

Comprehensive Analysis of Serpentine Line Design

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Abstract — Serpentine lines have been widely used in digital circuits to provide the required timing delays. Based on a full-wave simulation tool, some critical parameters that affect the delay characteristic of a serpentine line are carefully studied and analyzed. With the comprehensive study and analysis, a set of practical and useful design guides are concluded for designing a serpentine line to meet the delay specification.

Index Terms — cross-coupling, delay line, meander, serpentine.

I. INTRODUCTION

Integrated circuit (IC) technology advancement has resulted in higher operating frequency with shorter edge rates of the digital systems. With shorter edge rates, the delays of interconnecting traces on printed circuit board (PCB) can be comparable to gate delays, and therefore, require special design attention. Due to board size constraints, it is impossible to route long straight signals trace of equal delays. Hence, various design techniques are employed to achieve the intended delays without taking too much board space. One such example is the serpentine or the meander line. Its ease of implementation to meet the board space constraints has made it a popular technique amongst designers.

However, the cross-coupling effects due to the close proximity of the segment lengths can significantly deteriorate the time delay from its intended value. Thus, designers have to carefully design the serpentine lines to meet the stringent timing delay requirements. Though some design parameters affecting the propagation delay as well as signal integrity (SI) are mentioned in various literatures [1-5], no comprehensive analysis on how the various parameters affect the delay and SI has been carried out. Through the use of a powerful 3D EM simulation software, this paper performs a comprehensive analysis of design parameters, such as segment spacing, segment length, number of bends and type of bend, for a serpentine line.

II. SIMULATION AND VALIDATION

As an initial validation, a serpentine line as shown in Fig. 1 has been fabricated on a single-layer double sided PCB. The size of the PCB is 124 mm by 61 mm with a thickness of 1.6 mm. The characteristic impedance of the trace is designed to be 50 Ω , with trace width of 3.2 mm and trace thickness of 1.4 mils. The segment spacing is 2 mm and the segment length is 25.4 mm. The dielectric constant of FR4 is about 4. Based on the dimensions given above, the model constructed using an EM simulation tool [6] is shown Fig. 2. The comparisons of measured and simulated S-parameter and TDR results are given in Fig. 3 and Fig. 4, respectively. In general, good agreements between the measured and simulated results are observed. It gives us good confidence in the subsequent simulation analyses using the EM simulation tool.



Fig. 1 Fabricated serpentine test sample



Fig. 2 Simulation model in CST Microwave Studio

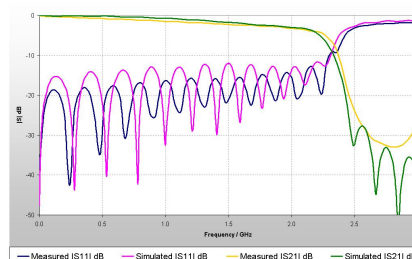


Fig. 3 Measured and simulated S11 and S21

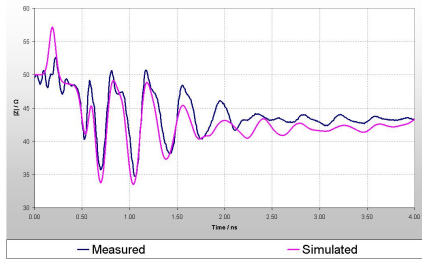


Fig. 4 Simulated and measured TDR results

III. DESIGN AND ANALYSIS

Fig. 5 and Fig. 6 show the top view and cross-sectional view of the serpentine structure to be used for the analysis, respectively. The total physical length of the serpentine line is 7.62 cm (3 inches). With the given cross-sectional geometry in Fig. 6, the characteristics impedance is found to be 50Ω . Fig. 7 shows the parameters for the time-domain simulation to perform the serpentine design analysis. Ports 1 and 2 are the injecting and the receiving ports, respectively. The impedances of both ports are specified at 50Ω to emulate the ports of a network analyser. P1 and P2 are the monitoring probes for waveform observation purposes. A square pulse of 1 GHz with rise time of 100 ps and 50% duty cycle defined and injected into Port 1 of the serpentine structure. The time-domain response is monitored by probe P2.

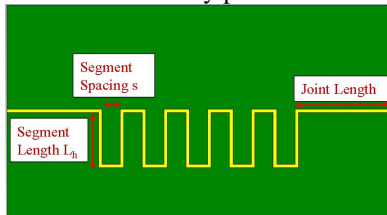


Fig. 5 Design parameters of the serpentine line to be analyzed

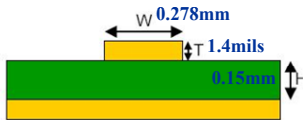


Fig. 6 Cross-sectional view of the serpentine line ($\epsilon_r = 4$)

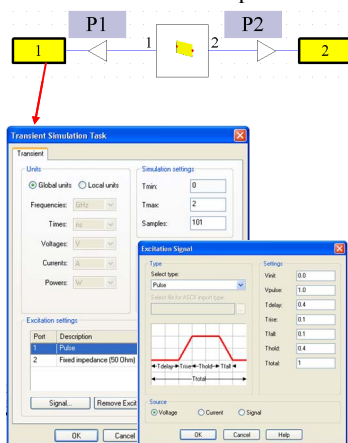


Fig. 7 Circuit simulation in CST Design Studio Environment, with external ports 1 and 2 and observation probes P1 and P2 defined

A. Segment Spacing

The segment spacing (s) is defined as the separation distance between the two adjacent parallel segments. The purpose of this section is to study the impact of the coupling between these segments on the performance of the serpentine line. The degree of coupling will be very much dependent on s . By varying s , we could investigate its effect on the propagation characteristic of the signal on the serpentine line. Fig. 8 shows the time-domain responses for the serpentine line with $s = H, 3H, 5H$ and $10H$, where $H = 0.15$ mm is the distance between the line and the reference plane. The segment length is kept unchanged at $L_h = 30H = 4.5$ mm. The legend “Input” refers to the input pulse waveform to the structure observed by P1. The Legend “Straight” refers to the output signal waveform observed by P2 for a straight trace of length 7.62 cm, without bends. The remaining waveforms are output waveforms observed by P2 with varying s , in terms of H .

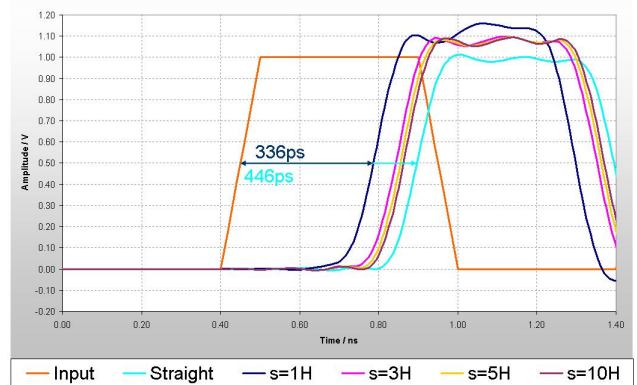
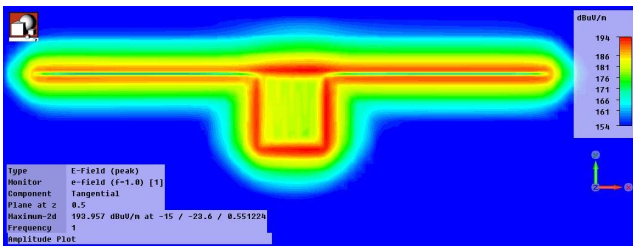


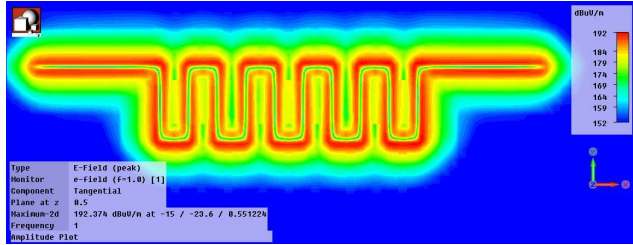
Fig. 8 Effects of spacing between segments (s) on propagation delay of the serpentine line, with $L_h = 30H = 4.5$ mm

From in depth analysis of Fig. 8, when $s < 3H$, the rate of increase in propagation delay is 28 ps/H. However, this rate reduces significantly to 1.6 ps/H for $s > 4H$. To compromise between the routing area and the desired propagation delay, the optimal s should be 3 to 4H. To understand the propagation behaviour with varying s , Figs. 9 (a) and (b) show the near-field distributions of the serpentine delay line at 0.5 mm above the reference plane for $s = H$ and $s = 10H$, respectively.

For the case of $s = H = 0.15$ mm, beside the field distribution along the serpentine line, very strong field coupling is observed across the adjacent segments. It indicates that besides the usual signal propagation path along the serpentine line, there is another alternative shorter path through the strong coupling between segments, which results in shorter propagation delay of the overall signal. For another case where $s = 10H = 1.5$ mm, the field coupling between segments is rather weak, and hence, the signal propagation is dominated by the path along the serpentine line. It explains why the delay for serpentine line with $s = 10H$ is much closer to the propagation delay of a straight microstrip trace of identical length.



(a)



(b)

Fig. 9 E-field at 0.5 mm above reference plane at 1 GHz, for (a) $s=H=0.15$ mm and (b) $s=10H=1.5$ mm, with $L_h=30H=4.5$ mm

B. Segment Length

The next design parameter to be studied is the segment length (L_h). Segment with long L_h behaves as a transmission line when its delay is comparable to the signal rise time. In this section of analysis, L_h will be varied to study its effect on propagation delay. Similarly, $H = 0.15$ mm is the distance between the reference plane and the trace. The segment spacing is kept constant at $s = 3H = 0.45$ mm.

Fig. 10 shows the simulation results with $L_h = 3H, 15H$ and $30H$. The legends “Input” and “Straight” are similar to those defined in Fig. 8. Based on the simulation results, longer L_h results in shorter propagation delay. This is due to the coupling effect between the segment lengths. To understand the cause of such a behaviour, Fig. 11 shows the E-field distribution at 1 GHz for $L_h = 3H = 0.45$ mm and $L_h = 30H = 4.5$ mm. In general, the field distribution is quite similar to that in Fig. 9. For the case of $L_h = 3H$, the field distribution is strong along the serpentine line, indicating that the signal propagates along the line. However, it is not the case for $L_h = 30H$. For long L_h , strong cross coupling between adjacent segments occur, which provide another alternative path for the signal to bypass the full length of the line. Thus, it results in shorter propagation delay. It is recommended to keep L_h as short as possible, preferably not longer than $15H$.

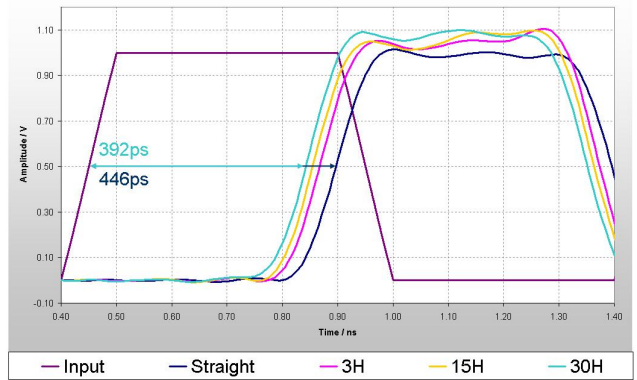
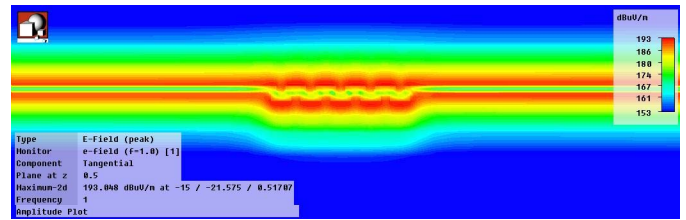
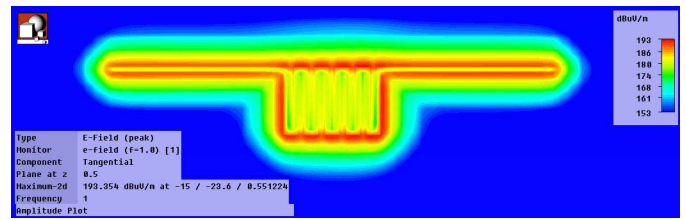


Fig. 10 Effect of L_h on propagation delay of the serpentine line, with $s=3H=0.45$ mm



(a)



(b)

Fig. 11 E-field at 0.5mm above reference plane at 1GHz for (a) $L_h=3H=0.45$ mm and (b) $L_h=30H=4.5$ mm, with $s=3H=0.45$ mm

C. Number of Bends

In reality, it is almost impossible to route the whole serpentine line continuously, given today’s highly populated PCB. Rather, multiple shorter sections of serpentine lines are adopted in practical applications. Such a design also helps to reduce near-field radiation coupling to the other signal lines in close proximity. Figs. 12 (a) and (b) show the E-fields at 5 mm above the reference plane at 100 MHz for 5 and 10 bends, respectively. The segment spacing s is fixed at $3H=0.45$ mm and the segment length $L_h = 15H = 2.25$ mm, with $H=0.15$ mm. It is clearly observed that increasing number of bends causes a larger area of strong near-field coupling, which increases the probability of interference to the nearby signal traces. Hence, multiple groups of smaller number of bends will help to reduce crosstalk coupling to other nearby traces.

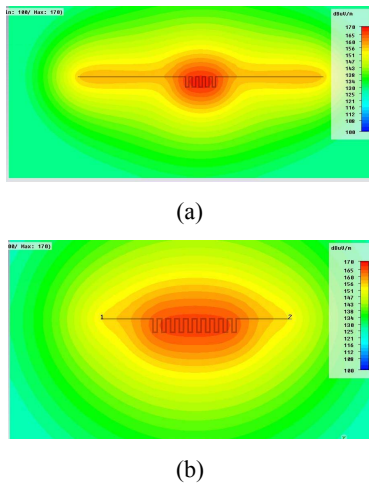


Fig. 12 E-field at 5 mm above reference plane at 100 MHz for (a) 5 bends and (d) 10 bends, with $s=3H=0.45\text{mm}$ and $L_h=2.25\text{mm}$

D. Types of Bends

Bends are inevitable in serpentine line design. However, they exhibit impedance discontinuities with increasing edge rate. The TDR results in Fig. 13 show the impacts of three types of bend, right-angled bend, S-bend and 45-degree bend, on impedance discontinuities. For example, the right-angled bend causes a dip when the signal reaches the first bend. The impedance resumes back to the characteristic impedance of the trace after the bend. The impedance then dips again at the second bend and now it does not have sufficient time to resume back to the initial impedance due to the relative short length between segments. At the third bend, the impedance dips again and resumes back to the initial value. It dips again at the fourth and final bend. Fig. 13 shows that the right-angled bend exhibits the largest impedance variation.

Large impedance variation indicates large impedance discontinuity, which results in higher surface current at the bends, as shown clearly in Fig. 14 for the case of the right-angled bend. Based on the simulated results, S-bend has the least impedance discontinuity and 45-Degree bend is slightly worse than the S-bend but is much better than the right-angled bend.

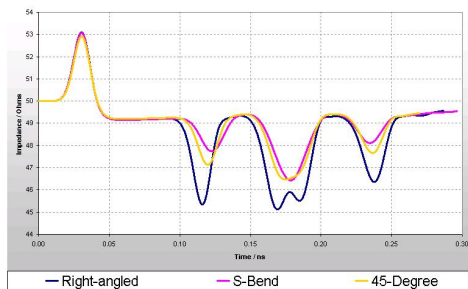


Fig. 13 Effects of different bending on trace impedance

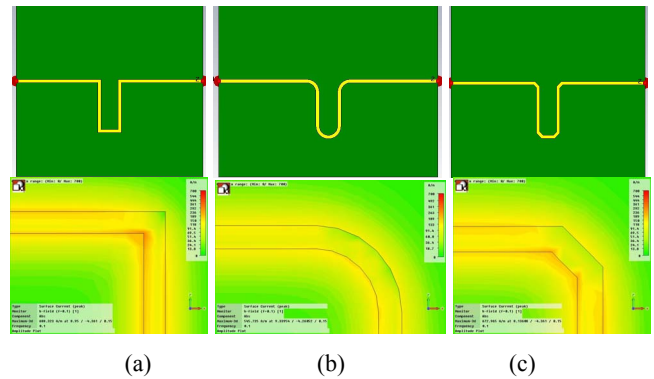


Fig. 14 Current density distribution at 100 MHz for (a) right-angled bend, (b) s-bend and (c) 45-Degree bend.

IV. CONCLUSIONS

In this paper, all the critical parameters to design a serpentine line to achieve the necessary delay are analyzed using a full-wave EM simulation tool. As a quick rule of thumb, optimal segment spacing (s) should be kept to 3 to 4H apart, where H is the separation between the trace and the reference plane. The segment length (L_h) is recommended to be kept as short as possible, preferably not more than 15H. Also, groups of 3-5 bends is recommended if reducing radiated emission as well as near-field signal coupling to the neighboring signal lines are of concern. Final, use 45-degree bends instead of right-angled bends provides fairly good design without too much layout complexity.

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