A New Twisted Differential Line Structure on High-Speed Printed Circuit Boards to Enhance Immunity to Crosstalk and External Noise

Dong Gun Kam, Heeseok Lee, Jonghoon Kim, and Joungho Kim

***Abstract*—Differential signaling has become a popular choice for high-speed interconnection schemes on Printed Circuit Boards (PCBs), offering superior immunity to external noise. However, conventional differential transmission lines on PCBs have problems, such as crosstalk and radiated emission. To overcome these, we propose a Twisted Differential Line (TDL) structure on a multilayer PCB. Its improved immunity to crosstalk noise and the reduced radiated emission has been successfully demonstrated by measurement. The proposed structure is proven to transmit 3 Gbps digital signals with a clear eye-pattern. Furthermore, it is subject to much less crosstalk noise and achieves a 13 dB suppression of radiated emission.**

***Index Terms*—Crosstalk, differential signaling, radiated emission, transmission line, twisted differential line, twisted pair.**

I. Introduction

THE operational frequencies of high-speed digital systems have increased at such a rapid pace over the past few years that nowadays high-speed PCBs have to transmit and receive digital signals whose spectral contents can reach tens of gigahertz. To ensure reliable operation at such a high data rate, differential signaling has become a popular choice for multigigabit digital applications, such as Serial-ATA, Fiber Channel, Inifiniband, OIF, RapidIO, and XAUI [1]. This is because the differential signaling is more robust, in that it is less susceptible to external noise. Conventional differential line structures on multilayer PCBs include coupled microstrip, coplanar strip, or strip lines. However, these conventional differential lines still have problems, such as crosstalk and radiated emission. To overcome these problems of conventional differential lines, we propose a new Twisted Differential Line (TDL) structure, which is applicable to high-speed and high-density PCBs. As is well known in the field of cable interconnection, a twisted pair provides a simple means of reducing the susceptibility to external noise [2]. The concept of the twisted pair can be readily applied to the differential lines on PCBs, which further enhances immunity to crosstalk and other external noise.

Fig. 1 illustrates the proposed TDL structure, where the concept of the twisted pair is realized in a multilayer PCB. It is comprised of two-segmented conductor traces on a first and a second layer of the PCB, crisscrossing each other using many vias. The TDL has several advantages because of its physical configuration. The electromotive force (EMF) in a loop, which is generated by an external time-varying magnetic field, is canceled out by the EMF of the subsequent loop. The advantages of the TDL become obvious when several differential pairs run in parallel on a PCB as shown in Fig. 2. By using TDLs, we minimize the crosstalk between the differential pairs because the TDL increases the effective spacing between two adjacent

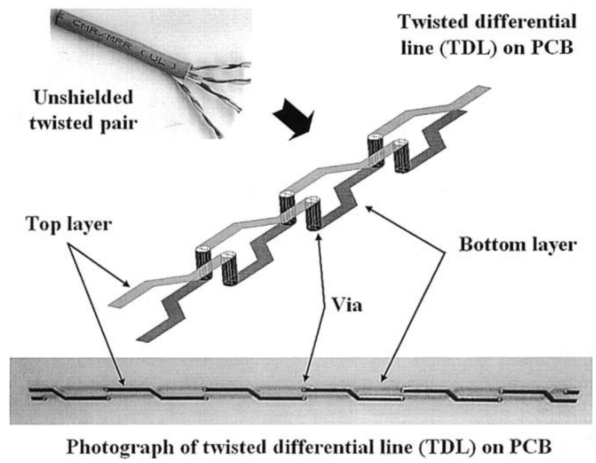

Fig. 1. Schematic and the photograph of the newly proposed twisted differential line (TDL) structure on high-speed PCBs. The proposed TDL is proven to have an improved immunity to crosstalk and external noises.

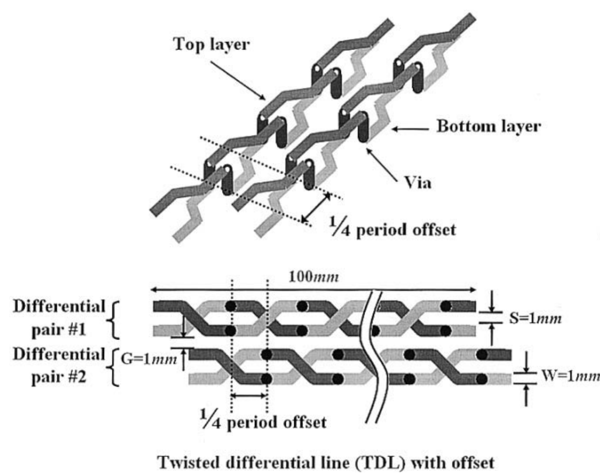

Fig. 2. Test PCB layout of the TDL pairs for the eye pattern, crosstalk, and radiated emission measurement.

Manuscript received October 9, 2002; revised December 16, 2002. The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

The authors are with the Terahertz Interconnection and Package Laboratory, Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, Korea (e-mail: teralab@ee.kaist.ac.kr; http://tera.kaist.ac.kr).

Digital Object Identifier 10.1109/LMWC.2003.815181

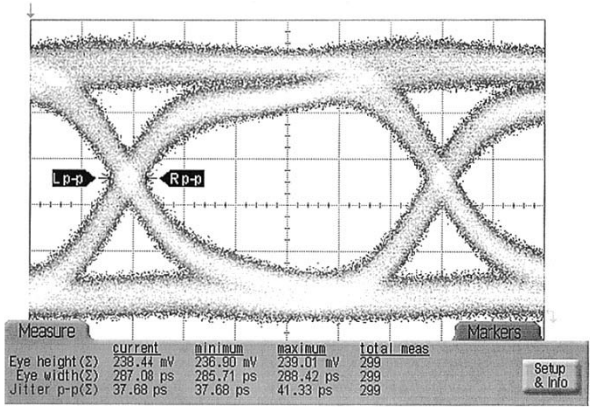

Fig. 3. Measured eye pattern of the proposed TDL with a data rate of 3 Gbps.

pairs, therefore reducing the average mutual capacitance and inductance between the pairs [3]. Furthermore, if we offset all the neighboring vias, each trace of a differential pair is equally influenced by adjacent traces of the next differential pair. This balanced crosstalk [4] cancels out by virtue of the differential signaling.

The improved immunity of the proposed TDL to crosstalk, and the reduced radiated emission have been successfully demonstrated by measurements. The TDL is proven to transmit a 3 Gbps signal with a clear eye-pattern. Furthermore, it is demonstrated that it suffers much lower crosstalk and achieves 13 dB suppression of radiated emission.

II. Measured Eye, Crosstalk, and Radiated Emission From Proposed TDL

Fig. 2 shows the layout of the test differential line structures on the PCB. The test PCB has both conventional coupled microstrip lines and the proposed TDL, which were fabricated on a 0.6-mm-thick FR-4 substrate ($\epsilon_r = 4.5$). The coupled microstrip lines have the same dimensions as the TDL.

First, we measured the eye patterns for the proposed TDL with a 3 Gbps data rate. As shown in Fig. 3, the clear eye-pattern of the TDL demonstrates successful digital data transmission over 3 Gbps. Because the TDL contains many vias and segmented traces, it has greater conduction loss and reflections at discontinuities compared with the conventional differential lines. However, as we use more twists on the TDL we increase the noise immunity. Therefore, the number of twists should be determined to make an optimal tradeoff between the transmission bandwidth and the noise immunity.

Second, we measured the far-end crosstalk (FEXT) voltage waveform of two differential pairs with TDR/TDT measurements. The FEXT between neighboring differential pairs is of interest when the differential pairs run in parallel on PCBs. An input pulse of 500 mV height and 330 ps rise-time was stimulated on one pair, and the FEXT was measured at the end of the other pair. The measured FEXT voltage waveform is shown in Fig. 4. The FEXT of the TDL is significantly reduced, to 5.2 mV, compared with the coupled microstrip lines, at 40.3 mV. This is a remarkable achievement in high-speed PCB design, even maintaining the transmission bandwidth. It should be noticed that the offset scheme of the via positioning (Fig. 2) improves the crosstalk immunity further. With the offset scheme, each trace of a differential pair is equally influenced by the adjacent traces of the next differential pair. A line on a differential pair is influenced from one line of the next pair, and it is influenced from the other line of the next pair after a quarter of a period. Therefore, every line is properly balanced, and therefore this balanced crosstalk can be canceled out by virtue of differential signaling.

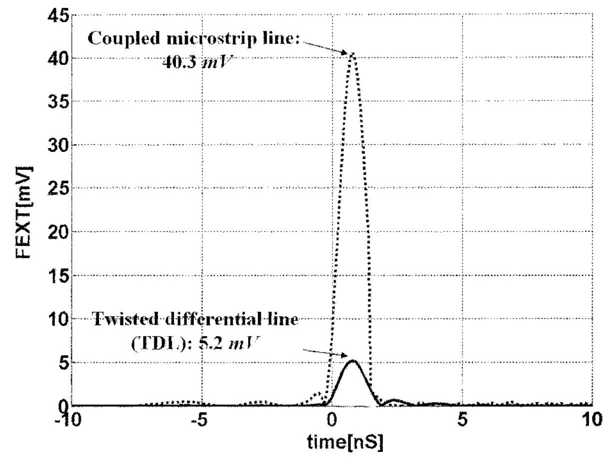

Fig. 4. Comparison of the measured far-end crosstalk (FEXT) voltage waveforms of the two differential line structures.

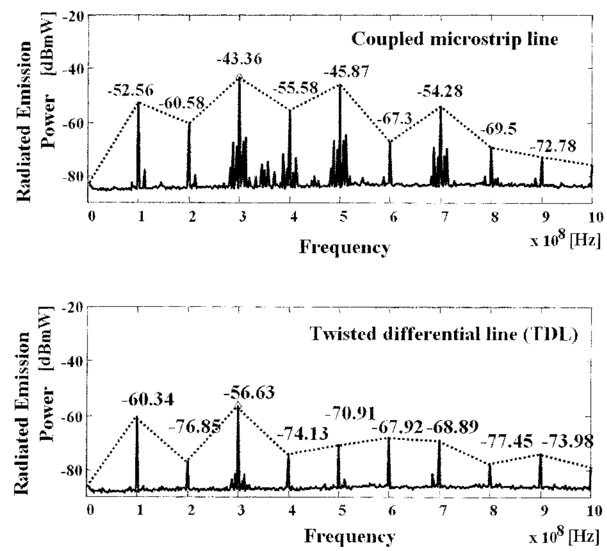

Fig. 5. Measured radiated emission spectrum from the differential lines on a PCB. (a) Radiation from the conventional differential line and (b) radiation from the proposed TDL.

Third, we also measured the radiated emission spectrum from the test differential lines using an anechoic chamber. The digital periodic signal was applied using a clock generator of 100 MHz, and the spectrum was composed of the harmonics of 100 MHz. Fig. 5 shows that the TDL achieves 13 dB suppression of radiated emission compared with the coupled microstrip line. This is because each current loop on the TDL produces an electromagnetic field, which is canceled out by the electromagnetic field from the next loop. As the number of twists is increased, the reduction of the radiated emission is enhanced.

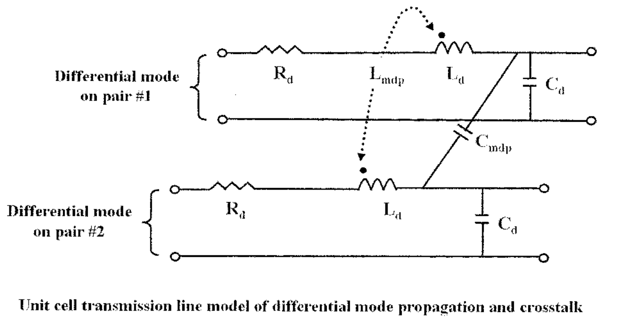

Fig. 6. Unit cell transmission line model of the differential mode propagation and crosstalk on PCBs.

TABLE I
EXTRACTED MODEL PARAMETERS OF THE DIFFERENTIAL LINES FROM THE S-PARAMETER MEASUREMENT AND SUBSEQUENT MODELING PROCEDURE. THE MODEL SCHEMATIC IS SHOWN IN FIG. 6

	Coupled Microstrip Line	Twisted Differential Line		
Number of twists in 100 mm	0 twist	16 twists	10 twists	6 twists
R_d [mΩ/mm]	66.6	88.7	87.3	90.4
L_d [nH/mm]	0.541	0.777	0.803	0.799
C_d [fF/mm]	61.0	70.1	58.6	51.1
Z_{diff} [Ω]	94.2	105	117	125
L_{mdp} [pH/mm]	12.4	1.12	1.64	2.99
C_{mdp} [fF/mm]	4.05	0.35	0.31	0.34
*α [x10^{-4}/mm]	3.54	4.21	3.73	3.61
t_{delay} [ps]	620	780	725	670

*) calculated at 1GHz

III. CROSSTALK MODEL PARAMETERS OF A TDL

In the test PCB, the number of twists on the TDL varies from 6 to 16 in a 100 mm line. We determined the equivalent circuit model of the TDL, depending on the number of twists, as well as the coupled microstrip line, as shown in Fig. 6. R_d (resistance), C_d (capacitance), and L_d (inductance) represent the differential mode propagation in each pair. The crosstalk between the two adjacent differential pairs is represented by L_{mdp} (mutual inductance between the adjacent differential pairs) and C_{mdp} (mutual capacitance between the adjacent differential pairs). The entire coupled lines of 100 mm length were described by a cascaded connection of 100 unit cells. The model was obtained from S-parameter measurements and a subsequent parameter fitting process for frequencies up to 3 GHz [5].

Table I presents the fitted model parameters. The differential line impedance of the TDL ranges from 105 Ω to 125 Ω, depending on the number of twists, which is calculated from $Z_{diff} = \sqrt{L_d/C_d}$. The enhanced crosstalk immunity of the TDL is obviously reflected in L_{mdp} and C_{mdp}. First, the mutual inductance (L_{mdp}) is considerably smaller in the TDL. This is because the magnetic fields generated by two consecutive loops in the TDL cancel each other. Second, the mutual capacitance (C_{mdp}) is also greatly reduced by applying the offset scheme. A quarter of a period offset scheme was found to be the most effective, which is illustrated in Fig. 2. The offset scheme on the TDL enables the two lines in a differential pair to be equally affected by the lines of adjacent pairs, reducing the crosstalk between the pairs, which run in parallel on a PCB. As a result, the mutual capacitance of the TDL is only 10% of that of the coupled microstrip lines. Third, for the TDL, the number of twists does not change L_{mdp} and C_{mdp} significantly. However, when the total length of the line is increased, the number of twists will more strongly affect the crosstalk immunity. At design, the number of twists should be carefully determined to optimize the tradeoff between the transmission bandwidth and the noise immunity. Fourth, it was found that adding more twists also increases the time delay and the attenuation constant. This is because the physical length of the line is increased. In Table I, the time delay (t_{delay}) was measured from TDR/TDT measurements, and the attenuation constant (α) was calculated from the extracted model parameters as $\alpha = \mathrm{Re}\{\sqrt{(R_d + j\omega L_d)(j\omega C_d)}\}$.

IV. CONCLUSION

Since the adoption of differential signaling, crosstalk noise has remained the major problem as the required data rate has continually increased. It was demonstrated that the proposed TDL delivers a promising solution for high-speed and high-density digital interconnection designs on PCBs. The differential line impedance of the TDL is easily controllable over a wide range by changing the number of twists and by changing the dimension of the line and via. Although the number of layers may be increased, depending on the layer stacking and the assignment of the ground plane by using the TDL scheme, the routing area does not increase. Therefore, we can achieve improved noise immunity while keeping the same routing area. Furthermore, because the lines of a TDL pair are tightly coupled to each other and the electromagnetic fields are well confined, the effect of the reference plane discontinuity becomes minimal [6]. Even without a ground reference plane, the TDL can support the data transmission at a very high data rate. Even though our consideration in this paper was limited to the PCB level interconnections, the TDL can be readily applied to other level interconnections including packages, connectors, and chips.

REFERENCES

[1] H. Wu *et al.*, "Design and verification of differential transmission lines," in *Proc. 10th Topical Meeting Electrical Performance of Electronic Packaging*, Oct. 2001, pp. 85–88.

[2] H. Ott, *Noise Reduction Techniques in Electronic Systems*, 2nd ed. New York: Wiley, 1988.

[3] R. Voelker, "Transposing conductors in signal buses to reduce nearest-neighbor crosstalk," *IEEE Trans. Microwave Theory Tech.*, vol. 43, no. 5, pp. 1095–1099, 1995.

[4] N. Kim *et al.*, "Reduction of crosstalk noise in modular jack for high-speed differential signal interconnection," *IEEE Trans. Adv. Packag.*, vol. 24, no. 3, pp. 260–267, 2001.

[5] M. Sung *et al.*, "Microwave frequency crosstalk model of redistribution line patterns on wafer level package," in *Proc. 10th Topical Meeting on Electrical Performance of Electronic Packaging*, Oct. 2001, pp. 109–112.

[6] P. E. Fornberg *et al.*, "The impact of a nonideal return path on differential signal integrity," *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 1, pp. 11–15, 2002.