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Signal Transmission Analysis of Differential Pairs Using Semicircle-Shaped Via Structure

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***Abstract*—**In this paper, the signal transmission analysis of the semicircle-shaped via structure for the differential pairs is presented in the frequency range up to 10 GHz. In order to improve the signal transmission properties in the differential pairs, single via is separated centrally into two semicircle-shaped sections, which are interconnected with the traces of differential pairs respectively. This via structure make possible to route differential pairs using only one via. In addition, it can improve impedance discontinuity around its region and then enhance the signal transmission properties in the differential pairs. The electrical analysis such as S-parameter calculation and eye diagram simulation has been performed to investigate the improvement of the signal transmission property in the differential pairs with new via structure.

***Keywords*—**Differential pairs, signal transmission property, via, S-parameter.

I. INTRODUCTION

RECENT trends in the development of electronic components and digital products have required high-speed operation, miniaturization, and multifunction. Because of these trends, high density technologies to components mounting and trace routing have been introduced in the printed circuit boards (PCBs). In addition, input/output signal transmission speed is also continuously increasing. However, single-ended signaling can be difficult to obtain the signal integrity in PCBs with high wiring density and high-speed operation [1-2]. As a result, a high-speed signal in a digital data transmission technology has been adopted as a differential signaling [3-4].

The differential signal is out-of-phase with each other, as opposed to the two adjacent traces should use the way to transfer data. It is possible to transfer high speed data with low voltage operation and low power consumption by detecting the phase difference between the two signals at the receiver. In addition, the differential signal has advantages in reducing crosstalk, electromagnetic interference, power-ground resonance, and common mode noise. However, two signal traces are required to transmit data and then it causes an increase in wiring area of PCB.

Via in high speed operation with several Gbps is known as one of the main reasons to deteriorate the signal fidelity. Thus, it is necessary to minimize the signal reflection around via area by optimizing via structure. This effect can increase the transmission rate in the differential signaling technology.

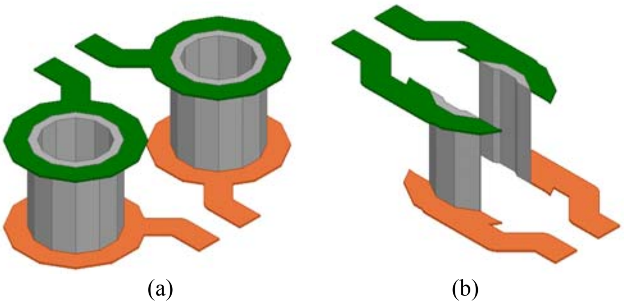

Fig. 1. Via structure for differential signaling: (a) conventional via pairs and (b) new via pairs

In this paper, the via pairs for the differential signaling are proposed to improve signal transmission properties while enhancing the effective area of the wiring. The signal transmission properties such as insertion loss, reflection loss, and eye diagram are investigated in this work.

II. VIA STRUCTURE

By maintaining a constant spacing between two traces of the differential signal line on PCB, its characteristic impedance can obtain a consistent value (100 Ω). However, if via is used, the signal traces can not keep same line spacing. For a conventional via structure, it requires a wide wiring area on PCB due to its large design rule and results in an increase in the spacing between two traces. Therefore, these effects can cause a decrease of the differential impedance and then the impedance discontinuity may be occurred in the differential pairs. Finally, the signal reflection at the via region is increased and then its signal transmission characteristics can be degraded. Therefore, the via structure and its placement on PCB are one of main design factors that determine a signal quality in the differential pairs.

For high-speed differential signaling, the via pairs with a relatively constant spacing are proposed and its signal transmission properties are analyzed in this work. Fig. 1 shows the conventional via pairs and the new via pairs for the differential lines on 4-layer PCB stackup configuration. As shown in Fig. 1(a), the signal traces are routed in pairs by placing two conventional vias. Because these vias are necessary to separate the others with a wide spacing, the distance between signal lines is increased and then the

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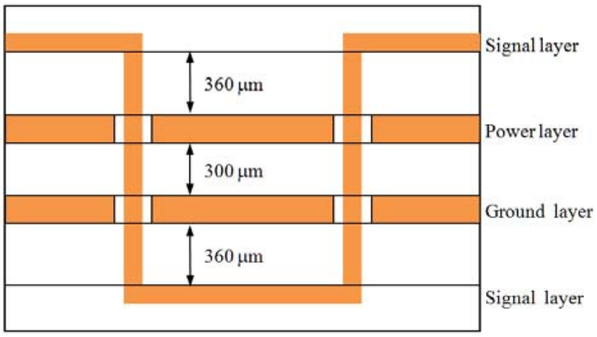


Fig. 2 Cross section of the via transition in the 4-layered printed circuit board

impedance discontinuity occurs around the via area. In a new structure of Fig. 1(b), single via is divide centrally into two truncated parts that are interconnected with the traces of differential pairs respectively. Therefore, the spacing between two separated vias can maintain a relatively constant value even around via area. So, new via pairs have the advantages of keeping the consistent impedance matching and improving the signal fidelity of the differentia pairs.

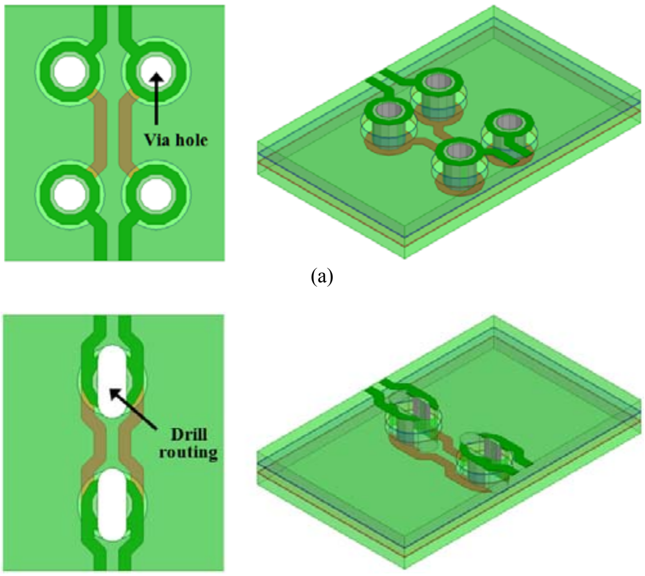
After the general fabrication process for the via is performed, new via pairs are formed through drill routing process which is intersecting its central area. The drill routing with smaller drill diameter than the via hole's diameter can provide two physically-separated and electrically-isolated vias. The conventional differential pairs have generally two vias with a shape of circle. But new differential pairs have two semicircle-shaped vias. Compared to conventional via pairs, new via pairs have the advantages of reducing by 50% of wiring area and then improving the complexity of the wiring design.

III. Design and Analysis

PCB stackup and differential signal line width/spacing are determined using 2-dimensional (2D) calculations (ANSYS 2D Extractor) for satisfying the differential impedance of 100 Ω. Fig. 2 shows a cross section of the via transition in 4-layered PCB with a thickness of 1.2 mm. The differential signal line with its thickness of 18 μm is routed from top layer to bottom layer through via transition and its line width and spacing are designed to be 300 μm and 340 μm respectively. The PCB has two solid inner planes for power supply and current return with their copper thickness of 35 μm and the height between top/bottom layer and plane has 360 μm. All the dielectric layers are assumed to be a dielectric constant of 4.4 and a loss tangent of 0.02. Except for whether or not to apply the drill routing, the same design parameters are used in both the PCBs with the conventional via and the new via. In the via structure, its land diameter of 1.8 mm, the via hole diameter of 1.0 mm, and the drill routing diameter of 0.4 mm were used. Because of the diameter's difference between via hole and drill routing, single via can be divided into two vias. But the signals can flow through the sidewall of these via hole.

TABLE I
DIFFERENTIAL IMPEDANCE OF THE CONVENTIONAL VIA PAIRS AND NEW VIA PAIRS

Parameter	CONVENTIONAL VIA PAIRS	New via pairs
L_s (nH)	1.405	2.022
L_m (nH)	0.456	0.746
C_s (pF)	0.773	0.475
C_m (pF)	-0.057	-0.047
Z_{odd} (Ω)	36.4	54.6
Z_{diff} (Ω)	72.8	109.2



(a)

(b)

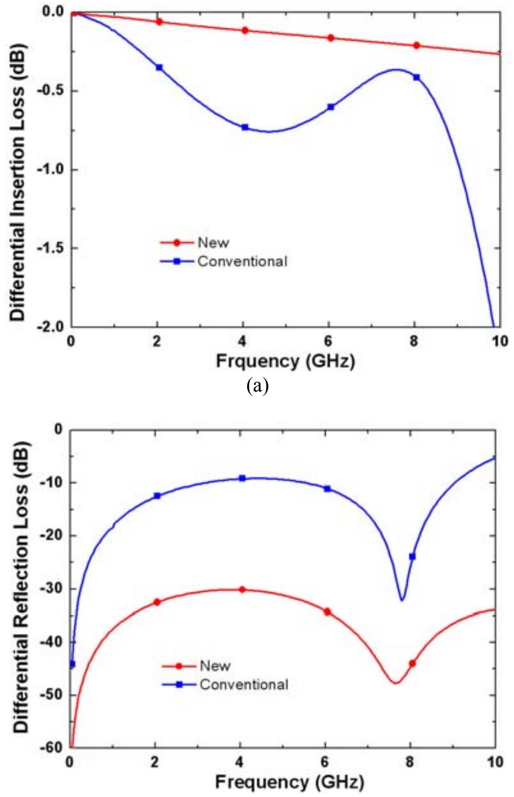
Fig. 3 Differential lines with (a) conventional via pairs and (b) new via pairs on the printed circuit board

In general, the signal transmission may be degraded by impedance discontinuities such as via and connector [3]. To analyze the difference of the impedance mismatching, the differential impedance (Z_{diff}) of each via pair is calculated using (1) and (2) [5]

$$Z_{odd} = \sqrt{\frac{L_s - L_m}{C_s + C_m}} \quad (1)$$

$$Z_{diff} = 2 \times Z_{odd} \quad (2)$$

where Z_{odd} is the odd mode impedance, L_s is the self inductance, L_m is the mutual inductance, C_s is the self capacitance, and C_m is the mutual capacitance. The via's inductances and capacitances are calculated using 3D simulation (ANSYS Q3D). The differential impedances, the inductances, and the capacitances for the conventional via pairs and the new via pairs are shown in Table 1. Compared to the inductances and the capacitances of the conventional via pairs, the self inductance (L_s) of the new via pairs is increased due to the reduction in the cross-sectional area of its hole while its self capacitance (C_s) is decreased due



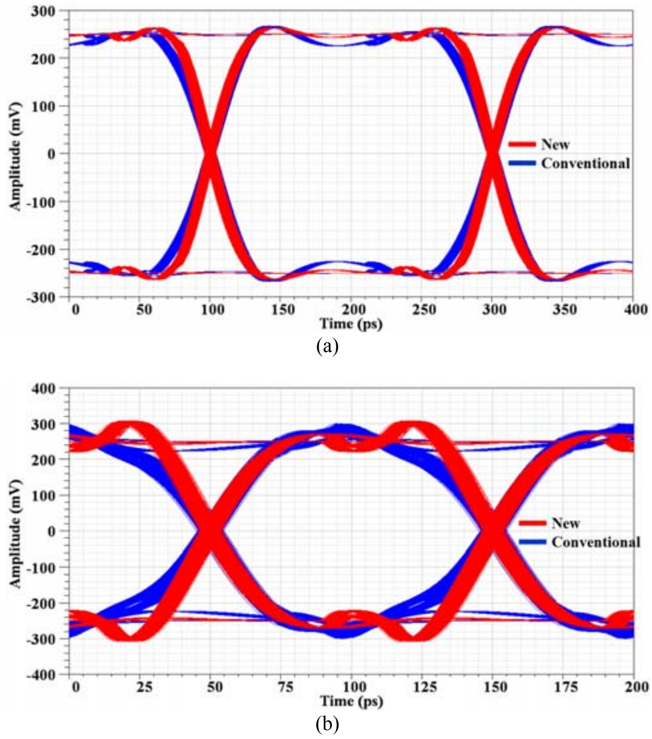
(a)

(b)

Fig. 4 Differential insertion loss (S_{dd21}) (a) and differential reflection loss (S_{dd11}) (b) of the differential lines with conventional via pairs and e new via pairs

to reduction in its copper dimension. The differential impedances of both via pairs are changed by these effects. The differential impedance of the conventional via pairs is calculated to be 72.8 Ω. However, that of the new via pairs is to be 109.2 Ω. Because the impedance matching is relatively closed to 100 Ω in the case of the new via, it is expected that its signal transmission will be improved.

The signal transmission properties of the differential pairs with each via pair are calculated using 3D calculation (ANSYS HFSS). Fig. 3 shows the 3D models of differential pairs. Their models include each via pair and the differential signal trace with a length of 6 mm. In order to investigate the change in the signal transmission properties by the difference of the via structure, the length of the differential traces is designed to be minimized. The differential insertion loss (S_{dd21}) and the differential reflection loss (S_{dd11}) of the differential pairs are shown in Fig. 4. In the result of the differential insertion loss, the differential lines with new via pairs have superior performance in all frequencies. Also, the differential reflection loss is improved by more than 20 dB in most of high frequencies as compared to the conventional via pairs. The differential insertion loss in the conventional via pairs increases rapidly at more than 8 GHz while one in the new pairs keeps a relatively steady loss even at 10 GH. The closer impedance matching through the change of the via structure cause the improved result of the differential return loss and also enhance the of the differential insertion loss. A major factor in improved impedance matching of the new via pairs is to maintain a constant spacing at each pair. These results demonstrate that the new via pairs can provide excellent signal fidelity at high-speed operation of up to 10 GHz.



(a)

(b)

Fig. 5 Eye diagrams of differential lines with a 2^{15}-1 bit PRBS data pattern and a data rate of (a) 5 Gbps and (b) 10 Gbps

In general, eye diagram is a useful metric of intuitively and clearly estimating the performance quality of high-speed digital signals through various interconnection structures such as via and connector [6-8]. The eye diagram is determined by overlapping the continuous voltage output for pseudo-random bit sequence (PRBS) input signals. Fig. 5 shows the eye diagrams of differential lines applying both via pairs. The eye diagrams are calculated using a 2^{15}-1 bit PRBS data pattern (ANSYS Designer). The differential signal has a pattern of a data rate of 5 Gbps and 10 Gbps with rise time of 42 ps and 21 ps respectively. As clearly shown in Fig. 5, it is obvious that the differential line with new via pairs shows better eye opening compared to that with conventional ones. Slight improvement in the eye height and falling edge at 5 Gbps operation is presented while noticeable eye opening is demonstrated at a data rate of 10 Gbps. This clearly difference is due to the fact that new via structure has superior signal transmission properties by reducing the impedance mismatching around its region.

IV. CONCLUSION

In this work, the signal transmission analysis of the differential pairs applying the semicircle-shaped via pairs is performed. To improve the signal transmission properties in the differential pairs on the PCB, single via is divided centrally into via pairs with a semicircle shape. Therefore, the new via pairs make possible to route differential lines using only one via and have advantage of reducing the wiring area and then improving the complexity of the routing design.

The differential impedance of the new via pairs is calculated to be 109.2 Ω. The impedance of the via pairs is well matched with the differential impedance. In S-parameter results of the differential lines applying the new via pairs, their differential insertion loss and the differential reflection loss are greatly improved in all the frequencies as compared to those of the conventional via pairs. Also, the better eye opening at 10 Gbps operation is presented through the eye diagram simulation of the differential lines. These results indicate that the new via pairs have advantage of providing excellent signal transmission properties at high-speed operation of up to 10 GHz.

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