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Measurement of Laddering Wave in Lossy Serpentine Delay Line

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Abstract: The clock signals are required integrity over the system, it is desirable that all clock signals are distributed with a uniform delay. The backward crosstalk among the sections of a serpentine delay line accumulates to appear as a laddering wave in the receiving waveform. This occurrence results in severe signal distortion. The lossy effect of thin-film serpentine delay line has been investigated with both simulation and experiment approaches. The test microstrip serpentine line was made on silicon substrate; the TDT measurement results have been verified with those obtained by the SPICE simulation. Due to the effect of the resistive line, the laddering waves in lossy serpentine were depressed.

Keywords: *lossy delay line; crosstalk; serpentine.*

Introduction

The number of applications of integrated circuits in high-performance computing, telecommunications, and consumer electronics has been rising steadily. The logic complexity per chip has been increasing exponentially. The monolithic integration of a large number of functions on a single chip usually provides:

1. Less area and volume
2. Less power consumption
3. Higher reliability
4. Higher speed

The stability of clock signals is highly important for high speed system. Clock signals should have minimum rise and fall times, specified duty cycles, and zero skew. In reality, clock signals have nonzero skews and noticeable rise and fall times; duty cycles can also vary. In fact, as much as 10% of a machine cycle time is expended to allow realistic clock skews in large computer systems [1]. Since clock signals are required almost uniformly over the system, it is desirable that all clock signals are distributed with a uniform delay.

Consequently, there is the needs of equal interconnect lengths to distribute clock signals with minimal skews. Several approaches have been proposed to minimize the clock skew. The most famous one is the H-tree method. The delay line is usually introduced to minimize the clock skew. The serpentine delay line shown in Figure 1 is a typical design, which consists of numbers of transmission line sections closely packed to each other [2].

Intuitively, the total time delay should be proportional to the total length of the delay line. However, the crosstalk may cause a drastic deterioration of the total time delay [3].

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Recently, thin-film module with small device dimension is utilized for high density interconnects. It is thus essential in this lossy delay line design to predict the penalty of the delay time incurred by the crosstalk between these closely packed transmission line sections.

2. Qualitative Description

Crosstalk problems are usually encountered in circuit boards and modules due to electromagnetic coupling between parallel transmission lines. An illustrative model has been proposed to qualitatively describe the physical mechanism [4]. Consider the simplest case of two parallel transmission lines. A ramp pulse of risetime t_r, *u*nder the assumption of weak coupling. Let τ be the per-unit-length propagation delay and l be the length of the transmission line. The crosstalk at the near and far ends can be written as

$$V_{NE}(t) = K_{NE} \bullet [V_A(t) - V_A(t - 2t_d)]$$

$$V_{FE}(t) = K_{FE} \bullet t_d \bullet \frac{d}{dt}[V_A(t - t_d)] \quad (1)$$

where $t_d = \tau \cdot l$, $V_A(t)$ is the voltage at the sending end of the active line, the proportional constants are

$$K_{NE} = \frac{1}{4}(k_C + k_L) = \frac{1}{4}\left(\frac{|C_{12}|}{C_{22}} + \frac{L_{12}}{L_{11}}\right)$$

$$K_{FE} = \frac{1}{2}(k_C - k_L) = \frac{1}{2}\left(\frac{|C_{12}|}{C_{22}} - \frac{L_{12}}{L_{11}}\right) \quad (2)$$

where C_{12} is mutual capacitance between the lines, C_{22} is self capacitance of the line and L_{12} is mutual inductance between the lines, L_{22} is the self inductance of the line. k_C and k_L are the capacitive and inductive coupling coefficients between the lines.

When the risetime t_r, is smaller than the round-trip time $2\ t_d$, the near end crosstalk will reach a saturated value of $V_{NEN} = K_{NE} \cdot V_A$. If $2\ t_d$ is smaller than t_r, the maximum value of the near end crosstalk will reduce proportionally. The crosstalk at the far end is of a much narrower width as compared with the near end crosstalk. Its maximum value is inversely proportional to the risetime and increases as the transmission lines become longer.

Consider the serpentine delay line shown in Figure 1, which consists of six parallel transmission line sections. All the sections have the same width to maintain the characteristic impedance. When the signal propagates along a certain section of the delay line, it will induce crosstalk in all other sections. If the risetime is smaller than the round-trip time 2 t_d. The signal reaches the receiver at $t = 6\ t_d$. *T*he crosstalk arriving the receiver at different time periods (at $t = 2n \cdot t_d$, where n is an integer) is of the same trapezoidal shape. Consequently, the whole waveform behaves like going “upstairs” and thus is named a “laddering wave.” For a serpentine delay line consisting of *2N* sections, the laddering wave before the main signal arrives will include N ladders. The highest level of the laddering wave before the arrival of the main signal is 2N-1 times the value of the near end crosstalk between two adjacent transmission lines [5].

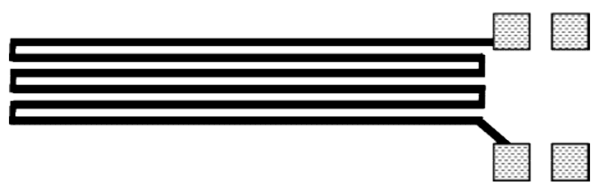

Figure 1. Schematic diagram of serpentine delay line

3. Simulation and Measurement

Let $V(z,t)$ and $I(z,t)$ denote the vectors of the voltages and currents along the transmission lines, respectively. They satisfy the telegraphists’ equations

$$\frac{\partial}{\partial z}V(z,t) = -[L]\frac{\partial}{\partial t}I(z,t)$$
$$\frac{\partial}{\partial z}I(z,t) = -[C]\frac{\partial}{\partial t}V(z,t) \quad (3)$$

where $[L]$ and $[C]$ are the inductance and capacitance matrices, respectively. By a suitable change of basis, the line voltages and currents can be transformed to the modal voltages V_d (z,t) and currents I_d (z,t) [6]. All the modes propagate independently to each other and the propagation delay τ are different for different modes.

Due to the small cross section of line and finite conductivity of the metallization, the thin-film line sections have notable resistance. Assume that the resistance matrix of the coupled transmission lines is diagonal and that each transmission line section has a total resistance of r. To simplify the analysis, the lossy transmission lines are modeled as lossless transmission lines with both ends cascading lumped resistance of $r/2$.

The coupled transmission lines can be decomposed into the superposition of the modes, each of which propagates independently and can be modeled as a single ideal transmission line by PSPICE [7]. The transformation from the modal voltages and currents back to the line voltages and currents can be fulfilled in terms of the voltage controlled voltage sources (VCVS) and the current controlled current sources (CCCS) [8]. Consider the six-section serpentine delay line in Figure 1 having the cross section shown in Figure 2. The driver and load resistances are chosen $R_S = R_L = 50\,\Omega$ while the risetime of the source $V_S(t)$ is 150 ps. The line resistance per unit length of each microstrip line is $r/l = 1.184\,\Omega$/cm. The capacitance and inductance matrices can be computed once the geometries of the lines and the substrate are given [9].

The six coupled transmission lines can be modeled as a PSPICE subcircuit, which consists of six single transmission lines, twelve VCVS's, and twelve CCCS's. Once a subcircuit models the coupled transmission lines, the complete circuit can be simulated by including the driver and receiver resistances and defining the nodal connections at both the near and far ends. Figure 3 shows the simulated waveform at the receiving end for the case with section length l = 3.8 cm. The laddering wave in the receiving waveform behaves like the qualitative descriptions in section 2. The ripple near the jump due to different modal propagation speeds is small and negligible. Although the delay line has six sections, the receiving waveform reaches about 0.065V after four delay units. The value is not greater than the receiver threshold level. Hence, the crosstalk does not result in delay penalty in this case.

Figure 2. Cross section of the six-section lossy serpentine delay line. (line width: 20μ*m*, line spacing: 20μ*m*, line thickness: 3μ*m*, dielectric thickness : 8μ*m*/ε_r=3.4)

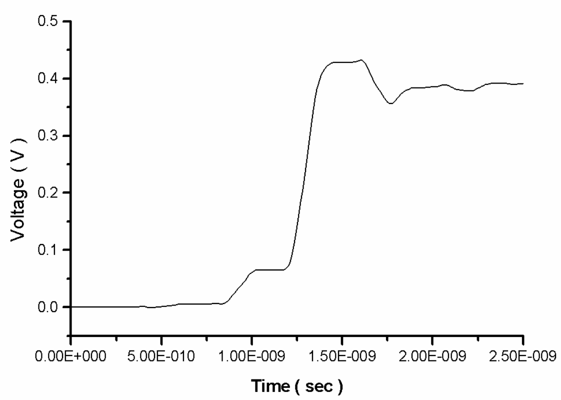

Figure 3. Simulation waveform of the serpentine delay line

A test vehicle has been fabricated with

thin-film technology on silicon wafer. The microstrip conductor is made by aluminum, constructed on a dielectric supporting layer above ground plane. The measurement of transit signal is done by the time domain reflectometer TEK-CSA803 with 50 Ω Cascade micro-probe.

There are ground pads near the signal pad to reduce the additional inductance during measurement. After the calibration process, a pulse of 1 volt (t_r = 150ps) was sent through signal pad, both TDR (time domain reflection) and TDT (time domain transmission) signal were measured.

Figure 4 shows the measured receiving waveforms for the cases of l = 3.8cm. The measured waveforms are quite similar to the simulated one shown in Figure 3. However, the measured ladder levels are slightly smoother than the simulated one. This discrepancy may be attributed to the neglect of the additional resistance due to the skin effect and the equivalent capacitance near the corners of the transmission lines. Both factors will slow down the leading edge of the signal. The results obtained by simulation and measurement show significant signal distortion in the rising edge.

For a serpentine delay line consisting of *2N* sections, the laddering wave before the main signal arrives will include N ladders. The highest level of the laddering wave before the arrival of the main signal should be 2N-1 times the value of the near end crosstalk between two adjacent transmission lines. But the results obtained by simulation and measurement of the lossy line, the highest level of the laddering wave was less then 2N-1 times the value. While the signal transmitted through the sections of the serpentine delay line, the resistive effect caused the transmitted signals degraded. Due to this effect of the resistive line, the laddering waves of serpentine were depressed. Consequently, lossy serpentine has less delay penalty than that of lossless line.

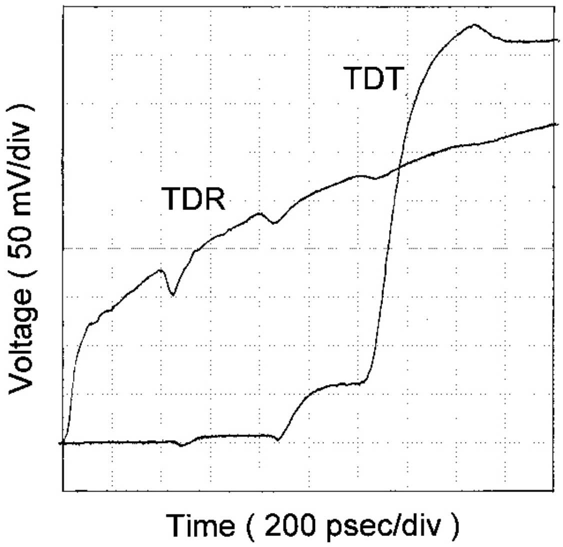

Figure 4. Measured waveforms of the lossy serpentine delay line

By performing the time domain simulation for different resistance value of transmission line section in serpentine line, we can observe the receiving signals with different line resistance. The levels of the three major ladders at the receiving end are shown in Figure 5. The t_d number indicates the receiving voltage at specific delay unit. As can be indicated on the figure, the ladder level is inversely proportional to the resistance of the transmission line section.

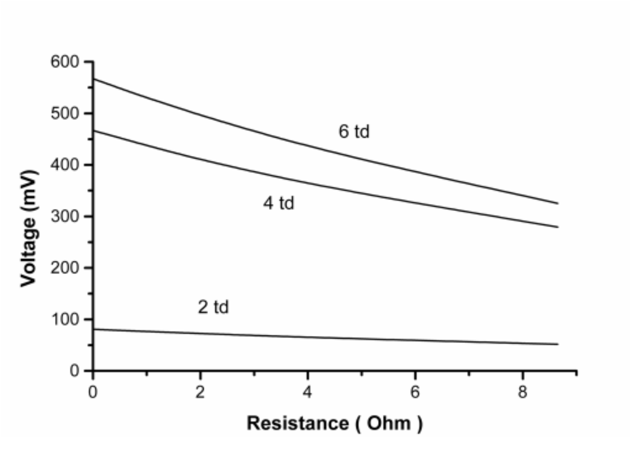

Figure 5. The relation of the ladder height of receiving signal vs line section resistance

4 Conclusion

The backward crosstalk among the sections of the lossy serpentine delay line accumulates in phase and appears as a laddering wave in the receiving waveform. The magnitude of the laddering wave is mainly dependent on the number of the sections and the coupling coefficients between adjacent sections. Measurement and simulation of signal distortion in lossy serpentine line have been performed. The laddering wave results in notable signal distortion. If the magnitude grows up to threshold level before the arrival of the main signal, it will cause delay penalty.

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