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Analysis of Laddering Wave in Double Layer Serpentine Delay Line

Fang-Lin Chao*

Chaoyang University of Technology
Taichung, Taiwan 413, Republic of China

Abstract: 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 and timing skew of the clock signal. The layout of double layer serpentine delay line can reduced crosstalk between lines. The waveform of double layer serpentine delay line has been investigated with simulation approach. The results obtained by the SPICE simulation shown that the laddering waves in double layer serpentine were retarded. Although a laddering wave still exist but the penalty of the delay time incurred by the crosstalk is depressed.

Keywords: *serpentine delay line; crosstalk; double layer*.

1. Introduction

For high speed printed circuit board, the stability of clock signals is highly important for signal integrity consideration. 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. It is desirable that all clock signals are distributed with a uniform delay. There is the needs of equal interconnect lengths to distribute clock signals with minimal skews. Serpentine delay line was usually introduced to minimize the clock skew [1]. 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]. Figure 2 shows the cross section of the serpentine delay line, it is usually a microstrip line with power and ground planes.

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]. It is thus essential to reduce the penalty of the delay time incurred by the crosstalk between these closely packed transmission line sections. The layout of double layer serpentine delay line is one of the approach to reduced crosstalk between lines. Figure 3 is a schematic layout of the double layer serpentine delay line, the serpentine can be place on either sides of the board to reduce the coupling effect. The solid line indicate the lines on surface and the dot line indicated the line on back side. Figure 4 shows the cross section of the double layer serpentine delay line, the lines on two sides of the board are connected by the though hole via. The dark line in the board is power and ground plane within the multilayer board.

It is interesting to observe the receiving waveform of this double layer serpentine de-

* Corresponding author; e-mail: flin@mail.cyut.edu.tw
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lay line and the amount of crosstalk that can be reduced. In this investigation, the SPICE equivalent circuit model was built and simulation waveform of double layer serpentine delay line will be presented.

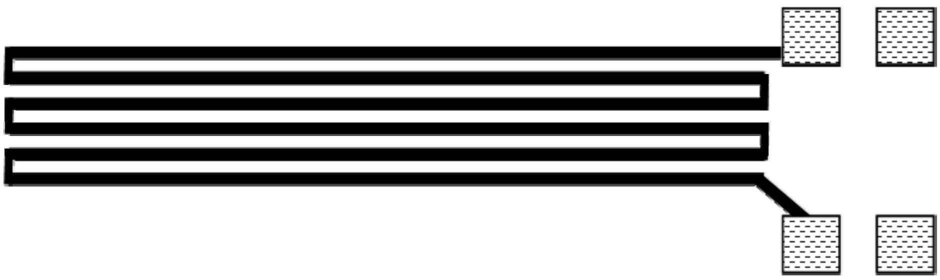

Figure 1. Schematic diagram of serpentine delay line.

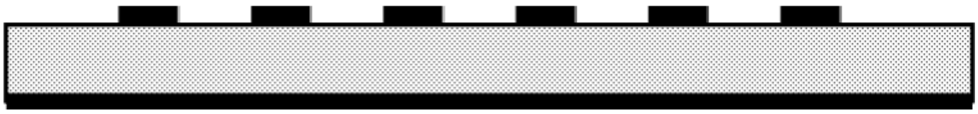

Figure 2. Cross section of the serpentine delay line.

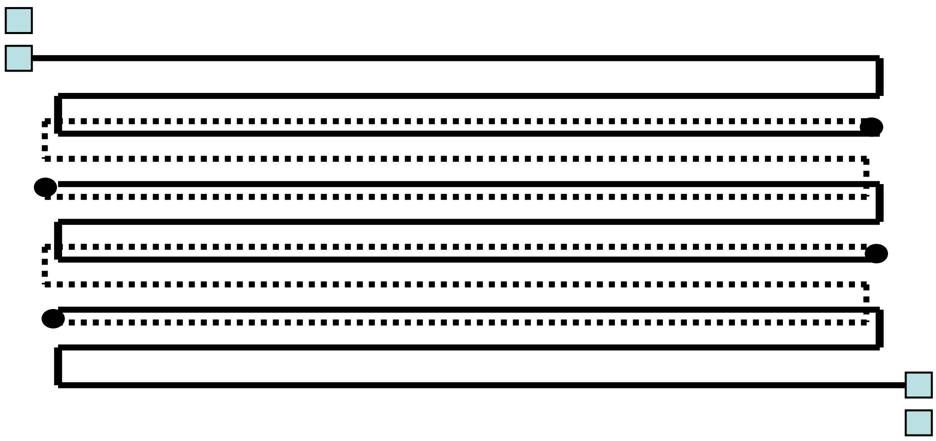

Figure 3. Schematic diagram of the double layer serpentine delay line.

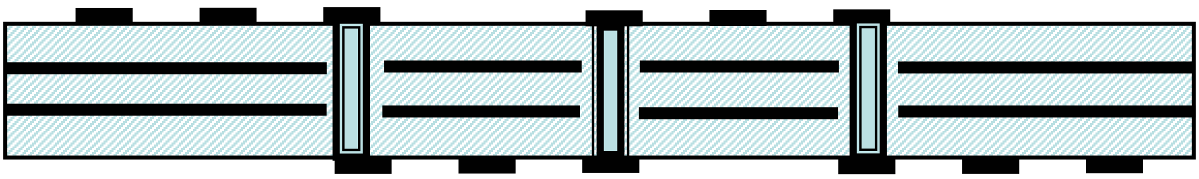

Figure 4. Cross section of the double layer serpentine delay line. (line width: 5.5 mil, line spacing: 6.0 mil, line thickness: 1.13 mil, dielectric thickness : 4 mil, ϵ_r =4.5, line length :10 cm)

2. Qualitative description

An illustrative model has been proposed to qualitatively describe the crosstalk mechanism [4]. Consider the simplest case of two parallel transmission lines. A ramp pulse of risetime t_r, under 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

$$V_{NE}(t) = K_{NE} \cdot \left[V_A(t) - V_A(t-2t_d)\right]$$
$$V_{FE}(t) = K_{FE} \cdot t_d \cdot \frac{d}{dt}\left[V_A(t-t_d)\right] \qquad (1)$$

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

$$K_{NE} = \frac{1}{4}(k_C + k_L) = \frac{1}{4}\left(\frac{|C_{12}|}{C_{22}} + \frac{L_{12}}{L_{11}}\right)$$
$$K_{FE} = \frac{1}{2}(k_C - k_L) = \frac{1}{2}\left(\frac{|C_{12}|}{C_{22}} - \frac{L_{12}}{L_{11}}\right) \qquad (2)$$

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. 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 $t = 6\ t_d$. The 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].

For double-layer serpentine delay line consisting of n sections in each segment (the coupling between layers were minimized by the ground plane), the highest level of the laddering wave is n-1 times the value of the near end crosstalk between two adjacent transmission lines. The n is small, therefore the amount of crosstalk will be much smaller. Owing to the spacing between serpentine segments is large, the coupling between segments is negligible.

3. Simulation

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

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

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.

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 SPICE [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 = 50Ω while the risetime of the source V_S (t) is 150 ps. The capacitance and inductance matrices can be computed once the geometries of the lines and the substrate are given [9]. The 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 5 shows the simulated waveform at the receiving end for the case with section length l = 10 cm. Line (a) is the waveform of serpentine line, 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 0.65V after four delay units. The value is greater than the receiver threshold level.

Line (b) on Figure 5 is the simulation waveform of the double layer serpentine delay line. The ladder wave before the main signal arrive is only about 0.18V which did not exceed the threshold level. Hence, the crosstalk does not result in delay penalty in this case. Due to the effect of the accumulation, the laddering waves of double layer serpentine can not be depressed. The results obtained by simulation still show some minor signal distortion.

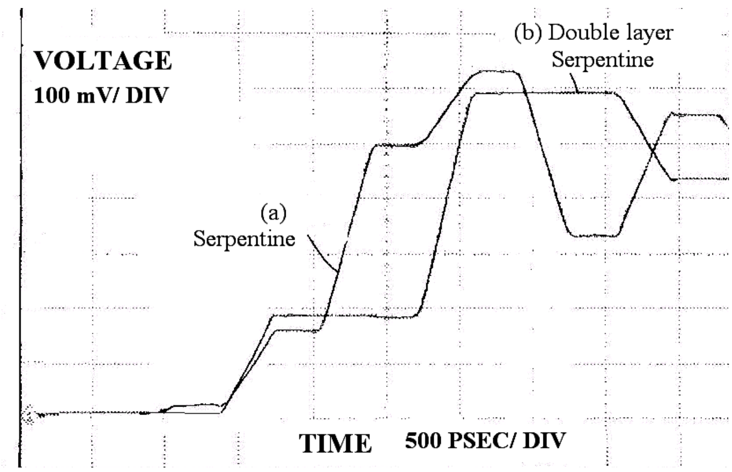

Figure 5. Simulation waveform of the double layer serpentine delay line.

4. Discussion

The major disadvantage of the double layer serpentine delay line is the additional via which connect serpentine segment between layers. At very high frequency, the discontinuity while the signals propagating through the via and signal lines can introduce reflection and energy loss, either radiating into the free space or exciting the radial waves between two metallization planes. At frequencies lower then 1 GHz, in this investigation, the discontinuity would physically introduce excess energy storage in the electric and magnetic fields, which can be modeled by lumped capacitance and inductance.

The equivalent circuits for some basic via structures have been presented by several investigators on the basis of quasi static analysis. Wu et al. [10] [11] applied the idea of partial equivalent element circuit (PEEC) to find the capacitances and the inductances of through hole via in the presence of power and grounding layers. As shown in Figure 6, h is the distance between plane, a_3 a_4 and a_5 are diameter of via upper metal plane and lower metal plane. Figure 7 shows the estimated equivalent capacitance for $a_5 = a_4$, $a_5 / a_3 = 2$. The additional capacitance depends on the ratio of the dielectric thickness and via diameter. Via structure might slow down the rise time of digital signal depending on its geometric parameters.

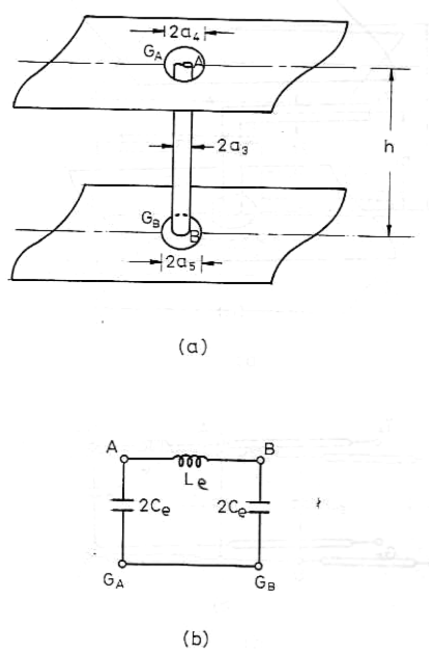

Figure 6. (a) Cross section and parameter setting, (b) equivalent circuit of the double metal layer via structure.

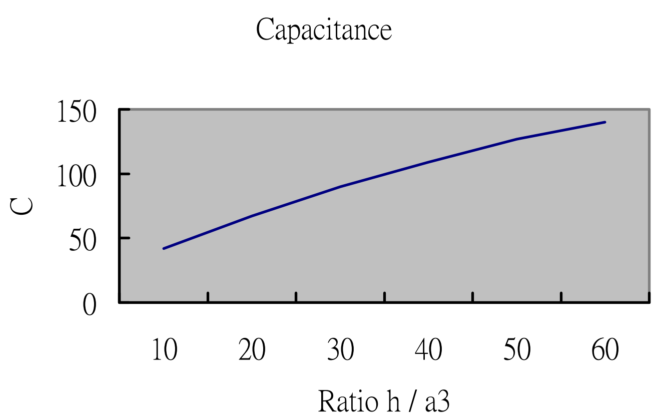

Figure 7. Excess capacitance of via in the presence of double metal layer

5. Conclusion

The backward crosstalk among the sections of the 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. SPICE simulation of signal distortion in double layer serpentine line have been performed. The laddering wave still results in notable signal distortion. But the accumulated magnitude is much lower than the threshold level, consequently it will not cause delay penalty.

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