# Parametric Investigation of Near End and Far End Crosstalks and Signal Integrity in Multiconductor Transmission Lines on Printed Circuit Board

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***Abstract-*** *Multiconductor transmission lines and interconnects carry signals with wide range of frequencies ranging from DC to few GHz. Due to mutual coupling among the lines; signal in the aggressor line induces crosstalks in the victim lines. Furthermore, signal in one line may be corrupted by the unwanted contributions from the neighboring line conductors. As the data speed increases, high frequency effects take over and the signals suffer from problems such as ringing, crosstalk, reflections, and ground bounce that seriously hamper the quality of the received signal. In order to estimate the signal quality, signal integrity analysis is needed. In this paper, an attempt has been made to investigate rigorously the near and far end crosstalks and signal quality in the multiconductor transmission lines mounted on the printed circuit boards by varying the parameters such as physical geometry of the lands, electrical property of the substrate ($\varepsilon_r$) and the nature of excitation signal. It has been observed that the coupling inductances and capacitances vary with the variation of geometry and the substrate parameter and that consequently cause an equivalent change in the crosstalks among the lines. A multiconductor transmission line computer code based on the method of moments is used to calculate the line parameters for different geometries. The time domain and frequency domain analyses of near end and far end crosstalks are made by using SPICE multiconductor subcircuit models. Some experimental results are presented to validate the analytical findings.*

***Key words****: Multiconductor transmission lines, Crosstalk, Signal Integrity.*

## 1. Introduction

The multiconductor transmission lines (MTL) etched on printed circuit boards (PCB) carry information in wide range of frequencies depending on their application. In an MTL system consisting of N conductors and a conducting shield or common return conductor, signal in one conductor induces unwanted signals on the other due to coupling line parameters, which is commonly known as crosstalk. Crosstalks in an MTL system are undesirable and sometimes very harmful. It can cause penetration of a signal excited in one simple transmission line (STL) into the near end and far end loads of another STL. The magnitude of crosstalk may set limits to the dynamic operating range of circuits, to the frequency band of their application and to the scale of miniaturization. This necessitates a rigorous investigation of signal integrity so that the circuit could be designed to provide relatively pure signals [1-2, 4-9]. In general, the MTL structure is capable of guiding wave whose frequencies range from DC to where the line dimensions are a fraction of wavelength. There are many applications for this wave guiding structure. A PCB consists of a planar dielectric on which conductors of rectangular cross section (lands) serve to interconnect digital devices as well as analog devices Crosstalk can be a significant functional problem with PCBs as it can degrade the quality of signal considerably. In the high speed circuits, among other factors, signal degradation due to crosstalk is very important quantity needed to be investigated thoroughly. Many researchers are working on crosstalks and their minimization techniques. In particular, for designing high speed interconnects on PCB substrates, crosstalk is a major factor that affects the signal integrity considerably. Application specific works are also being undertaken to investigate the influence of crosstalks on system performance [9-12].

In this paper, we have tried to investigate the crosstalks on PCB lands in a generalized way; no attempt has been made for minimization of the crosstalk. The calculated results have been validated by experimental investigations.

## 2. MTL Equation

Using distributed parameter model, equation for a loss-less MTL system are derived in matrix form as follows[1-3,6],

$$\frac{\partial}{\partial z}[V(z,t)] = -[L]\frac{\partial}{\partial t}[\mathrm{I}(z,t)] \qquad (1a)$$

$$\frac{\partial}{\partial z}[\mathrm{I}(z,t)] = -[C]\frac{\partial}{\partial t}[V(z,t)] \qquad (1b)$$

Where, $[V(z,t)]$ and $[I(z,t)]$ are voltage and current vectors whose dimensions depend on the number of conductors in the MTL system, and $[L]$

and $[C]$ are the per unit length (PUL) inductance and capacitance matrices, respectively. The off-diagonal terms of the matrices are the mutual parameters that are responsible for crosstalks. The equations (1a) and (1b) are coupled equations. Analytical and numerical methods are generally used to solve these coupled equations for predicting the crosstalk. Determination of the line parameters is the key step for solving equations (1a) and (1b) both in time and frequency domains. The circuit model of the transmission line as implemented in the SPICE/PSPICE environments can also be used to determine the time domain and frequency domain responses of the near end crosstalk (NEXT) and far end crosstalk (FEXT) in the victim lines [1, 4]. In this paper, the line parameters are calculated using a computer code based on the method of moments (MoM) [1-4, 13]. The results are used to feed the SPICE/PSPICE model and OrCAD 10. PSPICE is used to calculate the time domain and frequency domain responses for different geometrical and substrate parameters of the MTL system.

### 3. Determination of Per Unit Length Parameter

As has been mentioned earlier, MoM based computer code has been used to calculate the PUL inductance matrix [L] and capacitance matrix [C]. In this paper, as shown in Fig. 1, five parallel lines etched on a PCB are used for investigation.

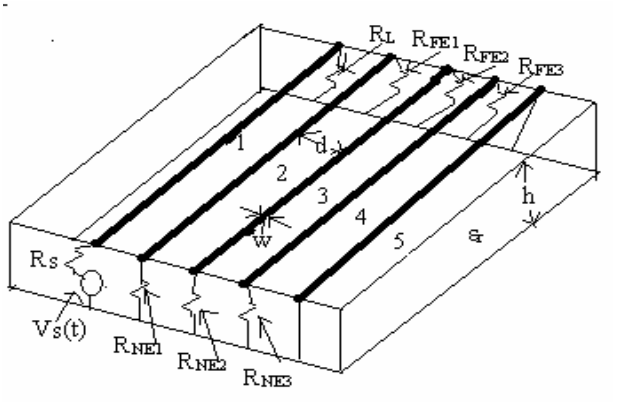



**Fig. 1 The layout of an MTL system with five lands on a PCB**

In Fig. 1, the leftmost land is designated as the reference conductor. The computed PUL inductance matrix [L] and capacitance matrix [C] for different PCB substrates are shown in Table 1 (a) and (b). For same circuit length and spacing among conductors, [C] varies with the dielectric constant, $\varepsilon_r$.

**Table 1 (a) Elements of the [C] matrix for an MTL system with four line conductors. Calculations are performed for two commercial PCBs GETEK ($\varepsilon_r$=3.9) and GE($\varepsilon_r$=4.7).**

| pF/m | GETEK $\varepsilon_r$=3.9 w=15mils, d=45mils | | GE $\varepsilon_r$=4.7 w=15mils, d=45mils | |
|---|---|---|---|---|
| | h=47mils | h=70 mils | h=40 mils | h=62 mils |
| $C_{11}$ | 27.1220 | 28.4718 | 30.0761 | 32.2045 |
| $C_{12}$ | -16.1792 | -16.2230 | -18.7159 | -18.9862 |
| $C_{13}$ | -2.75150 | -3.21406 | -2.75602 | -3.37270 |
| $C_{14}$ | -3.18907 | -3.44014 | -3.34410 | -3.63801 |
| $C_{22}$ | 36.4076 | 37.3091 | 41.3613 | 42.9964 |
| $C_{23}$ | -3.95402 | -4.44419 | -4.13545 | -4.92550 |
| $C_{24}$ | -2.75150 | -3.21406 | -2.75598 | -3.37269 |
| $C_{33}$ | 36.4076 | 37.3091 | 41.3613 | 42.9964 |
| $C_{34}$ | -16.1792 | -16.2230 | -18.7159 | -18.9862 |
| $C_{44}$ | 27.1220 | 28.4718 | 30.0761 | 32.2045 |

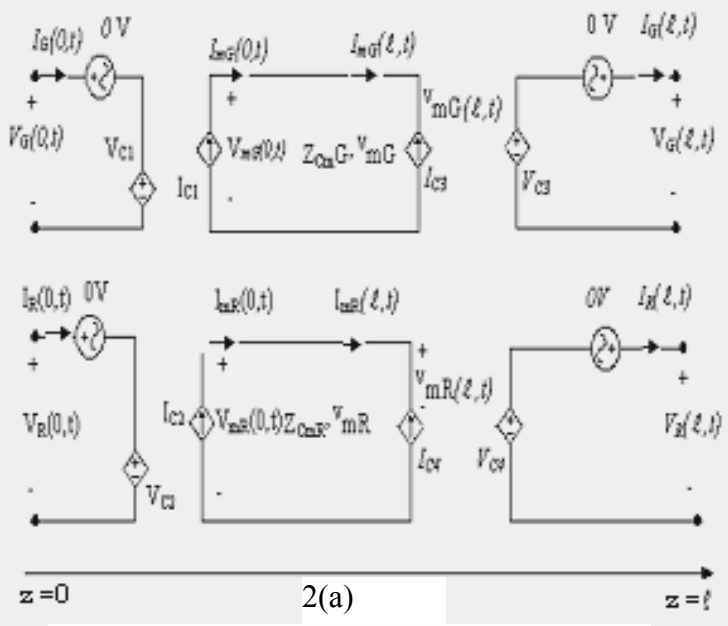
**Table 1 (a) Elements of the [L] matrix for an MTL system with four line conductors. Calculations are performed for two commercial PCBs GETEK ($\varepsilon_r$=3.9) and GE($\varepsilon_r$=4.7).**

| μH/m | GETEK $\varepsilon_r$=3.9 w=15mils, d=45mils | | GE $\varepsilon_r$=4.7 w=15mils, d=45mils | |
|---|---|---|---|---|
| | h=47mils | h=70mils | h=40 mils | h=62 mils |
| $L_{11}$ | 1.38237 | 1.38237 | 1.38237 | 1.38237 |
| $L_{12}$ | 0.690999 | 0.690999 | 0.690999 | 0.690999 |
| $L_{13}$ | 0.472266 | 0.472266 | 0.472266 | 0.472266 |
| $L_{14}$ | 0.552045 | 0.552045 | 0.552045 | 0.552045 |
| $L_{22}$ | 1.10665 | 1.10665 | 1.10665 | 1.10665 |
| $L_{23}$ | 0.415758 | 0.415758 | 0.415758 | 0.415758 |
| $L_{24}$ | 0.472266 | 0.472266 | 0.472266 | 0.472266 |
| $L_{33}$ | 1.10665 | 1.10665 | 1.10665 | 1.10665 |
| $L_{34}$ | 0.690999 | 0.690999 | 0.690999 | 0.690999 |
| $L_{44}$ | 1.38237 | 1.38237 | 1.38237 | 1.38237 |

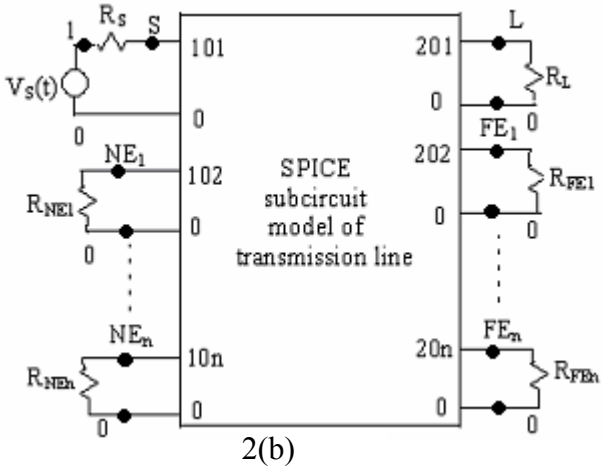
### 4. Time Domain and Frequency Domain analyses of NEXT and FEXT

As presented in the earlier in section 2, the MTL equations are coupled differential equations. They could be uncoupled to modal equations using similarity transformation. This technique has been developed in [1, 2]. A computer code is also available for building SPICE subcircuit model of the MTL system on different media such as microstrip lines, ribbon cable and PCB lands [1].

The complete SPICE model for the PCB structure is shown in Fig. 2 (a) and corresponding node numbering for the SPICE subcircuit model is shown in Fig. 2 (b)[1, 5]. This node numbering scheme is used in the subsequent texts and figures.



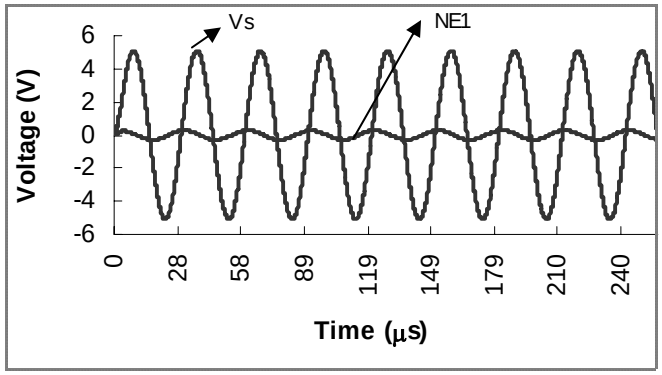

2(a)



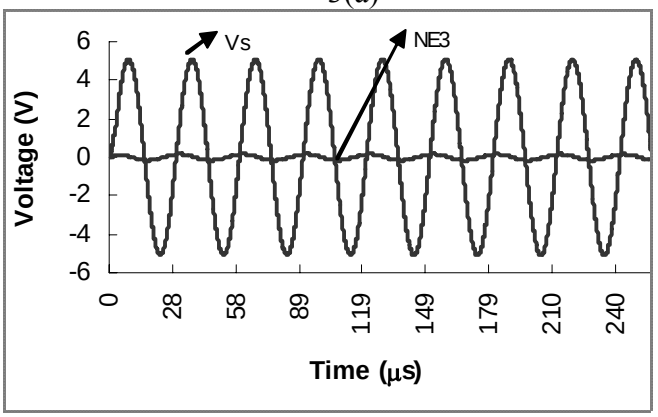

2(b)

**Fig. 2 (a) The complete SPICE model (b) Node numbering for the SPICE subcircuit model, source can be placed at the input node of all lines simultaneously.**

The time domain analysis of NEXT and FEXT are made by considering sine wave signal. Signal is applied to the near end of the first line and crosstalks are monitored on the neighboring conductors. Figures 3(a) and (b) depict the NEXT at nodes NE1 and NE3 (near end of the third line), respectively and Figs 4(a) and (b) depict FEXT at nodes FE1 and FE3 (far end of the third line), respectively for a 10 V (p-p) and 0.33MHz sine signal applied at node S. The line parameters are shown in Table 1 (a) and, (b) and $R_S$= $R_L$=50Ω, $R_{NE1}$= $R_{FE1}$= 50Ω, $R_{NE2}$= $R_{FE2}$= 50Ω, $R_{NE3}$= $R_{FE3}$= 50Ω are used in the SPICE model. The magnitude of the crosstalk in the far displaced is less than that in the conductor next to line containing the source.

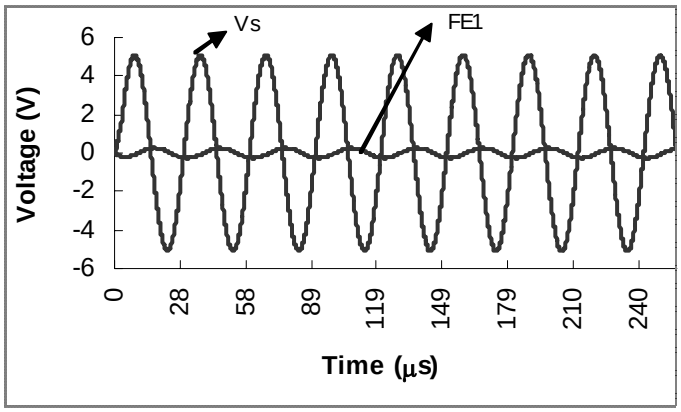



3(a)

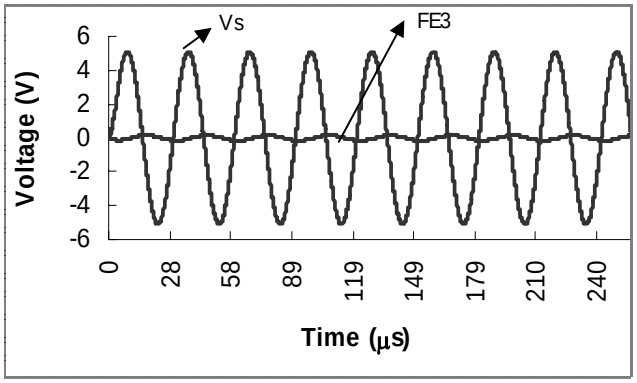



3(b)

**Fig. 3 (a) Source signal ($V_s$) at node S and NEXT at node NE1 and (b Source signal($V_s$) at node S and NEXT at node NE3 ( $\varepsilon_r$ =3.9, w=15mils, d=45 mils, h=47mils)**



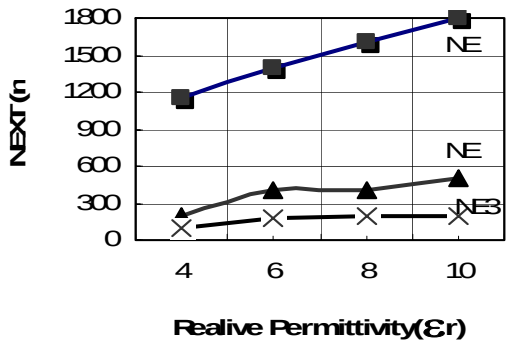

4(a)



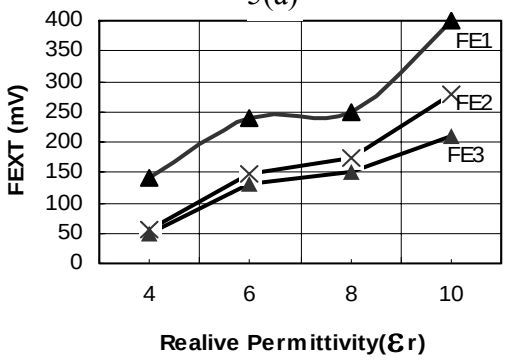

4(b)

**Fig. 4 (a) Source signal($V_s$) at node S and FEXT at node FE1 and (b Source signal($V_s$) at node S and FEXT at node FE3 ( $\varepsilon_r$ =3.9, w=15mils, d=45 mils, h=47mils)**

As the mutual capacitances among the MTLs depend on relative permittivity ($\varepsilon_r$), the crosstalks would also depend on the PCB types on which MTLs are etched. The peak value of the NEXT and FEXT are calculated for various values of $\varepsilon_r$ and the results are presented in Figs. 5(a) and 5(b), respectively for NEXT and FEXT



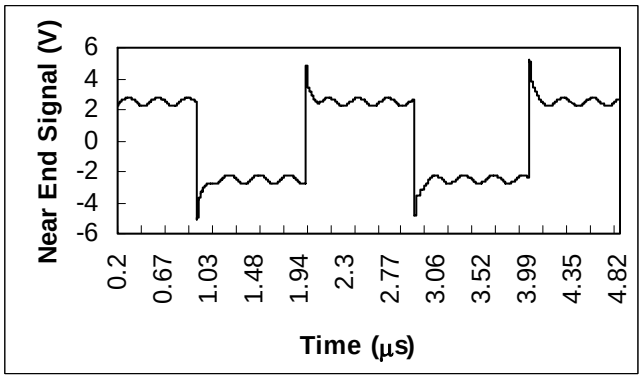

5(a)



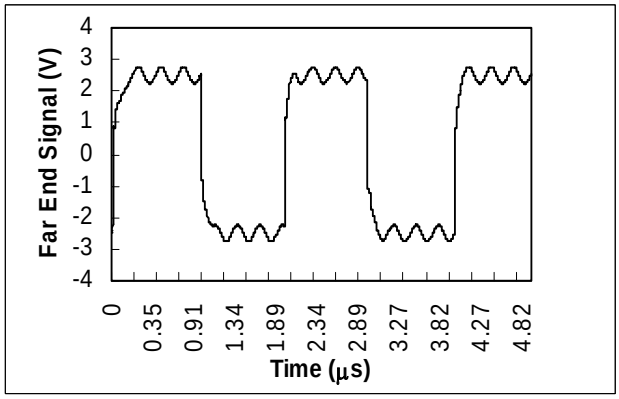

5(b)

**Fig. 6 (a) NEXT versus permittivity and (b) FEXT versus permittivity.**

In order to investigate the signal contamination, two lines are excited by two signals; a 10V (p-p), 3.33MHz sine signal applied in land 1 and a 10V, 2.33μs time period pulse signal applied in land 2 and the near end (NE2) and far end(FE2) signals in the land 2 are monitored. The results are shown in Fig. 6(a) and (b), respectively for near end and far end. It can easily be visualized from the figures that the original signals on both lines are contaminated by the crosstalk contribution from others and thereby signal quality is degraded.




6(a)

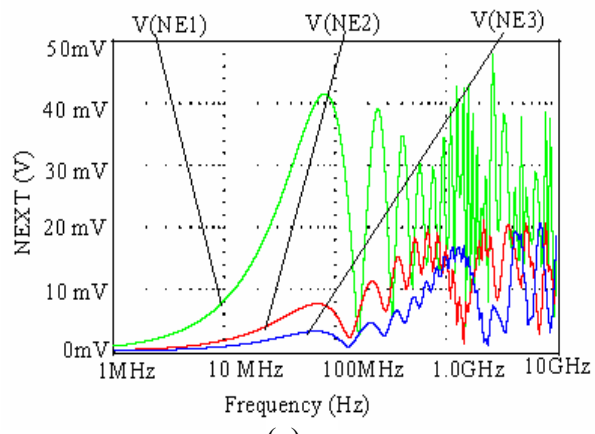



6(b)

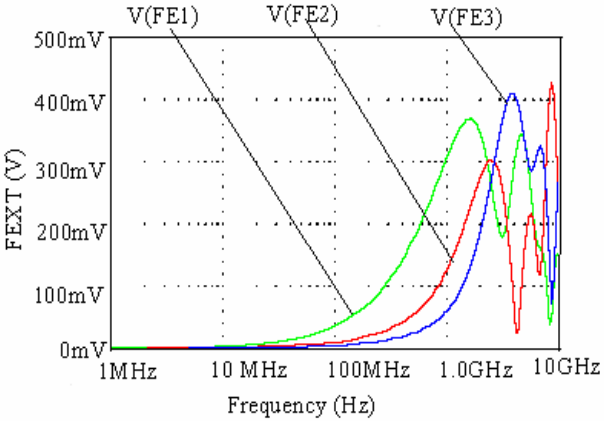
**Fig. 7. Signal contamination due to crosstalk from signals from neighboring lines. (a) Near end (NE2) signal and (b) Far end (FE2) signal. (h=62 mils, $\varepsilon_r$ =3.9, w=15mils, d=45mils)**

The sine wave signal in the first line is coupled with the pulse train in the second line and the signal integrity is lost eventually. As the far end terminations of the lines are not perfectly matched, the far end signals are contaminated greatly due to the reflection.

The frequency domain analysis is performed using sinusoidal source 1V (p-p). The source frequency is sweeped from 1 MHz to 10 GHz. The results are shown in Fig. 8(a) and (b). It can be seen from the figure that magnitude of NEXT and FEXT increases with frequency and at high frequency region some undulation appears and this will limit the speed of signal transmission over the MTL structure and miniaturization of the circuit.




(a)

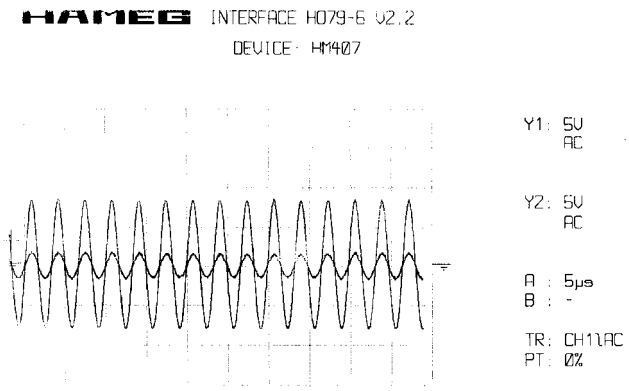



(b)

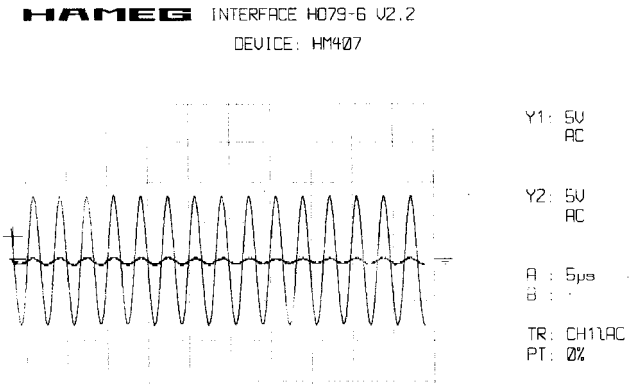
**Fig. 8 (a) NEXT and (b) FEXT in Frequency Domain. The signal is applied in the first line.**

## 6. Experimental Result

In order to investigate the crosstalks and signal integrity experimentally, a five conductor MTL system is etched on a PCB and time domain NEXT is measured by a digital storage oscilloscope (DSO). Figs. 9 (a) and (b) show the snapshots of the experimental oscillograms for the NEXT signal. The source, load, near end and far end resistances are same as that have been used in simulation. A continuous sinusoidal signal is applied in conductor 1 and the crosstalks on conductors 2 and 4 are monitored by the DSO. The closeness of the experimental results with their simulated counterparts can easily be visualized by comparing Figs 3(a) and (b) with Figs 9(a) and (b).




(a)




(b)

**Fig. 9 Oscillograms of the crosstalk measurements (a) NEXT on the second conductor and (b) NEXT on the fourth conductor**

In order to monitor the signal integrity experimentally, a sinusoidal signal is applied between the ground and the first conductor and a square wave is applied between the second conductor and ground. It has been observed that the second conductor signal is contaminated by the signal in the first conductor due crosstalk. The oscillogram of the experiment is shown in Fig. 10 and that agrees with the simulated result presented in Fig. 6(a).

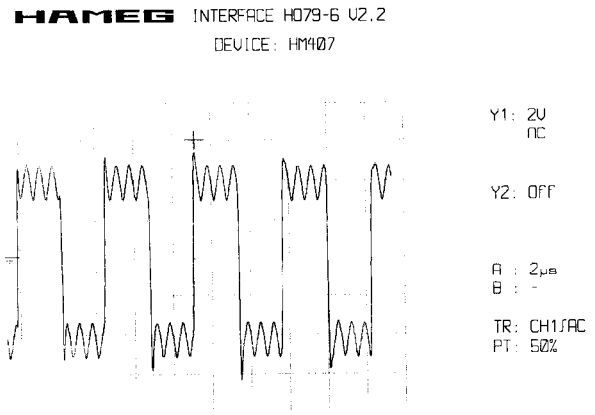



**Fig. 10. Oscillogram of the signal integrity measurement.**

## 7. Discussion and Conclusion

In this paper, a rigorous investigation is performed on the near and far ends crosstalks in MTL system on PCB structure generally used in electronic circuit boards. It has been observed that the magnitude of NEXT and FEXT is very sensitive with the size and substrate parameters. From the investigation, it has been observed that due to crosstalk among the lines, the simultaneous transmission of signals over the MTL system degrades the signal quality considerably. For a fixed set of parameters the magnitude of the crosstalk increases with increasing frequency. This type of analysis is particularly important to design PCB layouts and interconnects that handle high speed data. The time domain experimental results presented in Figs 9 and 10 show an excellent agreement with the theoretical findings. This investigation is not application specific [10-12]. However, PUL parameters are the crucial elements to be perfectly calculated in order to investigate the crosstalks and signal integrity which is common to all applications.

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