ANALYSIS OF VLSI INTERCONNECT STRUCTURES

Lawrence Carin[†], Qiang Xu[†], Kevin J. Webb[†], and Joseph A. McClintock[††]

[†]Electrical Engineering Department
University of Maryland
College Park, MD 20742

[††]Martin Marietta Laboratories
Baltimore, MD 21227

ABSTRACT

Theoretical and experimental results are presented for coupled microstrip structures typically used in VLSI, microwave, and millimeter-wave circuits. Full-wave data for pulse and time harmonic propagation is presented. Results from this work can be used in establishing design criteria for high-speed digital circuits.

I. INTRODUCTION

A typical VLSI circuit contains a large number of devices with planar metallic interconnects between them. Frequently these interconnects are in the form of microstrip, analogous to what might be used in a millimeter-wave or microwave integrated circuit. When designing VLSI circuits with particular signal rise-times, it is necessary to consider such parameters as line spacing, line lengths, device terminations, step changes in strip width, bends, and feed-throughs. In a typical CAD scheme, criteria for such design parameters would be in the form of empirical relations or look-up tables. The circuit designer can then consult these, or be alerted when these criteria have been violated.

For the rise-times currently being considered for VLSI circuits, a full-wave analysis of the interconnect problem is desirable. To study the device interconnect problem as a function of time, the digital signals are decomposed into the superposition of a discrete series of spectral components. The signal propagation can then be expressed approximately as a superposition of the solutions at particular frequencies. Microwave techniques can be utilized to find these time harmonic solutions.

A number of papers have given details of a two-dimensional full-wave solution, assuming zero conductor thickness [1]. This approach uses a spectral domain formulation (Fourier Transform with respect to the transverse spatial variable in the plane of the strip) with a Moment Method solution. Some theoretical studies of the time harmonic coupling and termination problem have been made for two terminated strips [2] and five infinite strips [3].

Multiple line terminated (with a device model, 50 Ω, or short) and unterminated (matched load) problems are studied. Theoretical and experimental frequency and time domain data for the two-line problem are presented which include effects of device terminations. These results clearly illustrate the time and spatial coupling phenomena for typical VLSI geometries.

II. RESULTS

The dispersive interconnect problem can be studied at discrete frequencies. With appropriate weighting coefficients, various pulse shapes can be reconstructed as a function of time and position on the excited and coupled lines. Consider the suspended two-line microstrip geometry, shown in Fig. 1, with appropriate dimensional parameters. When $l_1 = 0$, the microstrip geometry results. Waveguides of this form can be formulated in the spectral domain, which involves using a Fourier series representation of all field quantities in the transverse direction, parallel to the metallization (i.e. the x-direction) [1]. Galerkin's method, where the testing and basis functions are the same, may be used to obtain a satisfactory numerical solution. The strip currents can be expressed in terms of suitable basis functions, such as trigonometric functions modified by the edge condition.

Neglecting higher order modes, for N strips there are N normal propagating modes. The modes are found using the spectral domain Moment Method. The mode coefficients can be found subject to particular boundary conditions, for example current or impedance conditions, at specific z values. After the mode amplitudes are determined, coupling phenomena for both terminated and infinite strip geometries can be studied. When the dominant modes only are considered, the N coupled lines can be studied as a $2N$-port system [4]. The relationship between the port voltages and currents can be expressed in terms of an impedance matrix. For the symmetric two-line system shown in Fig. 1, there are four distinct z-parameters.

The two strip microstrip geometry ($l_1 = 0$) can be used to illustrate some interesting coupling and dispersive phenomena. The transmission line model for the two line problem with arbitrary terminations is shown in Fig. 2. The voltage and current on the two lines are expressed as

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$$v_1(z) = A_1 e^{-\gamma_e z} + A_2 e^{\gamma_e z} + A_3 e^{-\gamma_o z} + A_4 e^{\gamma_o z}$$
$$v_2(z) = A_1 e^{-\gamma_e z} + A_2 e^{\gamma_e z} - A_3 e^{-\gamma_o z} - A_4 e^{\gamma_o z}$$
$$i_1(z) = A_1 Y_e e^{-\gamma_e z} - A_2 Y_e e^{\gamma_e z} + A_3 Y_o e^{-\gamma_o z} - A_4 Y_o e^{\gamma_o z}$$
$$i_2(z) = A_1 Y_e e^{-\gamma_e z} - A_2 Y_e e^{\gamma_e z} - A_3 Y_o e^{-\gamma_o z} + A_4 Y_o e^{\gamma_o z}$$

where γ_e and γ_o are the even and odd propagation constants and Y_e and Y_o are the even and odd admittances, respectively. The time dependance, $e^{j\omega t}$, has been suppressed. The coefficients A_1, A_2, A_3, and A_4 are solved for by imposing the boundary conditions at the four ports. A suitable definition for the characteristic impedance of a line in a multi-line configuration is given in [2].

Consider first the infinite or matched line problem. A pulse at $z = 0$ can be reconstructed approximately from a finite set of spectral components, as shown in Fig. 3(a). The pulse has a 0.2 ns risetime. We can then study the dispersive and coupling effects as this pulse propagates down the microstrip line, using the full-wave techniques outlined. Figures 3(b)-(e) show the current pulse on the driven and coupled lines at a series of distances down the line. The geometry selected for this example has $w = 0.254$ mm, $s = 0.102$ mm, $\epsilon_r = 2.2$, and $d = 0.102$ mm. The top and side walls are chosen to be at a sufficient distance so as to have negligible effect on the guided modes ($2b = 4.0$ mm, $l_2 = 3.898$ mm). Significant coupling is shown at distances of 5, 10, 15, and 20 inches. The coupling phenomena is as expected for the rise and fall edges of the pulse. The pulses were constructed using frequency components up to 6 GHz. At these frequencies the odd and even mode propagation constants, calculated using the spectral domain technique, are approximately linear with frequency. Therefore, the small dispersion witnessed in the pulses is due to the fact that the odd and even modes propagate at different velocities, not from dispersion in the odd or even mode seperately. As pulse rise-times are reduced, it will become necessary to include frequency components into the millimeter-wave regime. The dispersive nature inherent in the odd and even modes will therefore become significant and the dispersion observed on coupled lines will subsequently increase.

Consider now the two-line problem with arbitrary impedance terminations. This model can be used to illustrate a typical circuit configuration where the lines are terminated in devices, such as CMOS gates. The problem is studied in the frequency domain. A CMOS model with appropriate component values is shown in Fig. 4. From the infinite line analysis for $w = 0.254$ mm and $s = 0.102$ mm, a length of 6 cm results in a coupled line signal which is greater than $26dB$ down at 1 GHz. It is illustrative to use this length in a terminated problem to show resultant coupling effects. In the two-line system, Port 1 is driven as shown in Fig. 2 , $Z_1 = Z_3 = Z_d$(driver), and $Z_2 = Z_4 = Z_r$(receiver). The currents as a function of position on the line are shown in Fig. 5, with line lengths of 6 cm. The end-points of the plots ($z/l = 0, 1$) correspond to the ports.

Coupled microstrip measurements were performed using an HP8510 Network Analyzer. The geometry used had $w = 0.010$ in, $s = 0.012$ in, $d = 0.004$ in, $\epsilon_r = 4.0$ (G-10 epoxy), and a line length of 16 in. The measured data after, appropriate normalization, is compared with the theory in Fig. 6. Results for S_{31} as a function of frequency with $Z_1 = Z_3 = Z_4 = 50\Omega$, and $Z_2 = 0$ are given in Fig. 6(a). Figure 6(b) gives S_{41} with $Z_1 = Z_2 = Z_4 = 50\Omega$ and $Z_3 = 0$. The comparison of experiment and theory supports the theoretical model. The theory can be extended to incorporate conductor loss effects using perturbational techniques.

III. CONCLUSION

Time domain and frequency domain data has been presented for VLSI interconnect networks using a full-wave analysis. These results clearly show the effects of terminations and line geometries on the interline coupling. The theory compares well with experiment. The results of this work can be used in the design of high performance circuits, where the accurate knowledge of these coupling and termination effects are essential.

IV. REFERENCES

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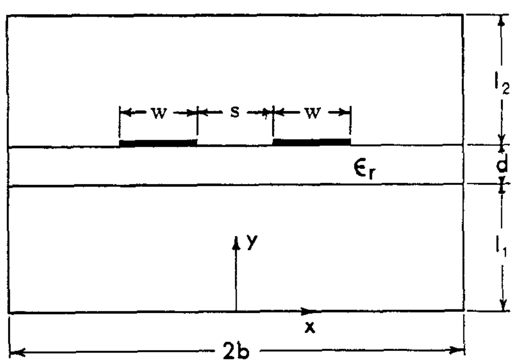

Figure 1. Shielded suspended microstrip with two strips.

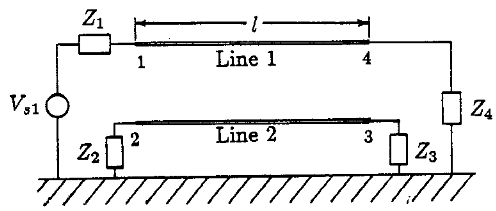

Figure 2. Equivalent circuit for determining line/port voltages and currents.

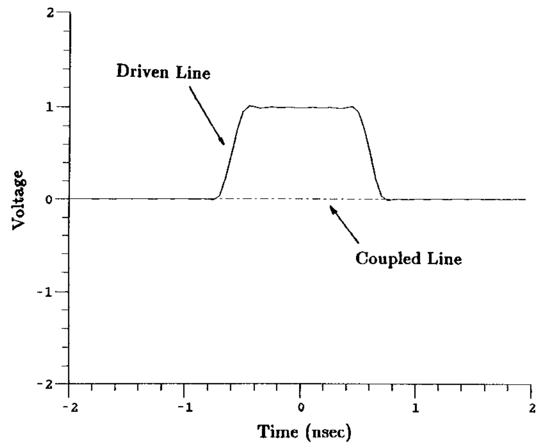

Figure 3(a). Current pulse at $z = 0$. Parameters used: $w = 0.254$ mm, $s = 0.102$ mm, $\epsilon_r = 2.2$, $d = 0.102$ mm.

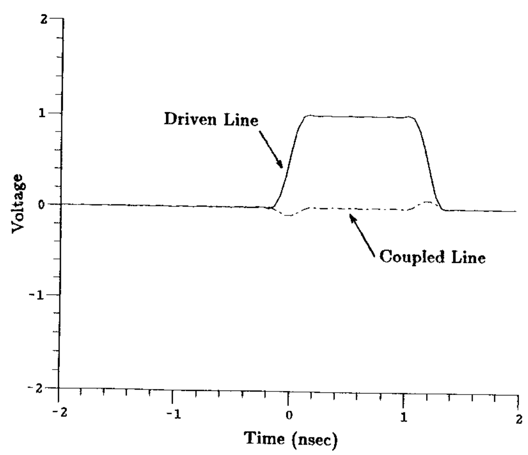

Figure 3(b). Driven and coupled line current pulses after propagating 5 inches.

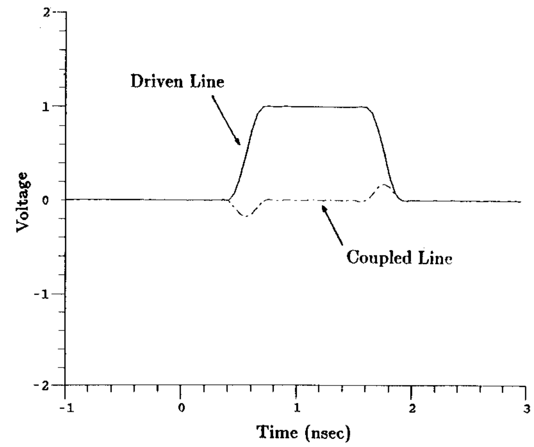

Figure 3(c). Driven and coupled line current pulses after propagating 10 inches.

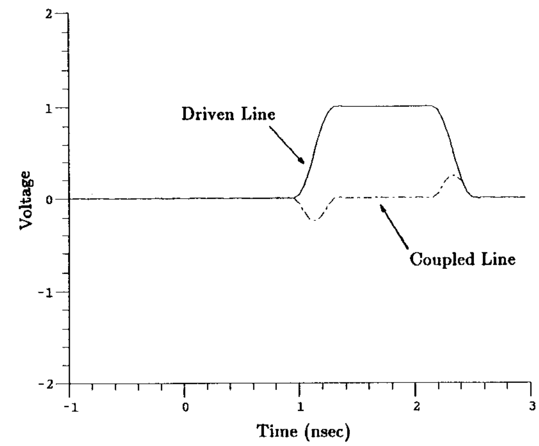

Figure 3(d). Driven and coupled line current pulses after propagating 15 inches.

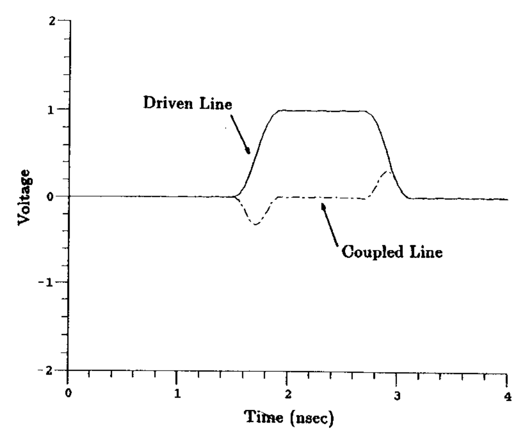

Figure 3(e). Driven and coupled line current pulses after propagating 20 inches.

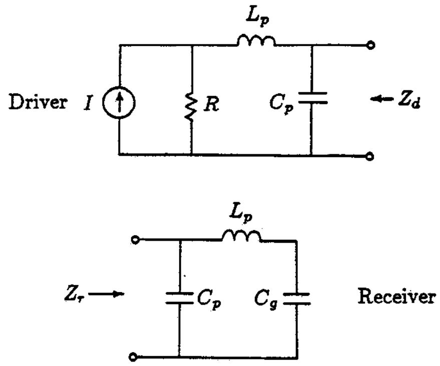

Figure 4. CMOS device input and output impedance models. C_p=3 pF, L_p=6nH, C_g=3 pF, R=20 Ω.

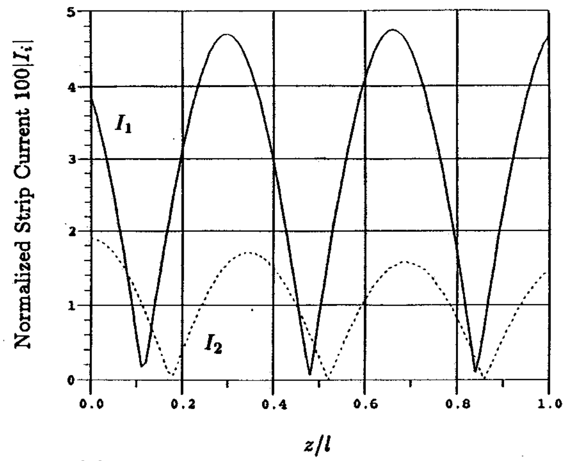

Figure 5(c). Normalized terminated line currents as a function of z with f=5 GHz.

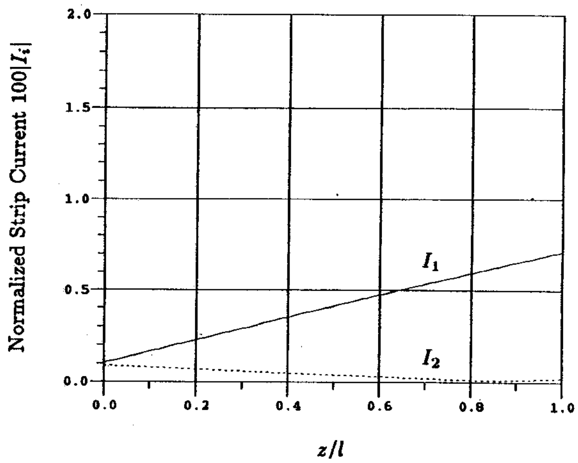

Figure 5(a). Normalized terminated line currents as a function of z with f=200 MHz. Parameters: V_{s1}=1 V, line length l=0.2 λ_0 at 1 GHz (6 cm), $Z_1 = Z_2 = Z_d$, $Z_3 = Z_4 = Z_r$, w=0.01 in, s=0.004 in, ϵ_r=2.2.

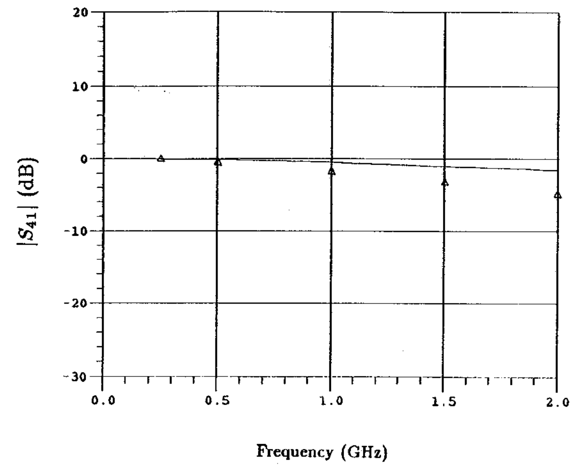

Figure 6(a). Theoretical and experimental $|S_{41}|$ data for the two-line microstrip geometry. The solid curve is the theory and the points are experimental results. Parameters: 16 inch line length, w = 0.010 in, s = 0.012 in, ϵ_r = 4, d = 0.004 in.

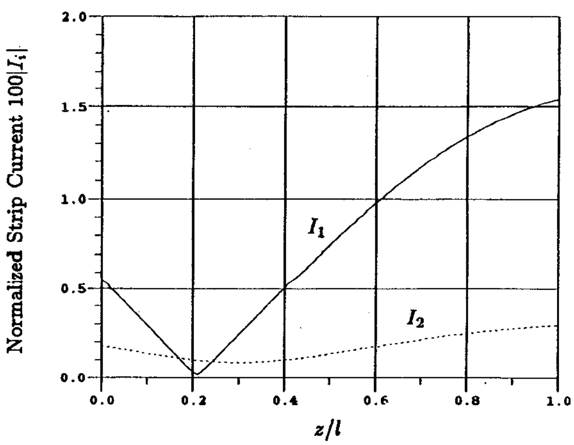

Figure 5(b). Normalized terminated line currents as a function of z with f=1 GHz.

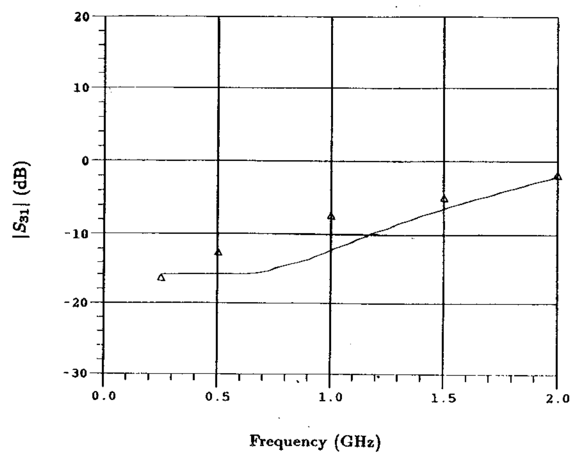

Figure 6(b). Theoretical and experimental $|S_{31}|$ data for the two-line microstrip geometry.