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

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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 multi-layer 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.

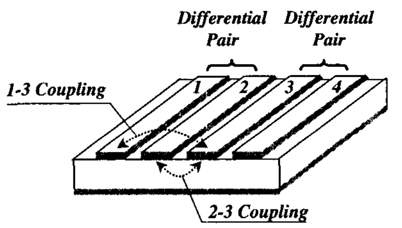
Index Terms – Twisted Differential Line, Differential Signaling, Crosstalk, Radiated Emission, Transmission Line, Twisted Pair

Ⅰ. Introduction

The ever-increasing processing speed of microprocessor motherboards, optical transmission links, intelligent hubs and routers, etc., is pushing the off-chip data rate into the Gbps range. In the last decade, high data rates were achieved by massive parallelism, with the disadvantages of increased complexity and cost for the IC packages and the printed circuit board (PCB). For this reason, the off-chip data rate should move to the range of Gbps-per-pin in the near future[1]. Indeed, the design roadmap of Semiconductor Industry Association (SIA) forecasts that a board-level clock frequency will be over 1 GHz in 2005[2]. To ensure reliable operation at such a high data rate, differential signaling has become a popular choice for multi-gigabit digital applications, such as Serial- ATA, Fiber Channel, Infiniband, OIF, RapidIO, and XAUI[3]. The differential signaling implies that two signal traces are sourced with an equal magnitude, and a 180-degree phase shift between them. Signaling in this manner offers benefits for some applications. If properly designed, one such benefit is reduced electromagnetic interference (EMI) due to the cancellation of the magnetic fields resulting from the opposing current flows. From signal integrity standpoint, the differential signaling is more robust, in that it is less susceptible to external noise. It has the ability to reject common mode noise such as crosstalk, simultaneous switching noise (SSN), power supply and ground bounce noise[4].

To support the differential signaling, differential transmission lines are required. Conventional differential line structures on multi-layer PCBs include the coupled microstrip lines (MCLIN), coplanar strips (CPS), edge-coupled striplines, and broadside-coupled striplines. While each of the conventional differential transmission lines has pros and cons of its own, all of them still have a common critical problem. In many cases, more than two differential pairs should run in parallel. [Fig. 1] represents the MCLIN configuration as a typical example. In such circumstances, a line is mainly affected from the line right next to it because all the lines are parallel in fixed order. For example, the line #2 is tightly coupled to the line #3. On the contrary, the line #1 is not much affected from the line #3. In this way, the two lines that constitute a whole differential pair are subjected to different levels of crosstalk. In other words, they suffer from differential crosstalk. Therefore, it cannot be canceled out by virtue of differential signaling. This is a common occurrence in any other conventional structures.

To overcome this problem of conventional differential line structures, we propose a new Twisted Differential Line (TDL) structure on a multi-layer PCB by using the concept of a twisted pair in the cable interconnection. The improved immunity of the proposed TDL to crosstalk and the reduced radiated



[Fig. 1] Conventional coupled microstrip line (MCLIN) configuration where two differential pairs (four lines) run in parallel.

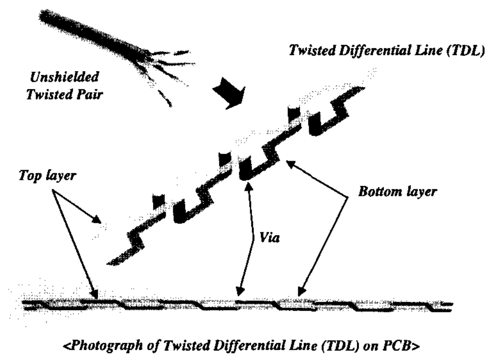
emission has been successfully demonstrated by measurements. The TDL is proven to transmit a 3 Gbps signal with a clear eye-pattern. Furthermore, it is demonstrated that it suffers much lower crosstalk and achieves considerable suppression of radiated emission.

Ⅱ. Proposed Twisted Differential Line Structure

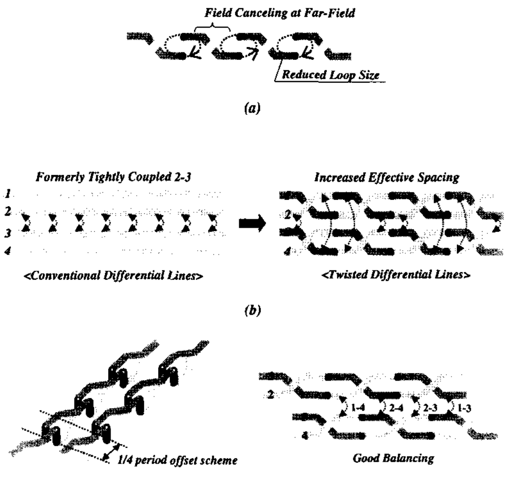
As is well known in the field of cable interconnection, a twisted pair provides a simple means of reducing the susceptibility to external noise[4]. Due to the signal and return wires being intertwined, any external signal collected by one wire is also collected by the other wire. Thus, a differential receiver can be directly used at the receiving end to filter out the signal common in both wires. It is further well known that the reduced loop area formed by the signal and return wires of a twisted pair greatly minimizes the radiated emission. This traditional concept of the twisted pair can be readily applied to the differential line on a PCB, which enhances immunity to crosstalk and other external noise.

[Fig. 2] shows the schematic and the photograph of the proposed TDL structure, where it mimics the twisted pair in the cable interconnection. The TDL is composed of two-segmented conductor traces on a first and a second layer of the PCB crisscrossing each other and many vias. The two-segmented conductor traces on the first layer are connected to those of the second layer through the vias to produce two continuous conductor traces.

The TDL has several advantages because of its physical configuration as illustrated in [Fig. 3]. First, the electromotive force (EMF) in a loop, which is



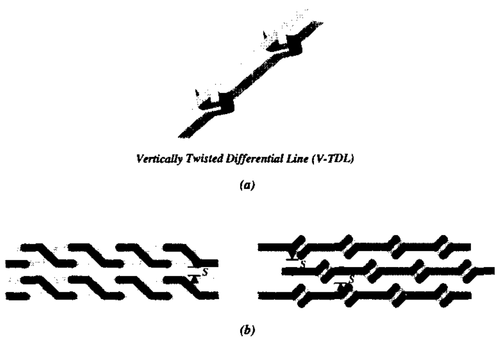
[Fig. 2] Schematic and photograph of the newly proposed Twisted Differential Line (TDL) structure on high-speed multi-layer PCBs.



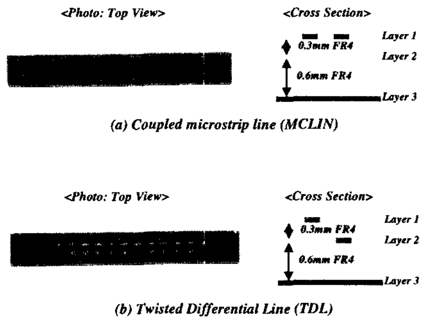
[Fig. 3] Several advantages of the proposed TDL due to its novel physical configuration.

generated by an external time-varying magnetic field, is canceled out by the EMF of the subsequent loop [Fig. 3(a)]. The advantages of the TDL become obvious when several differential pairs run in parallel on a PCB. In the conventional differential lines (see [Fig. 1]), two nearest-neighboring lines are tightly coupled over their entire length. However, in the TDL, any two formerly nearest-neighbor lines are periodically transposed [Fig. 3(b)][5]. This increases the effective spacing between them, therefore reducing the average mutual capacitance and inductance, and finally the crosstalk. Furthermore, if we offset all the neighboring vias, the four lines of the two differential pairs take turns affecting one another [Fig. 3(c)]. By using the offset scheme (a quarter of a period offset turns out to be the most effective), each trace of a differential pair can be equally influenced by adjacent traces of the next differential pair. This balanced crosstalk[6] cancels out by virtue of the differential signaling.

If a reference plane is in close proximity to a differential pair such as the MCLIN configuration, some portion of return current flows on the reference plane[7]. This can induce common-mode currents that can increase the radiated emission, even when the signal is sourced differentially. However, the proposed TDL can transmit over GHz signal even without a reference plane. The TDL supports the pure odd mode and it is safer from the common-mode radiation. On the other hand, it may exhibit much more current crowding in the edge of the conductors like an edge-coupled stripline, which can lead to significant increases in loss over typical lines. Thereby, we also propose Vertical TDL as shown in [Fig. 4]. In the Vertical TDL, two conductor traces vertically overlap and they widen only when they are twisted by changing layers [Fig. 4(a)]. Since the two lines are broadside-coupled, the conductor loss due to the current crowding effect at the edge can be reduced. Most of all, if we apply the offset scheme to the Vertical TDL (i.e. Vertical Offset TDL), we can route 1.5 times more signal lines in the same area, maintaining the crosstalk immunity [Fig. 4(b)].



[Fig. 4] Vertical TDL.



[Fig. 5] Photograph and schematic of the tested differential lines; (a) MCLIN, (b) TDL.

In designing the TDL, the increased length for twisting results in the increased time delay, which makes inroads on the timing margin of high-speed digital systems. Therefore, it should be balanced against the improvement in noise immunity. Finally, the differential impedance of the TDL is easily controllable over a wide range by changing the number of vias (i.e., the number of twists) as well as by changing the dimension of the line and via. The finite difference time domain (FDTD) method based on Floquet's theorem[8] may be very helpful in controlling the differential impedance in the early stage of design.

Ⅲ. Measured Eye, Crosstalk and Radiated Emission from Proposed TDL

First, we compared the TDL and the conventional MCLIN in terms of transmission bandwidth. [Fig. 5] shows the photographs and the schematic of the test differential line structures on the PCB, including (a) the MCLIN and (b) the TDL. Both were designed for the differential impedance to be 100 Ω. The pattern length is commonly 100 mm in a straight line. We employed a three-layer PCB and FR4 substrate having the relative dielectric constant (ε_r) of 4.5 between each metal layer. The third layer is used as a solid reference plane for both the MCLIN and the TDL. It corresponds to the power or ground plane in the conventional layer stacking. While the MCLIN used the first layer only, the TDL was implemented on the first and the second layer for twisting. Further, since through-hole vias were used for the TDL, there were anti-pads around the vias in the third layer isolating signal traces from the reference plane.

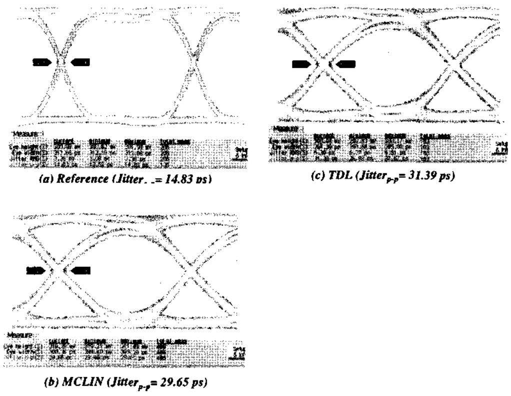
[Fig. 6] shows experimental setup. The pulse pattern generator (HP70841B) with the error detector (HP70842B) input the 3 Gbps 2^{31}-1 non-return-to-zero (NRZ) pseudo-random pulse sequence (PRBS) and its inverted sequence to one side of the tested differential lines. After passing the device-under-test (DUT), an output signal from the other side of the DUT was differentially detected at the digital sampling oscilloscope (Agilent 86100A). SMA connectors were used for the link between the DUT and coaxial cables, and the connector pad effect can be neglected due to long pattern length.

[Fig. 7] shows the measured eye diagram. [Fig.

[Fig. 6] Experimental setup for eye diagram measurement.

7(a)] can be considered as a reference, where the pulse pattern generator is directly connected to the oscilloscope without passing any DUT. In this case, the peak-to-peak jitter at the zero crossing point was measured 14.83 ps, and the eye height and the eye width was 381 mV and 312 ps, respectively. [Fig. 7(b)] shows the result of the MCLIN, where the peak-to-peak jitter, the eye height, and the eye width was 29.65 ps, 310 mV, and 300 ps, respectively. Lastly, [Fig. 7(c)] shows the result of the TDL, where the peak-to-peak jitter, the eye height, and the eye width was 31.39 ps, 300 mV, and 294 ps, respectively. It was commonly observed for the MCLIN and the TDL that the rising time became much slower compared with the reference, resulting from the connectors.

It should be noticed that the TDL showed a similar performance to the MCLIN. At a glance, since the TDL contains many vias and segmented traces, it is expected to have greater conduction loss and reflections at discontinuities compared with the conventional differential lines. Nevertheless, the clear eye-pattern of the TDL demonstrates successful

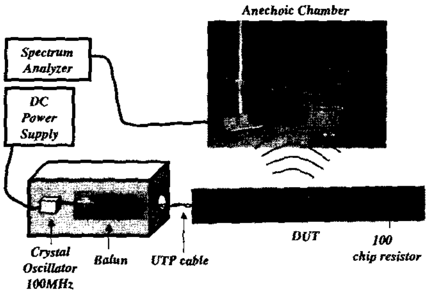


[Fig. 7] Measured eye diagram; (a) the pulse pattern generator is directly connected to the oscilloscope without passing any DUT (reference), (b) MCLIN, (c) TDL.

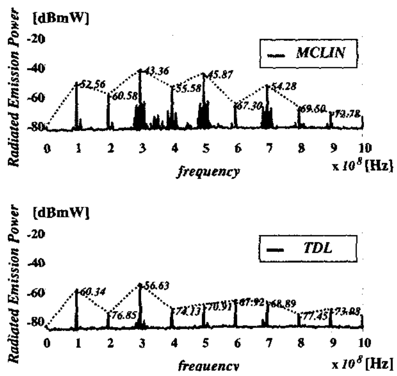
digital data transmission over 3 Gbps. In addition, as the number of twists increased, the measured jitter also increased. While the peak-to-peak jitter of the TDL of 6 twists in 100 mm was 31.39 ps (See [Fig. 7(c)], those of the TDL of 12 twists and 24 twists were measured 35.03 ps and 37.68 ps, respectively. Since the increased jitter makes inroads on the timing margin of high-speed digital systems as mentioned earlier, thereby it should be balanced against the improvement in noise immunity. Finally, the Vertical TDL showed a similar performance.

Second, we measured the radiated emission spectrum from the test differential lines in an anechoic chamber. [Fig. 8] shows experimental setup. The digital periodic signal was applied using a crystal oscillator of 100 MHz, and the spectrum was composed of the harmonics of 100 MHz. The balun (DC~600 MHz) and the unshielded twisted pair (UTP) cable were used for signal feeding. All the devices except the DUT were well shielded. The

MCLIN and the TDL (See [Fig. 5]) were compared, and each of them was terminated with a 100 Ω chip resistor.



[Fig. 8] Experimental setup for radiated emission measurement in anechoic chamber.

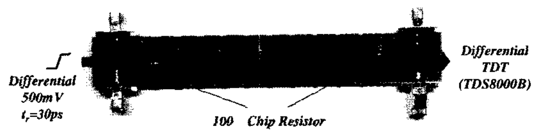


[Fig. 9] Measured radiated emission power.

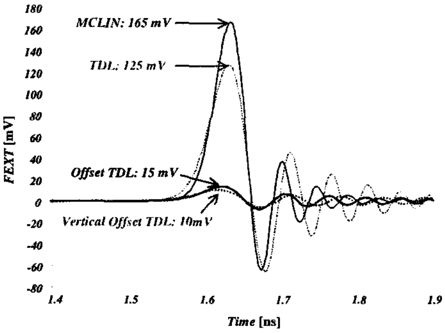
[Fig. 9] shows the measured radiated emission spectrum, where the peak envelope was indicated by a dotted line. In the case of MCLIN, the peak was observed −43.36 dBmW at the third harmonics, whereas the peak was −56.63 dBmW in the case of TDL. Therefore, the TDL achieves 13 dB suppression of radiated 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. In addition, as the number of twists is increased, the reduction of the radiated emission is observed to be slightly enhanced. We can also imagine that due to duality and reciprocity, the same conclusions with respect to elimination of emissions, can similarly be applied to the coupling of external electromagnetic waves.

Third, we also measured the far-end crosstalk (FEXT) voltage waveform of two differential pairs with differential time domain transmission (TDT) measurement. [Fig. 10] illustrates the experimental setup of crosstalk measurement. The digital sampling oscilloscope (TDS8000B) with TDR/TDT module (80E04) was used. A differential step pulse having 500 mV in magnitude and 30 ps in rising time was input to one end of a differential line, and the FEXT voltage was measured at the far end of the other differential line. At that time, the remained ports were terminated with 100 Ω chip resistors as shown in the figure.

We tested various types of differential lines including the MCLIN, the TDL, the Offset TDL, and the Vertical Offset TDL. Each of them was designed to have the differential impedance of 100 Ω. The gap between two differential pairs is commonly 1 mm from edge to edge in all cases. The measured FEXT voltage waveform is shown in [Fig. 11]. The FEXT of the TDL is somewhat reduced to 125 mV,



[Fig. 10] Experimental setup for crosstalk measurement with differential TDT.



[Fig. 11] Measured far-end crosstalk (FEXT) waveform.

compared with the MCLIN, at 165 mV. This results from the increased effective spacing between two differential pairs (See [Fig. 3(b)]. Furthermore, the FEXT of the Offset TDL is significantly reduced to 15 mV, less than one tenth of the FEXT of the MCLIN. 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 (See [Fig. 3(c)] improves the crosstalk immunity further. Lastly, the Vertical Offset TDL shows similar performance to the Offset TDL.

Ⅳ. CONCLUSIONS

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. 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.

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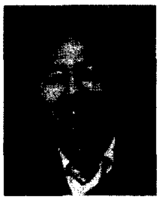

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