Guard Trace Design for Improvement on Transient Waveforms and Eye Diagrams of Serpentine Delay Lines

Guang-Hwa Shiue, *Member, IEEE*, Chia-Ying Chao, and Ruey-Beei Wu, *Fellow, IEEE*

***Abstract*—This paper investigates the utilization of the guard traces to improve the eye opening and jitter for serpentine delay lines. It is found that the guard trace can reduce the original time-domain transmission (TDT) and time-domain reflection (TDR) crosstalk noises by more than 50%, if shorted by only two grounded vias at both ends of the trace. The time domain analysis as well as the associated simple circuit modeling is presented to explain the occurrence of noise cancellation mechanism on the guard trace. In addition, narrow signal trace is proposed to improve the TDR waveform by compensating the impedance mismatch due to the inserted guard traces. Finally, the HSPICE simulation and time-domain measurements of crosstalk noises, TDR/TDT waveforms, and eye diagrams are performed to validate the proposed analysis and design.**

***Index Terms*—Crosstalk, eye diagram, grounded via, guard trace, serpentine delay line, signal integrity (SI), time-domain reflection (TDR), time-domain transmission (TDT).**

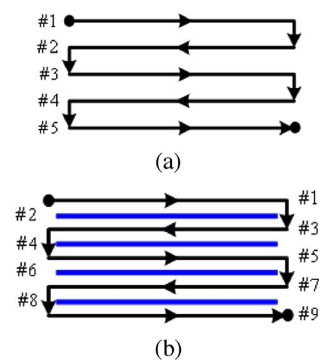

Fig. 1. Typical routing scheme for serpentine delay line (a) without and (b) with guard traces.

I. Introduction

As the cycle time of computer systems falls into the subnanosecond regime, the fraction of cycle time to accommodate the clock skew for the synchronization of clock signal among the logic gates has risen. While several approaches have been proposed to minimize the clock skew, the delay lines are usually employed in the critical nets of a package or printed circuit board (PCB), for example, the serpentine delay line routing scheme, as depicted in Fig. 1(a). Intuitively, the total time delay should be proportional to the total length of the delay line. However, the crosstalk noise induced by those closely packed transmission-line sections may cause drastic deterioration in the total time delay and time-domain waveforms which may even result in the false switching of logic gates [1]–[3].

Traditionally, the guard trace, i.e., a microstrip line grounded by a few plated via holes, is employed in reducing crosstalk between adjacent conductor paths in package or PCBs. Some design parameters have been found to be critical factors in determining crosstalk immunity [4]–[8], according to the analysis mostly in frequency domain. It is worthy noting that the utilization of the guard trace can not always reduce the crosstalk noise in time domain, especially when separation between two grounded vias is large. The guard trace may become the source of another ringing noise and enlarge the crosstalk noise for coupled transmission lines. Some design criterions on the number of grounded vias for guard trace have been proposed [9], [10], but the underlying mechanism of the resultant crosstalk noise waveform is not clarified, which will be revisited from the time-domain analysis in the Appendix of this paper. There are other designs to alleviate the ringing noise, e.g., employing a suitable overlying dielectric layer to the coupled lines [11], [12].

A serpentine delay line with the guard traces inserted into the cross-coupled conductors in the parallel section to improve the signal integrity, as depicted in Fig. 1(b), has been proposed and analyzed in frequency domain [13]. Nonetheless, it is as important to judge its efficiency from the time-domain waveforms, such as time-domain reflection (TDR), time-domain transmission (TDT), and eye diagram. Hence, this paper investigates further the TDT/TDR waveform and eye diagram of the guard-trace embedded serpentine delay line. It has been demonstrated that the inserted guard traces are capable of reducing crosstalk noise in the serpentine structure [14]. Moreover, it is found that the ringing noise can be suppressed by only two grounded vias. The detailed mechanism and the optimum selection of the grounded vias in the guard trace for the serpentine structures will be discussed.

The organization of this paper is as follows. Section II investigates the TDR/TDT waveforms and eye diagram for serpentine delay line with guard traces. The effects of the number of grounded vias are addressed in Section III, while the narrow

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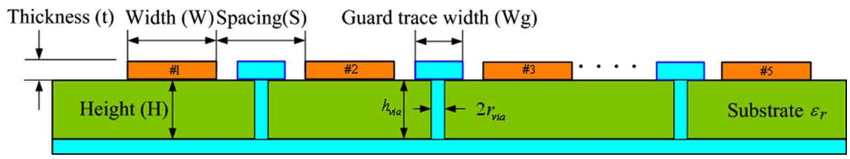


Fig. 2. Cross-sectional view of the serpentine delay line with guard trace in reference to Fig. 1(b).

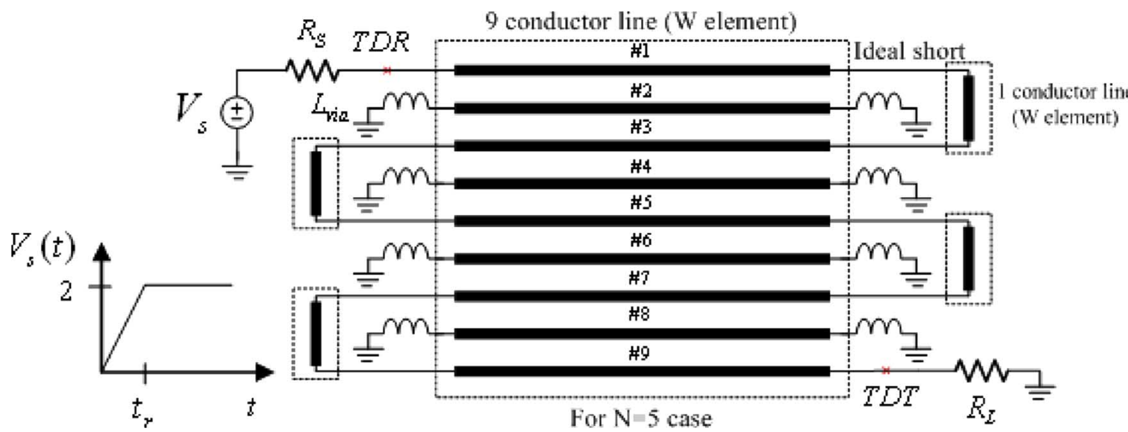


Fig. 3. Circuit model for guard-trace inserted serpentine delay lines in SPICE simulation.

signal trace design for compensating impedance mismatch is proposed in Section IV. This altogether shows significant improvement in the eye diagram in Section V. The experimental validation is presented in Section VI and brief conclusions are drawn in Section VII.

II. Time-Domain Transient Waveforms

Consider the typical serpentine delay line formed by coupled microstrip lines in Fig. 1(a) and with guard trace in Fig. 1(b). Fig. 2 shows the cross-sectional views of the delay line, depicting all structural parameters, e.g., line with (W), trace length (ℓ), separation between two grounded vias (d), trace width (W_g), spacing between coupled lines (S), trace thickness (T), substrate height (H), height $(h_{\rm via})$, and radius $(r_{\rm via})$ of grounded via, and dielectric constant (ε_r). It is known that the near-end crosstalk V_n among the sections of a serpentine delay line accumulates in phase to appear as a laddering wave on the TDT waveform [1] while the far-end crosstalk V_f appears as a train of voltage dips on the TDR waveform. Furthermore, the accumulation of crosstalk will deteriorate the eye opening and jitter [3]. Because the guard trace is traditionally employed in reducing crosstalk noise between adjacent traces, the serpentine delay line with guard traces inserted between the parallel lines in Fig. 1(b) is proposed. The combined structure can reduce the crosstalk and thereby, result in the improvement of TDT/TDR waveforms and eye diagram [14].

The transient crosstalk noise waveforms of two coupled microstrip lines have been analyzed in Appendix. It is known that the large spacing between grounded vias will result in large voltage peaks on crosstalk noise waveforms. Here, consider a serpentine delay line with guard traces in the cross-sectional view in Fig. 2 with $W = 3$ mm, $H = h_{\rm via} = 1.5$ mm, $t = 0.035$ mm, $r_{\rm via} = 0.25$ mm, $W_g = 0.5$ mm, losstan$= 0.02$, and $\ell = 60$ mm. The driver and load resistances are chosen $R_S = R_L = 50\ \Omega$ while the rise time of the source $V_S(t)$ is 75 ps.

Fig. 3 shows the circuit model used in the HSPICE simulation for the guard-trace inserted serpentine delay lines. The multiple coupled transmission lines as well as the guard traces are modeled by W-elements, thereby taking into account the finite transmission lines loss. The bends are modeled by small section of transmission lines, while the bend corners are neglected because their influence on the simulated waveform is not significant. In addition, the guard traces are only grounded by two vias at the both ends, each of which is modeled by a series inductance [15]

$$L_{\rm via} \approx \mu_0 \frac{h_{\rm via}}{2\pi}\left[\ln\left(\frac{4h_{\rm via}}{r_{\rm via}}\right) + \frac{r_{\rm via}}{2h_{\rm via}} - \frac{3}{4}\right]. \quad (1)$$

Note that (1) is just the partial inductance of via. It neglects the inductance due to the via pad and the end effects of the finite transmission line, which are inevitable when forming a loop. However, the error is small for short vias and is neglected here.

Fig. 4 shows the simulated TDT and TDR waveforms of five-section serpentine delay line with section spacing $S = 1$ mm and 2 mm. Both the cases with and without guard traces are simulated and compared. By calculating the near- and far-end crosstalk coefficients, the maximum crosstalk noise in the TDR and TDT waveforms can be predicted approximately by simple analytic formulae [3]. The predicted and simulated maximum voltage levels of the laddering wave noise are summarized in Table I. It can be found that inserting guard traces reduces the maximum voltage level of the laddering wave on TDT by more than half of that without the guard traces, and similarly for the voltage drops on TDR waveform. Also included in Fig. 4 are the full-wave results based on the finite integration simulator CST [16]. They are in perfect match with the HSPICE simulation

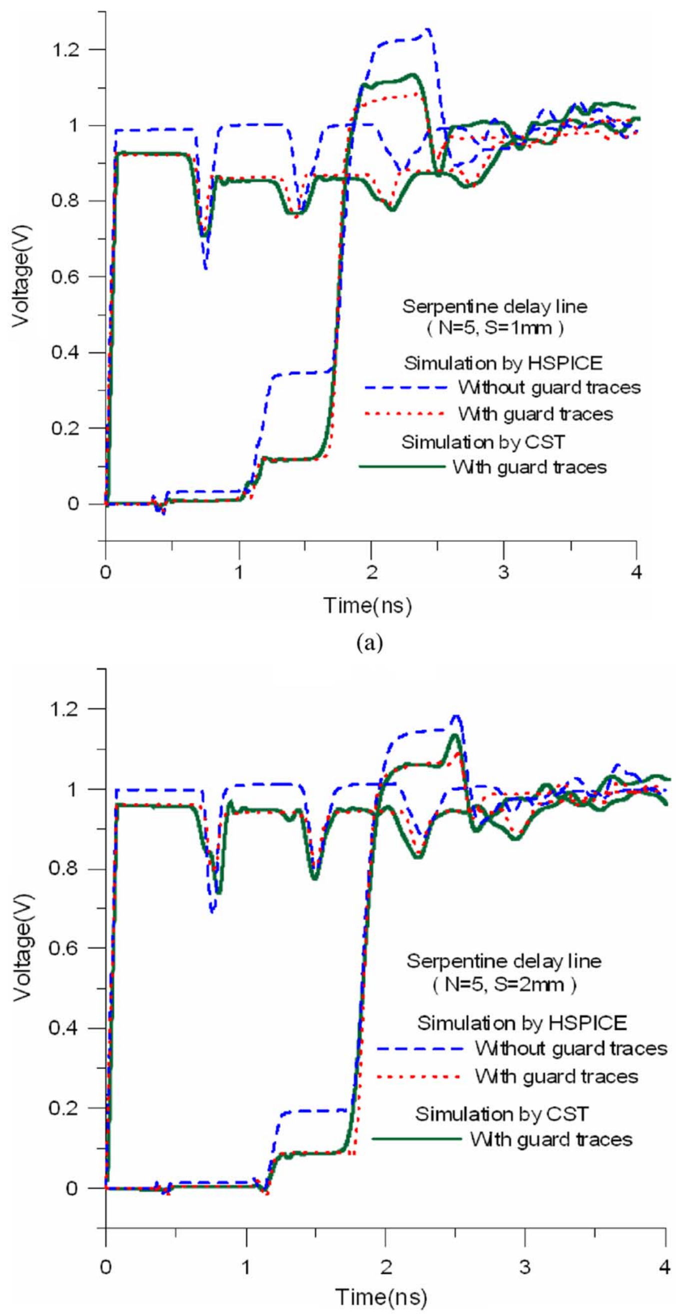


Fig. 4. Comparison between simulated TDR/TDT waveforms of serpentine delay line with and without guard traces. Section number is $N = 5$ and trace spacing is (a) $S = 1$ mm and (b) $S = 2$ mm.

results, thereby verifying the simplified circuit model shown in Fig. 3.

On the other hand, Fig. 5 shows the simulated TDT waveforms with section number $N = 5$ and 7 as a parameter. From Figs. 4 and 5, the smaller the section spacing S or the larger the section number N, the more seriously the crosstalk distorts the TDR and TDT waveforms [3]. It is found that the reduction ratio in TDT noise due to the guard traces is more significant for the above two cases when the crosstalk noise is larger. Furthermore, it is found that the main signal propagating through the serpentine delay line with guard traces will arrive slightly earlier than that without guard traces.

For the case of $S = 1$ mm and $N = 7$ in Fig. 5, the maximum voltage level of the laddering wave without guard trace is larger than the threshold voltage (0.5 V), which may lead to penalty in the desired time delay [1]. By inserting guard traces, the crosstalk noise can be reduced and the signal integrity of the TDT waveform can be greatly improved.

III. Effects due to Different Numbers of Grounded Vias

From the time-domain analysis in the Appendix for a pair of coupled transmission lines with guard traces inserted in between, a larger spacing between grounded vias will result in larger voltage peaks on near- and far-end crosstalk noise waveforms. However, it is interesting to note from Figs. 4 and 5 that there are no voltage spikes on TDR and TDT waveforms for guard-trace inserted serpentine delay lines, even though the guard traces are grounded by only two vias.

Consider a serpentine delay line having the same cross-sectional parameters in Fig. 2 but $\ell = 120$ mm. Fig. 6 compares the TDR/TDT waveforms of serpentine delay lines for the guard trace with two and three grounded vias, which correspond to via spacing $d = 120$ mm and 60 mm, respectively. It is worthy noting the appearance of voltage peaks on TDR/TDT waveforms in Fig. 6 for the case of three and five grounded vias. In contrast, the case of guard traces with two vias does not appear voltage peaks on TDR/TDT waveforms although the via separation is larger.

Let T_d be the delay time when the signal propagates on one parallel section of serpentine delay line. As per the analysis for time domain waveform of coupled microstrip lines in the Appendix, the physical mechanism can be described as follows.

From $t = 0$ to T_d: When the ramped pulse propagates along the conductor section #1 of serpentine delay line shown in inset of Fig. 7, it will induce forward crosstalk noise propagating toward the right-hand side of the guard trace #2 (called $V_{f,g}$) and conductor section #3 (called $V_{f,s}$), respectively. At the same time, another far-end crosstalk noise (called $V_{f,sg}$) induced from the forward crosstalk along the guard trace #2, $V_{f,g}$, will appear on the right-hand side of trace #3. The two far-end noises $V_{f,s}$ and $V_{f,sg}$ will combine together like coupled microstrip lines with guard trace in Fig. 17.

From $t = T_d$ to $2T_d$: Due to the serpentine routing scheme, the main signal, noise $V_{f,s}$, and noise $V_{f,g}$ will propagate towards left-end of the conductor sections #3, #1, and #2, respectively. The main signal on the conductor section #3 will induce crosstalk noises propagating toward the left-hand side of the guard trace #2 (called $V'_{f,g}$) and conductor section #1 (called $V'_{f,s}$), respectively. The noise $V'_{f,g}$ propagates and accumulates, but in reverse polarity with the propagating noise $V_{f,g}$. Fig. 7 shows the time-domain waveform on guard trace #2 at four different positions. Please note that $V_{f,g}$ and $V'_{f,g}$ cancel each other and the combined signal amplitude becomes smaller and smaller. On the other hand, the noise $V'_{f,g}$ on guard trace #2 will also induce another noise $V'_{f,sg}$ at the left-end side of

TABLE I
LADDERING WAVE AND VOLTAGE DROP NOISE LEVELS OF THE SERPENTINE DELAY LINE WITH/WITHOUT GUARD TRACES

		First Voltage Drop on TDR Waveform			The Highest Ladder on TDT Waveform		
		w/o guard trace	w/ guard trace	Reduction ratio	w/o guard trace	w/ guard trace	Reduction ratio
S=1mm	Analytic formulae [3]	355mV	123mV	65.4%	348mV	114mV	67.2%
	HSPICE Simulation	361mV	135mV	62.6%	347mV	115mV	66.9%
S=2mm	Analytic formulae [3]	332mV	143mV	56.9%	193mV	83mV	57.0%
	HSPICE Simulation	327mV	140mV	57.2%	193mV	86mV	55.4%

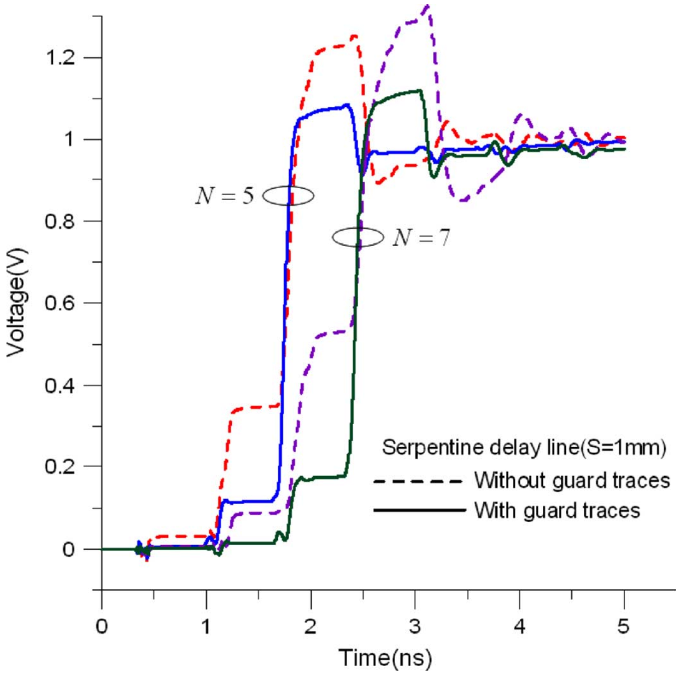


Fig. 5. Comparison between simulated TDT waveform of serpentine delay line with and without guard traces. Trace spacing is $S = 1$ mm and section number is $N = 5$ and 7.

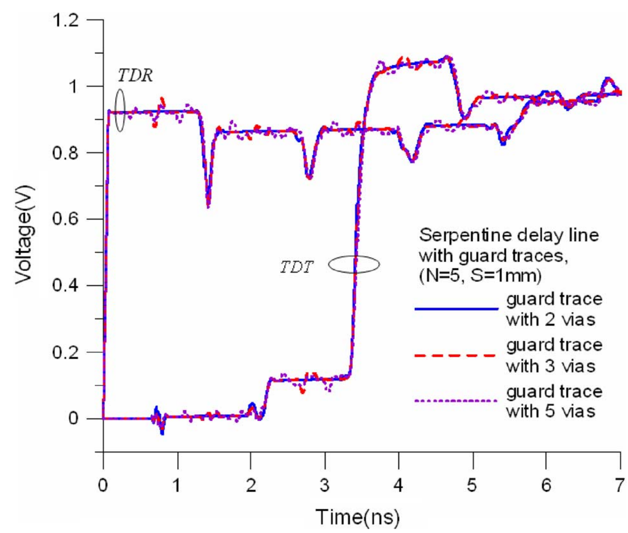


Fig. 6. Comparisons of TDR/TDT waveforms of serpentine delay line with guard traces and different numbers of grounded vias.

conductor section #1. The two far-end noises $V_{f,sg}$ and $V'_{f,sg}$ will mostly cancel each other at $t = 2T_d$ at the left-end side of conductor section #1. As a result, the far-end crosstalk can only cause minor effects on TDR and TDT waveforms, as depicted in Fig. 6.

In case of three grounded vias on the guard trace, the cancellation mechanism does not happen. The induced forward crosstalk noise on the guard trace #2 bounces back at $t = 0.5T_d$ and results in far-end noise which appears earlier than the main signal, thereby causing the voltage peaks on the flat level of laddering wave of TDT waveform in Fig. 6, and similarly for TDR waveform.

For more grounded vias, there will be more voltage peaks but the magnitude becomes smaller, although not shown here. The cancellation mechanism mentioned above does not hold for more grounded vias either. For layout and simplicity consideration, the best design for the guard trace in suppressing the crosstalk effects on serpentine delay line is to insert only two grounded vias at the both ends of each guard trace.

In the above description, it is assumed of weak coupling so that the main signal barely decays during propagation and perfect refection although there is finite via inductance. Also, the via pad in normal manufacturing technology is larger than the spacing between the traces. To have a grounded guard trace, the via pads are usually offset to make room for the layout detour of the signal trace around the corner. Thus, there will be additional extra time delay for the main signal to propagate through the detoured trace. These factors will deteriorate the cancellation mechanism, but only slightly unless at very high frequencies.

IV. COMPENSATION FOR LINE IMPEDANCE

Due to the additional guard traces, the characteristic impedance of serpentine delay line will be smaller. Hence, the reflection noise becomes larger and results in larger voltage drop on TDR waveform. The narrow strip design can be adapted to compensate the impedance mismatch due to the additional guard traces.

Consider the aforementioned serpentine delay line structure with section $N = 5$. Fig. 8 shows the design chart for the guard-trace inserted microstrip line to yield characteristic impedance of 50 Ω. In compensated case, the trace widths of the first and last sections are modified from 3 mm to 2.6 mm and the other from 3 mm to 2.3 mm according to Fig. 8 for spacing $S = 1$ mm condition. And, for spacing $S = 2$ mm condition, the strip

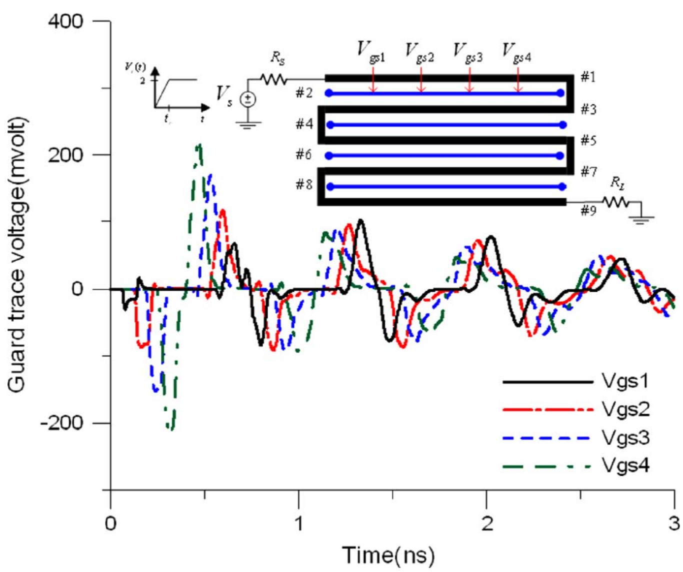


Fig. 7. Voltage on guard trace at different positions.

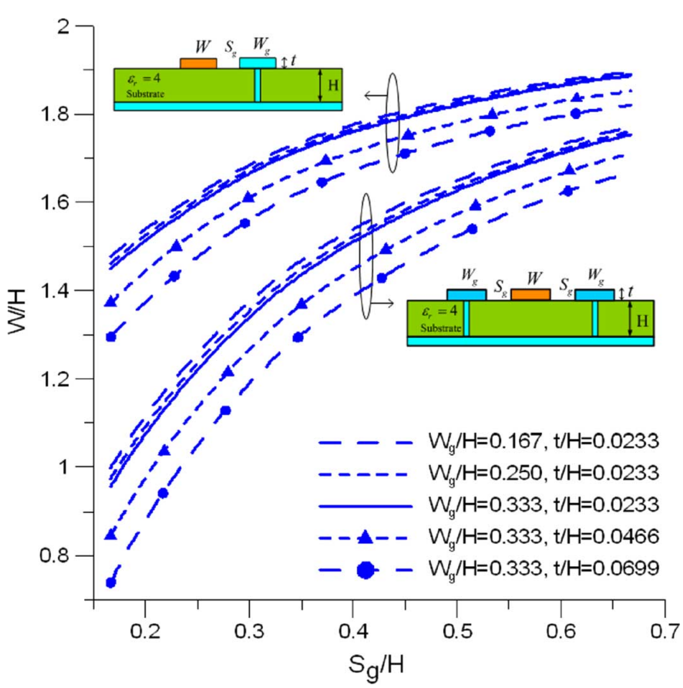
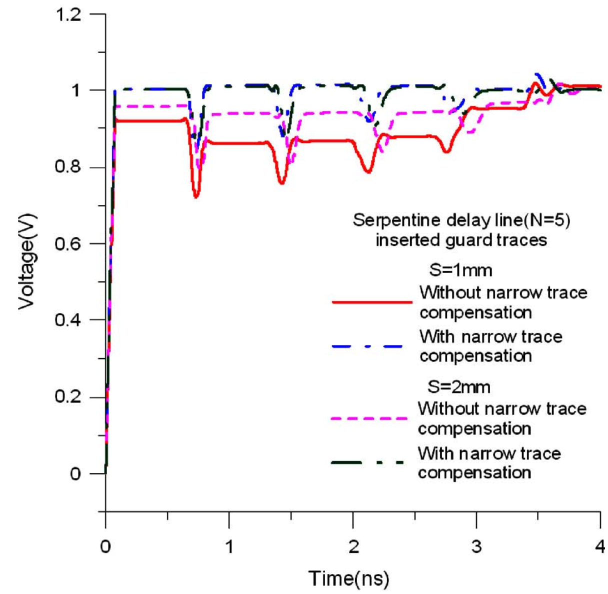


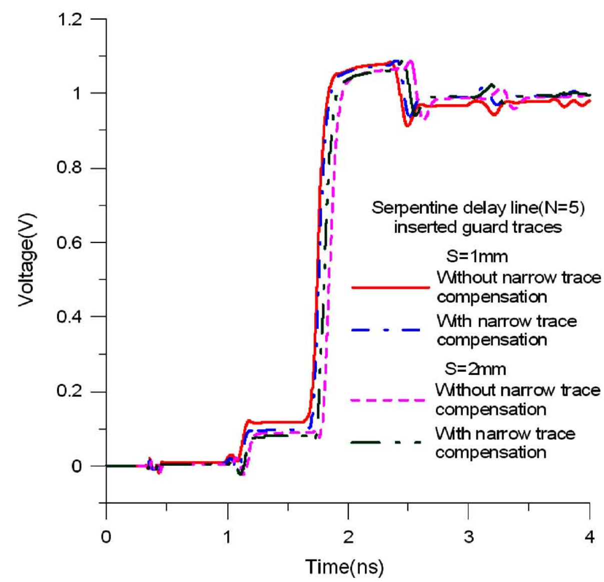
Fig. 8. Design chart of impedance 50 Ω versus physical dimension of guard-trace inserted serpentine delay line with narrow strip compensation.

widths of the first and last sections must be modified from 3 mm to 2.77 mm and the other from 3 mm to 2.56 mm.

Fig. 9 shows the TDR and TDT waveforms with and without narrow strip compensation. Owing to the narrow strip compensation, the voltage level on TDR waveform is improved significantly. In addition, the narrow strip compensation will slightly reduce the magnitude of the laddering wave voltage. Consequently, the narrow strip compensation scheme for serpentine delay line with guard traces achieves better signal integrity on both TDR and TDT waveforms.



(a)



(b)

Fig. 9. (a) TDR and (b) TDT waveforms of serpentine delay line with guard traces. Both cases with and without narrow strip compensation are compared.

V. Eye Diagram Improvement

It is interesting to examine the effects on eye diagram due to the crosstalk reduction by using guard traces for serpentine delay line. In HSPICE simulation, the pseudorandom incident signal is launched with rise/fall time 75 ps, data rate 3.5 Gb/s, and voltage swing of 2 V. Recall the two routing schemes in Fig. 1 with the same cross-sectional parameters and section number $N = 5$ in Fig. 2. The simulated eye diagrams are shown in Fig. 10. It can be found from Fig. 10(a) how badly the crosstalk deteriorates the eye opening and jitter of the serpentine delay line, especially in case of smaller spacing $S = 1$ mm and more section number $N = 7$. The eye is almost closed, which means failure in the signal transmission.

It is evident from Fig. 10(b) that employing guard traces can relieve this problem significantly. In comparison with the eye

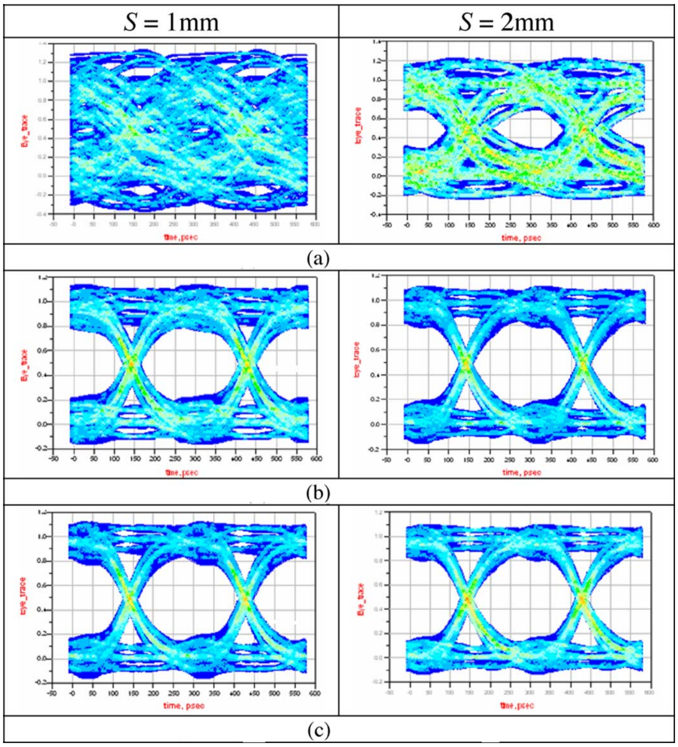


Fig. 10. Eye diagrams with section number $N = 5$ and different spacing S. (a) Without guard trace. (b) With guard traces. (c) With guard traces and narrow strip.

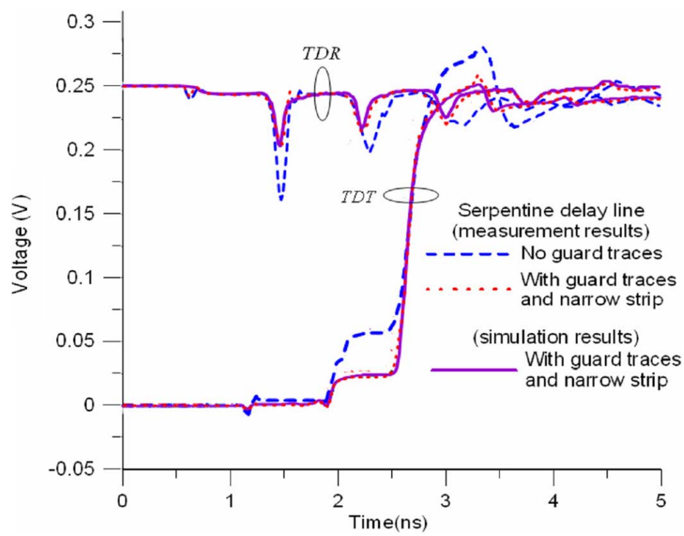


Fig. 11. Comparisons of TDR and TDT waveforms between simulated and measured results of serpentine delay line with guard traces and narrow strip compensation.

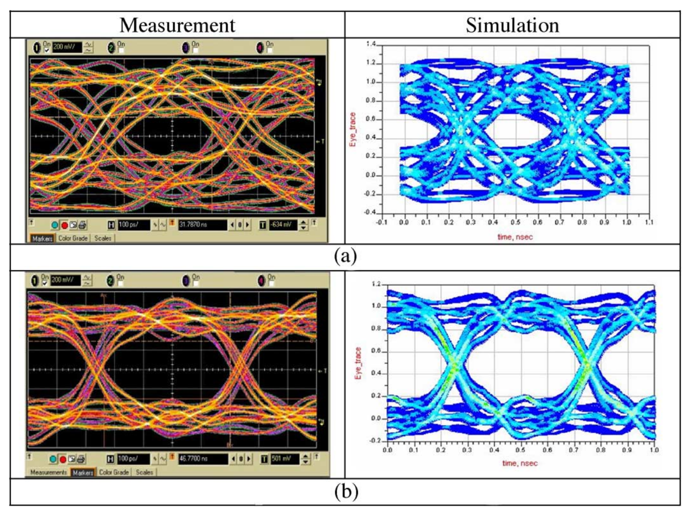


Fig. 12. Comparisons of eye diagrams between simulated and measured results of five-section serpentine delay line with and without guard traces. (a) Without guard trace. (b) With guard traces and narrow strips.

diagram of delay line without guard traces, the employment of guard traces and narrow strip compensation improves the eye height from 0 to 0.555 V, eye width from 1.3 ps to 258 ps, and jitter from 233 ps to 35.7 ps for $S = 1$ mm. For $S = 2$ mm, the improvement is from 0.312 V to 0.645 V in eye height, from 180 ps to 264 ps in eye width, and from 113 ps to 32.9 ps in jitter.

VI. Experimental Validation

Consider the five-section serpentine delay line having the cross-sectional parameters in Fig. 2: $W = 3$ mm, $S = 1.5$ mm, $W_g = 0.5$ mm, $H = 1.5$ mm, $t = 0.035$ mm, $\ell = 60$ mm, $\varepsilon_r = 4.1$, and $\mathrm{losstan} = 0.037$. Two kinds of serpentine delay lines are manufactured: the original one and with both guard trace and narrow strip compensation. In the narrow strip compensation, the strip widths of the first and last microstrip sections are modified from 3 mm to 2.7 mm while the others from 3 mm to 2.5 mm for the impedance match.

The experiment is performed on the time domain reflectometry TEK/CSA8000. With both the source and load resistances being 50 Ω, the launching voltage source is drawn out of the reflectometry for SPICE simulation. Fig. 11 compares the simulated and measured waveforms for the guard-trace inserted serpentine delay line with narrow strip compensation. It is evident that the simulated waveforms agree well with the measured ones. Moreover, using the guard traces and narrow strip compensation, the level voltage drop and laddering wave is improved significantly on TDR and TDT waveforms.

Furthermore, the comparisons of eye diagrams between simulated and measured results for five-section serpentine delay line are shown in Fig. 12. The experimental verification is performed on the time-domain pattern generator Anritsu/MP1763C and oscilloscope Agilent/548855A. The launching pseudorandom voltage source with rise time 85 ps, voltage amplitude 1 V, and data rate 2 Gb/s is also drawn out of the pattern generator for SPICE simulation. The simulated digital pulse waveforms by HSPICE are imported into the simulator ADS [17] to obtain the individual eye diagrams in comparison with the measured data.

Good consistency can be found in reference to Figs. 12 and 13. Although there is slight discrepancy, the results acquired by the qualitative model, quantitative analysis, simulation, and measurement have all justified the crosstalk noise effects on TDR/TDT of serpentine delay line and the improvement on signal integrity by inserting guard traces. The improvement can be more effectively for the cases of larger

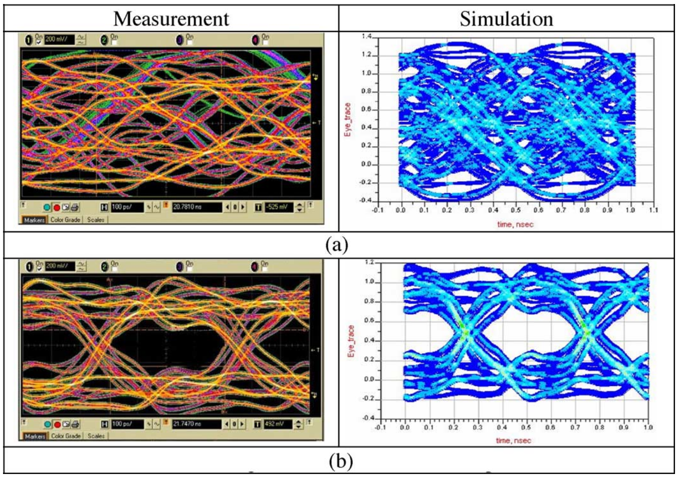


Fig. 13. Comparisons of eye diagrams between simulated and measured results of seven-section serpentine delay line with and without guard traces. (a) Without guard trace. (b) With guard traces and narrow strips.

crosstalk noise, say with more sections or smaller separation between two sections.

VII. Conclusion

The guard trace is usually inserted between coupled transmission lines to reduce the crosstalk noise. However, it can not always reduce the maximum voltage of crosstalk noise, especially when the separation between two grounded vias is large. In the Appendix of this paper, a qualitative time-domain analysis is proposed to explain the occurrence of the peak voltages of the crosstalk noise in time domain. Furthermore, if the grounded vias are sufficiently closely spaced, the guard trace can reduce the crosstalk and obtain good eye diagram, while still realizable under practical routing constraint.

The insertion of guard trace among the parallel sections of serpentine delay line helps reduce the near- and far-end crosstalk noise on the receiving and driving ends. Owing to the serpentine configuration, the forward propagating noises due to the insertion of guard trace can be cancelled at the receiving and driving ends if the guard trace is shorted with two grounded vias at the both ends. As demonstrated by the HSPICE simulations and reflectometry measurement, the TDT/TDR waveforms and eye diagram can be improved significantly. The reduction in the maximum voltage level of the laddering wave by adding guard traces is easily noticeable. Further improvement on TDR and TDT waveforms can be achieved by using the guard traces and narrow signal strip width.

Appendix
Crosstalk of Guard-Trace Inserted Coupled Lines

Consider typical coupled microstrip lines shown in Fig. 14(a), and all structural parameters in Fig. 15(a). Under the assumption of weakly coupling, lossless, and matched loads at both ends, the main signal in the active line is rarely influenced by the presence of the crosstalk noise. Then, with respect to the ramped step

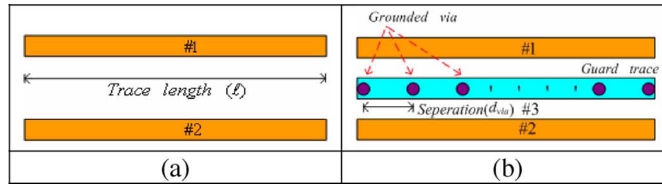


Fig. 14. Typical routing scheme for coupled microstrip lines, (a) without and (b) with guard trace.

voltage V_i on the active line, the saturated near- and far-end crosstalk voltages in the victim line can be written as [18]

$$V_n \approx V_i \times k_{\text{near}} = V_i \times \frac{1}{4}\left(\frac{L_m}{L_s} + \frac{C_m}{C_s + C_m}\right) \tag{2}$$

$$V_f \approx -V_i \frac{T_d}{t_r} \times k_{\text{far}} = -V_i \times \frac{T_d}{2t_r}\left(\frac{L_m}{L_s} - \frac{C_m}{C_s + C_m}\right) \tag{3}$$

where L and C are inductance and capacitance with subscript s and m denoting self and mutual terms, T_d is the line delay time, t_r is the rise time, k_{near} and k_{far} are the near- and far-end crosstalk coefficients, respectively.

In order to reduce the crosstalk between the coupled microstrip lines, a grounded guard trace can be inserted between the parallel lines as shown in Fig. 14(b). In the extreme case of closely spaced grounded vias, the guard trace can be regarded as an ideally grounded line, resulting in reduction of crosstalk coefficients by 50% or more.

For practical routing, the number of grounded vias for the guard trace is limited. As the rise time of high-speed signal goes shorter, the finite separation between two grounded vias of guard trace is not negligible. It may deteriorate the efficiency of crosstalk noise reduction. For larger separation, the guard trace may even become another noise source [8] on the crosstalk noise waveforms.

Consider a pair of coupled microstrip lines with guard trace depicted in Fig. 14(b) and cross-sectional view in Fig. 15(b) with $W = 3$ mm, $S = 6$ mm, $H = h_{\text{via}} = 1.5$ mm, $t = 0.035$ mm, $W_g = 3$ mm, $\varepsilon_r = 4$, $\text{losstan} = 0.02$, $r_{\text{via}} = 0.5$ mm, and line length $\ell = 60$ mm. The driver and load resistances are chosen $R_S = R_L = 50\ \Omega$, while the rise time and the ramped step voltage source $V_S(t)$ are 100 ps and 2 V, respectively. Fig. 17 shows the circuit model used in the HSPICE simulation, where the coupled transmission lines together with the guard trace are modeled by W-elements and the grounded vias by equivalent inductances.

Fig. 17 shows the near- and far-end crosstalk noise waveforms of the coupled microstrip lines with the via separation d as a parameter by HSPICE simulation. It is obvious from Fig. 17(a) that, in spite of the presence of some peaks, the average near-end crosstalk voltage, V_{n_flat}, is reduced by half due to the inserted guard trace no matter what the via spacing is. From Fig. 17(b), the far-end crosstalk voltage can be reduced only when the grounded vias along the guard trace are sufficiently closely spaced.

It is worthy noting the appearance of large voltage peaks on the near- and far-end crosstalk waveforms, especially when the via separation is large. To circumvent these large peaks which

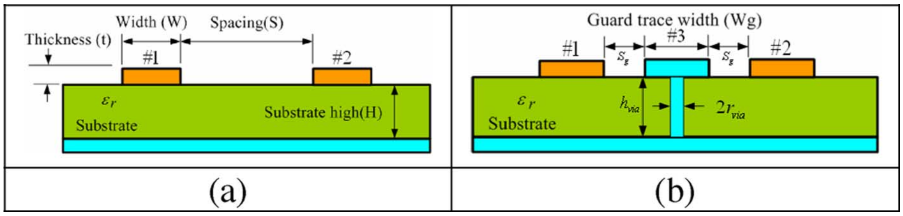


Fig. 15. Cross-sectional view of coupled microstrip lines in Fig. 15, (a) without and (b) with guard trace.

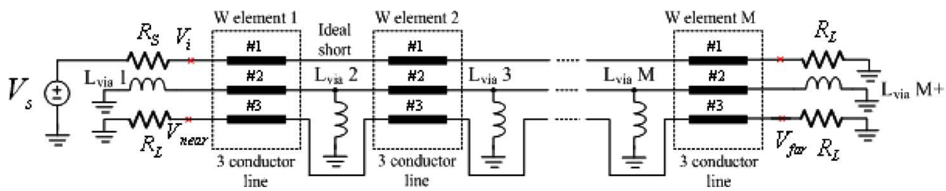
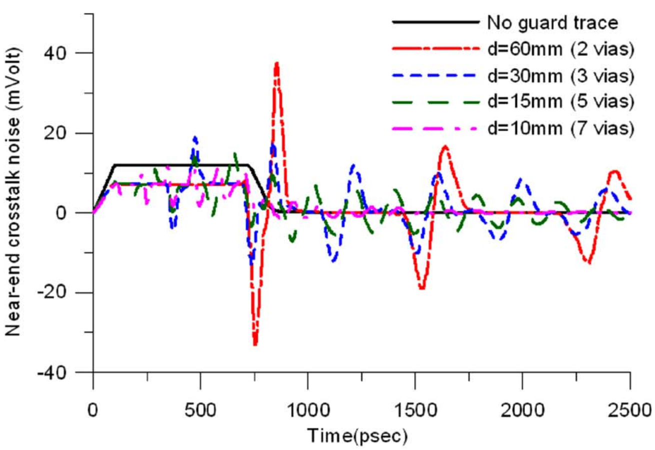
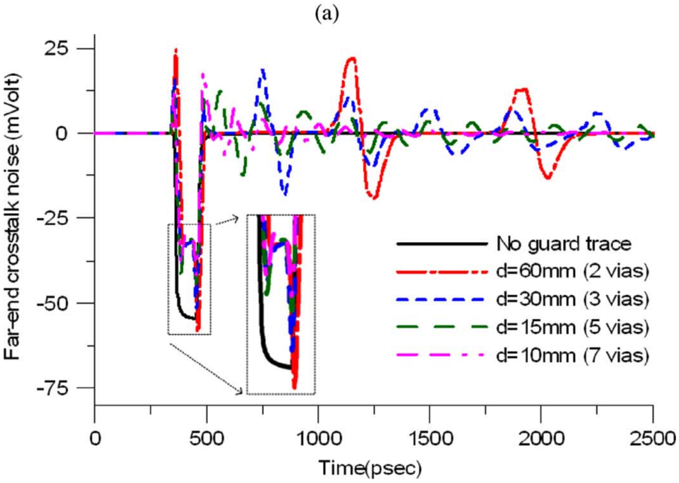


Fig. 16. Circuit model used in HSPICE simulation for coupled microstrip lines with guard trace and grounded vias.



(a)



(b)

Fig. 17. Comparison of simulated crosstalk noise waveforms with via separation on guard trace as a parameter. (a) near- and (b) far-end crosstalk.

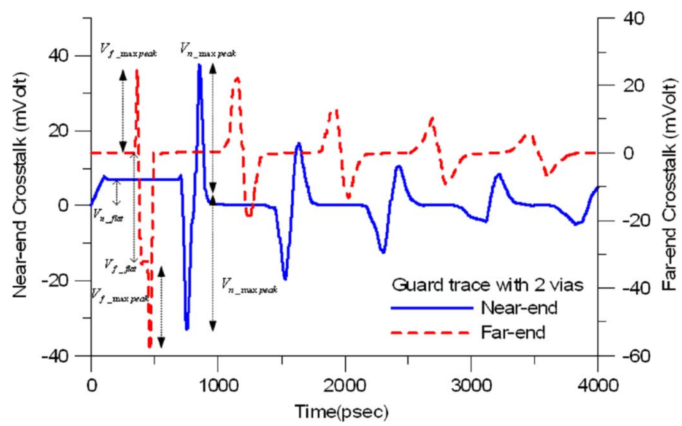


Fig. 18. Simulated crosstalk noise waveforms with guard trace of two vias.

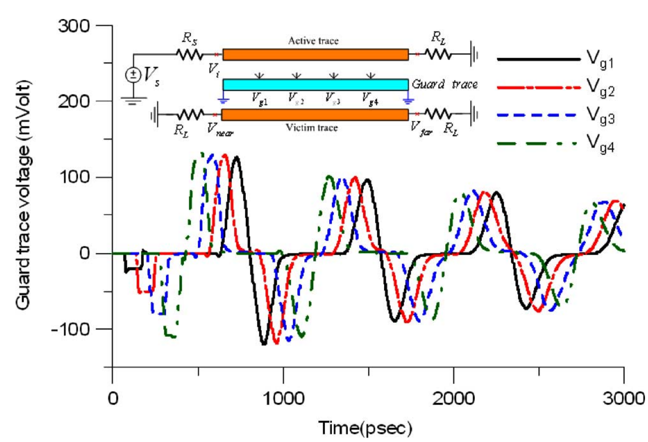


Fig. 19. Simulated crosstalk noise waveforms on guard trace with two vias.

degrade the signal integrity, the grounded vias should be closely spaced to ensure the efficiency of crosstalk noise reduction. In light of the routing constraint for practical manufacturing consideration in multilayer PCB or package structures, it is interesting to further investigate the amplitude of voltage peaks versus the via separation.

The simulated crosstalk noise waveforms of the coupled microstrip lines with guard trace of only two grounded vias are shown in Fig. 18. To help explain the complicated coupling scheme, the simulated crosstalk along the guard trace at four locations are also shown in Fig. 19.

Let $V_{n\_\max\ \mathrm{peak}}$ and $V_{f\_\max\ \mathrm{peak}}$ denote the peak voltages of the first pair of positive and negative spikes straddling on near- and far-end crosstalk waveforms in Fig. 18, respectively.

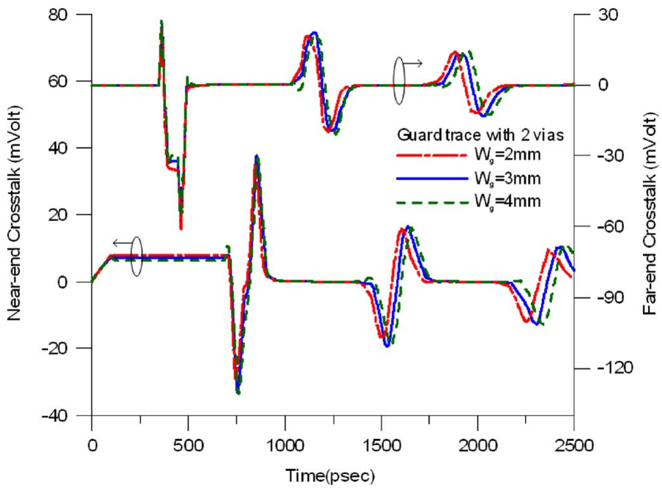


Fig. 20. Simulated crosstalk noise waveforms with guard trace of two vias for various lengths $\mathrm{W_g}$.

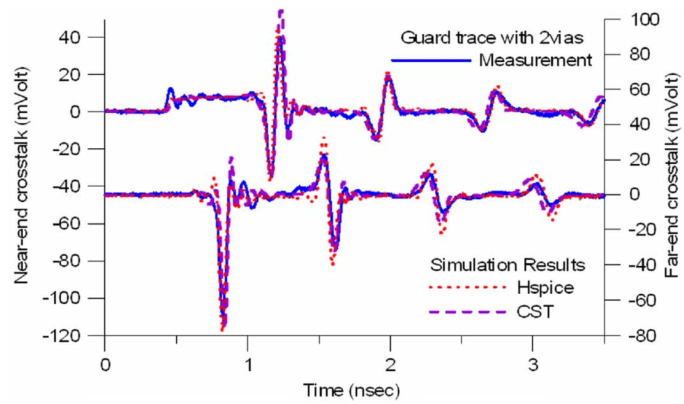


Fig. 21. Comparison of simulated and measured crosstalk noise waveforms for coupled microstrip lines with guard trace of two vias.

The two spikes can be attributed to the forward crosstalk noise induced on the guard trace. Due to the large via separation, the guard trace picks up the forward crosstalk noise from the active line shown in Fig. 19, which then serves as noise source. For smaller via separation, the accumulated noise is small so that the guard trace can behave like an ideal ground.

The physical mechanism can be briefly described as follows. When the ramped pulse propagates along the active line, the forward crosstalk noises will propagate to the right-hand side and appear on both the guard trace and victim line at the far end. At the same time, the forward crosstalk noise, $V_{f,g}$, on the guard trace will induce another forward crosstalk noise, $V_{f\_\max\ \mathrm{peak}}$, to appear on the far end of the victim line. It deserves noting that the far-end noise is proportional to the time derivative of the short pulse propagating on the guard trace, which makes it to behave like two narrow but large spikes.

When the forward crosstalk noise, $V_{f,g}$, on the guard trace encounters the grounded via, it inverts the voltage polarity and propagates towards the left-end of the guard trace as shown in Fig. 19. During the propagation, it will induce another forward crosstalk noise, $V_{n\_\max\ \mathrm{peak}}$, to appear on the near end of the victim line. Following the same reasoning, the other voltage peaks can also be found.

To investigate the effects of guard trace width on the reduction of crosstalk noise, Fig. 20 shows the simulated crosstalk noise waveforms with guard trace of two vias for various widths $W_g = 2, 3$, and 4 mm. In general, the guard trace width has not much influence on the near- and far-end crosstalk. The wider the guard trace is, the smaller flat voltage V_{n_flat} on near-end crosstalk and V_{f_flat} on far-end crosstalk, but the peak voltages on near- and far-end crosstalk will increase slightly. Also, the period of voltage peaks on crosstalk noises will increase slightly.

Fig. 21 shows the comparison between the simulated and measured crosstalk noise waveforms for coupled microstrip lines with guard trace of only two vias. Both the HSPICE and full-wave CST simulations are included to check the accuracy of the circuit modeling in Fig. 16. Here, the same structure and cross-section parameters have been used, but with $\varepsilon_r = 4.4$, and $\mathrm{losstan} = 0.025$. The experimental verification is performed on the time domain reflectometry TEK/CSA8000. With both the source and load resistances chosen to be 50 Ω, the launching voltage source is drawn out of the reflectometry for HSPICE simulation. It is noticed that the crosstalk noise waveforms by measurement, HSPICE, and full-wave CST are in good agreement.

For two parallel coupled lines, the reduction in average voltage level of the near-end crosstalk noises by inserting guard trace can be found from Fig. 21. There are large spikes in near- and far-end crosstalk noises, which are contributed to the ringing noise on guard trace as depicted in Fig. 19. The measured waveforms are in good agreement with the simulation results, which justifies the important effects of the grounded vias on the signal integrity of the coupled lines with guard trace.

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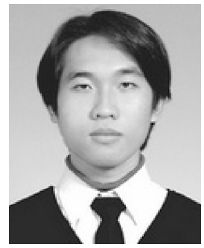

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