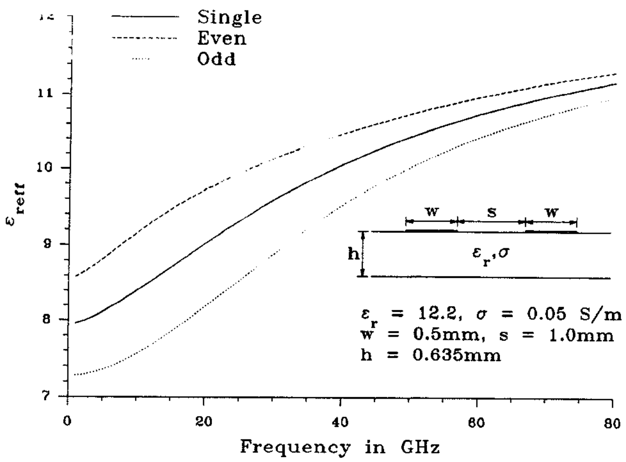

Figure 2: Effective dielectric constant vs. frequency for lossy coupled microstrips.

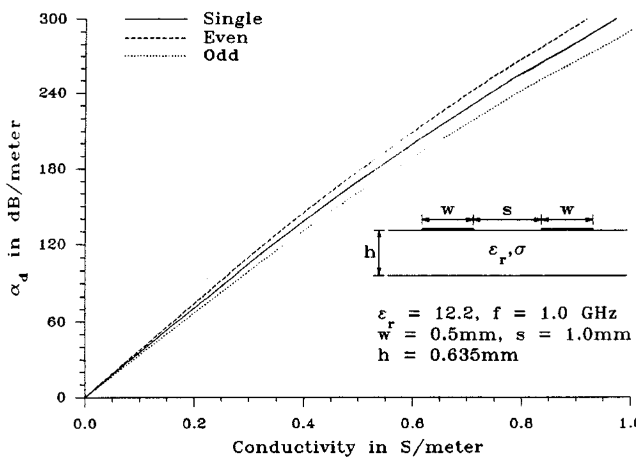

Figure 3: Attenuation constant vs. conductivity for lossy coupled microstrips.

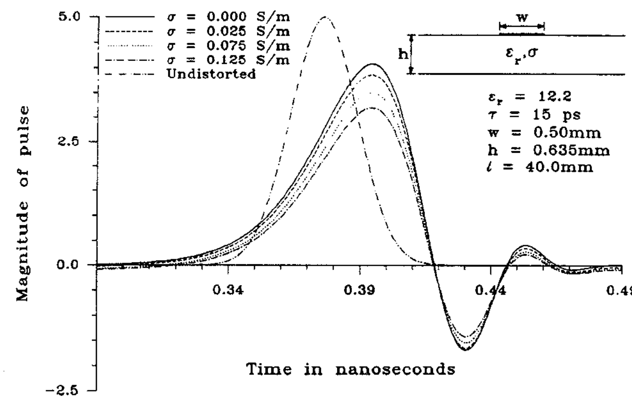

Figure 4: Pulse distortion on isloated, lossy microstrip line.

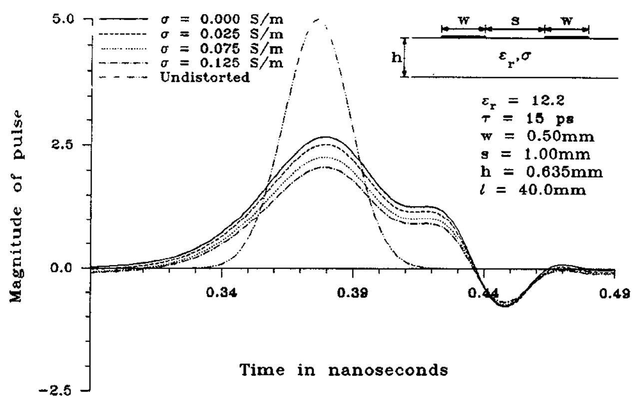

Figure 5: Pulse distrortion on coupled, lossy microstrip lines, signal line response.

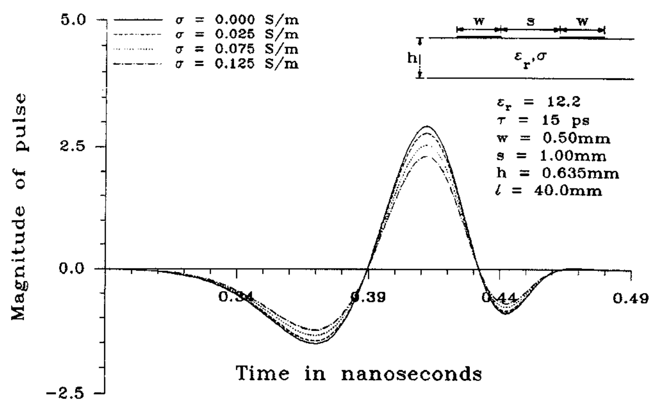

Figure 6: Pulse distortion on coupled, lossy microstrip lines, sense line response.