

LONG-LINE EFFECTS FOR MULTI-CONDUCTOR LINES EMBEDDED IN AN INHOMOGENEOUS MEDIUM

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Abstract: Crosstalk phenomena between two parallel conductors are well known up to a frequency range where the line length corresponds to one or two wavelengths. In this paper, considering the influence of the difference in two phase constants, or phase velocities in balanced and unbalanced modes, we examined crosstalk to a neighboring trace in addition to the throughput characteristics of the exciting trace up to frequencies of more than 10 wavelengths with 1-meter-long printed circuit board (PCB). We calculated characteristics of the far-end and near-end crosstalk and the throughput for the model, and we found that the results of theoretical calculations indicated the tendencies of the characteristics by our experiments.

Key words: Parallel transmission lines, crosstalk, inhomogeneous medium

1. Introduction

Recent electronic systems and equipment employ multi-conductor lines such as cables for USB (Universal Serial Bus), SCSI (Small Computer System Interface) or LAN systems and parallel multi-traces on a large PCB. Crosstalk problems occur in higher frequencies with high-speed digital devices so that signal integrity (SI) problems may become serious. Interfering phenomena among the parallel lines or cables are well known, and they are utilized in the application as couplers, filters, etc., in microwave circuits. From the view point of EMC, crosstalk is a problematic issue [1]. In this paper, far-end and near-end crosstalk problems in relatively high frequency regime are analyzed.

We studied crosstalk phenomena for long parallel two lines with an inhomogeneous medium on a ground plane in higher frequency regime corresponding to a line length of more than ten wavelengths. We analyzed the far-end and near-end crosstalk and through-end transmission characteristics with transmission-line theory considering the difference in phase constants in balanced and unbalanced modes. We compared the results of the theoretical analysis with the experimental, and resultantly discussed long-line effects.

2. Theory

Let consider a transmission line system composed of inhomogeneous medium in a transverse plane, as

seen in Fig. 1. Due to the different dielectric constant of mediums in the transverse plane in respect of balanced and unbalanced modes, the phase constant of balanced mode, β_b , is different from the one of unbalanced mode, β_u .

We consider crosstalk phenomena in parallel transmission lines on PCB as shown in Fig. 2. The PCB with material FR4 is usually used for applications. The two traces on the top surface have the same widths (1mm) and thickness' (0.035mm) and the bottom surface is a ground plane.

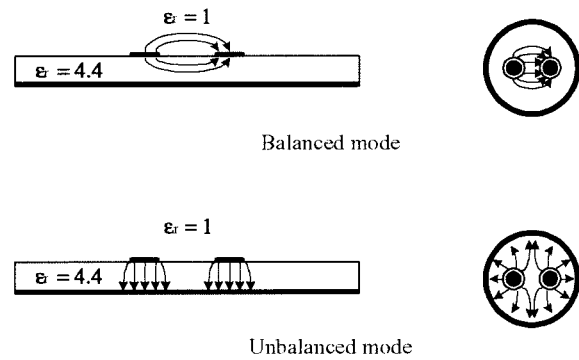


Fig.1 Transverse plane of PCB and pair cable in balanced and unbalanced modes

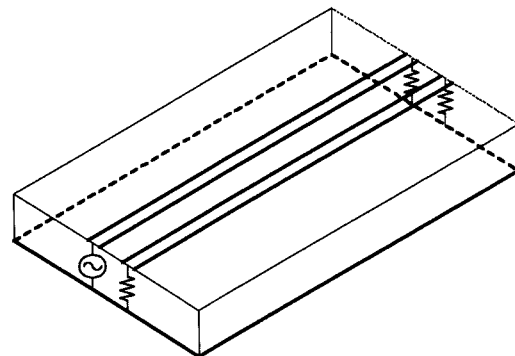


Fig.2 Two traces and ground on PCB

For two-conductor lines, when the transmission lines are in inhomogeneous medium as PCB, there are two modes of electromagnetic waves traveling along the parallel lines with different phase velocities in the balanced and unbalanced modes. To analyze the transmission characteristics as crosstalk, the fol-

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lowing chain matrix of (1) is available [2]. The equations were derived from the telegrapher's equations by decomposing the propagation modes into the balanced and unbalanced modes.

$$P = \begin{bmatrix} [A] & [B] \\ [C] & [D] \end{bmatrix} \quad (1)$$

where,

$$[A] = [D] = \begin{bmatrix} \cosh(\gamma_u l) + \cosh(\gamma_b l) & \cosh(\gamma_u l) - \cosh(\gamma_b l) \\ \cosh(\gamma_u l) - \cosh(\gamma_b l) & \cosh(\gamma_u l) + \cosh(\gamma_b l) \end{bmatrix}$$

$$[B] = \begin{bmatrix} 2Z_u \sinh(\gamma_u l) + \frac{Z_b}{2} \sinh(\gamma_b l) & 2Z_u \sinh(\gamma_u l) - \frac{Z_b}{2} \sinh(\gamma_b l) \\ 2Z_u \sinh(\gamma_u l) - \frac{Z_b}{2} \sinh(\gamma_b l) & 2Z_u \sinh(\gamma_u l) + \frac{Z_b}{2} \sinh(\gamma_b l) \end{bmatrix}$$

$$[C] = \begin{bmatrix} \frac{1}{2Z_u} \sinh(\gamma_u l) + \frac{2}{Z_b} \sinh(\gamma_b l) & \frac{1}{2Z_u} \sinh(\gamma_u l) - \frac{2}{Z_b} \sinh(\gamma_b l) \\ \frac{1}{2Z_u} \sinh(\gamma_u l) - \frac{2}{Z_b} \sinh(\gamma_b l) & \frac{1}{2Z_u} \sinh(\gamma_u l) + \frac{2}{Z_b} \sinh(\gamma_b l) \end{bmatrix}$$

We set $\gamma_{(b,u)}$ and $Z_{(b,u)}$, the propagation constants and the characteristic impedances, respectively, of the balanced and unbalanced modes.

For lossless system, the characteristic impedance, capacitance, inductance and phase constant in the balanced mode, Z_b , C_b , L_b , β_b and in the unbalanced mode, Z_u , C_u , L_u , β_u are given as

$$Z_{(b,u)} = \sqrt{\frac{L_{(b,u)}}{C_{(b,u)}}}, \quad \beta_{(b,u)} = \omega \sqrt{L_{(b,u)} C_{(b,u)}} \quad (2)$$

$$C_b = \frac{c_1 c_2 - (c_m)^2}{c_1 + c_2 + 2c_m}, \quad L_b = L_1 + L_2 - 2M$$

$$C_u = c_1 + c_2 + 2c_m, \quad L_u = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}$$

where $c_{(1,2)}$ and c_m are, respectively, self capacitances and mutual capacitances of the line system. Figure 3 shows the case for Fig. 2. The trace capacitances to ground, c_1 and c_2 and capacitance between traces, c_m on PCB in inhomogeneous medium, (a) and (b). $L_{(1,2)}$ and M are, respectively, the self inductances and mutual inductance.

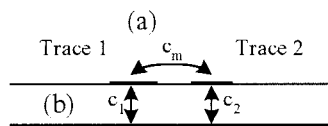


Fig.3 Capacitance c_1 , c_2 and c_m

From (2), β_b and β_u , the phase constants of balanced and unbalanced modes are depending on inductance L and capacitance C of the traces in the balanced and unbalanced modes. Therefore, the difference in the phase velocities, v_b , v_u in the balanced

and unbalanced modes, which are inversely proportional to the phase constants, may cause the crosstalk phenomena.

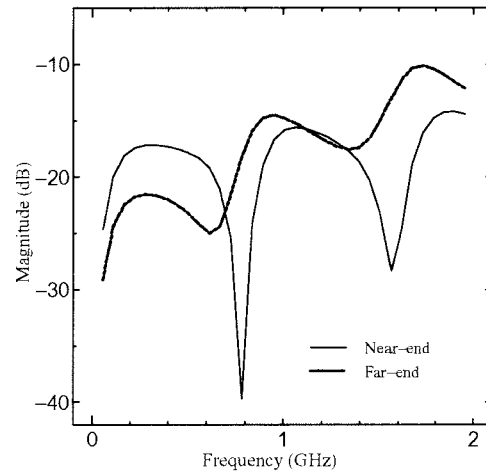


Fig.4 Theoretical example of characteristics for far-end and near-end crosstalk for the short line of 100 mm in an inhomogeneous medium.

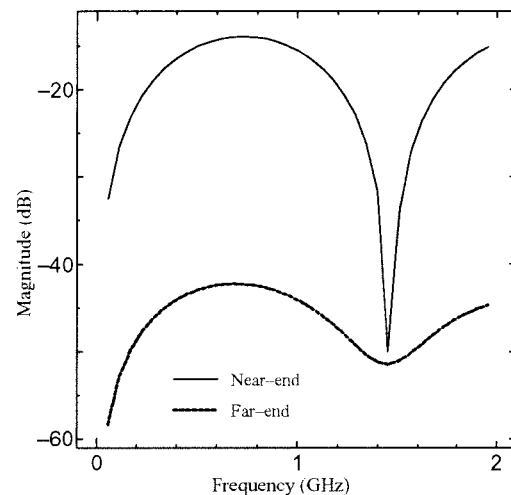


Fig. 5 Theoretical characteristics of far-end and near-end crosstalk for the short line of 100 mm in a homogeneous medium of air.

When the lines are in inhomogeneous media, i.e., having different materials like (a) and (b) in Fig. 3, the far-end crosstalk levels are larger than the near-end ones in higher frequencies as seen in Fig.4. On the contrary, in a homogeneous medium when materials (a) and (b) in Fig. 3 are the same, the far-end crosstalk levels is smaller than the near-end ones in every frequency as seen in Fig. 5.

It is, therefore, obvious that the inhomogeneous medium along the traces causes the phenomena so that the far-end crosstalk is greater than the near-end crosstalk in high frequencies.

In time domain, the phenomena appear relatively serious effects such that an impulse-like crosstalk at the far end is observed in relatively high level com-

pared with one at the near end [3]. This impulse-like crosstalk level may cause a malfunction of device followed in a neighboring trace in some cases.

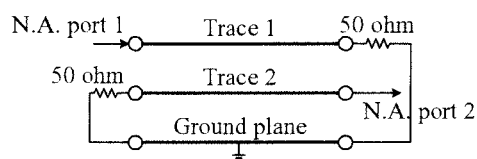
In most cases we have turned an attention to the phenomenon shown in Figs. 3 and 4 for electrically short line, but a long-twisted pair line is, for example, commonly used in LAN. In such case, it should be studied what phenomena would happen in a long line compared with the wavelength concerned. Next, we will focus on long-line effects.

3. Long-line effects for two-conductor line

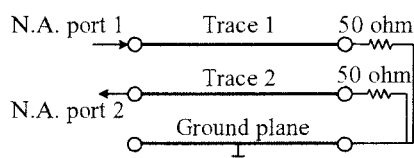
Long lines are used in various fields. The long line means that the length is electrically long compared with a wavelength concerned. In this section we consider the line-length dependency in a frequency region of more than ten times wavelength.

3.1. Experimental circuits

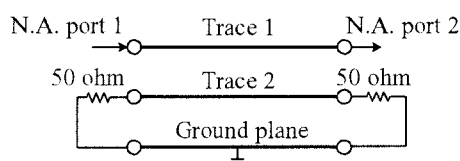
For experiments, we used a PCB instead of wire-type lines because of maintaining the line arrangement uniform easily. It has two traces on the surface and a ground plane on the bottom. The length, width, and thickness of the trace are 1 m, 1 mm and 0.035 mm, respectively, and the space between them is 1 mm. At the ends of the traces, SMA connectors were attached for the connection of terminal resistors or cables to ports of a network analyzer. For the investigation of crosstalk with less influence of dielectric dispersion, the frequency range was adopted less than 3 GHz, where the long-line effects would be studied.



(a) Circuit for far end crosstalk



(b) Circuit for near end crosstalk



(c) Circuit for throughput

Fig.6 Experimental circuits.

Figures 6 (a), (b) and (c) show the circuits for experiments carried out to investigate the far-end and near-end crosstalk and throughput transmission characteristics with an aid of a network analyzer (NA). The trace ends except NA ports were terminated with 50-ohm loads. All characteristics are measured in terms of scattering matrices, S_{21} .

3.2. Experimental results and discussion

Figures 7 (a), (b) and (c), show the experimental results comparing with the theoretical calculation's results for the near-end and far-end crosstalk and throughput transmission characteristics. In theoretical calculation, we did not take into account the loss factors of conductor and dielectric. Figure 8 shows the comparison among the three magnitudes of experimental results. Comparison of the measured and calculated results does not seem in good agreement, but the tendency of the characteristics is very similar with each other. From these results, we found the crosstalk phenomena different from those for short line in Fig. 4 as follows.

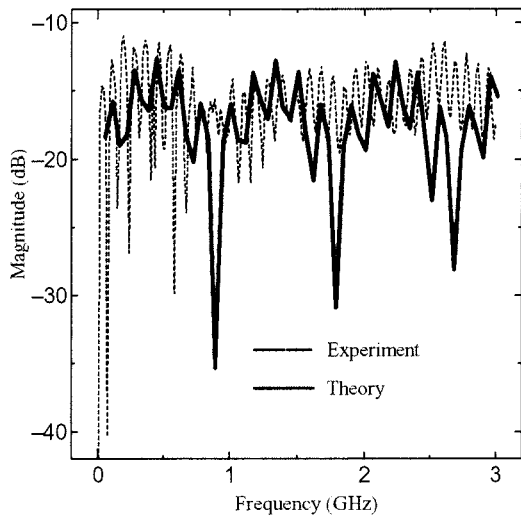
(1) All of the magnitude characteristics periodically oscillate in small pieces and the envelope of the magnitude also waves on a large scale. The first three wave-like pieces corresponds to those shown in Fig. 4. Until now, most of all studies have targeted only on the first one or two pieces, that is, in a frequency range corresponding line length of less than one wavelength or so.

(2) By predicting the result as shown in Fig. 4, the far-end crosstalk would gradually increase according as frequency increases. But there would arise a serious question whether the magnitude of far-end crosstalk approaches to 0 dB or not. From the results in Fig. 7 (b), the magnitude approaches near to 0 dB in relatively low frequencies but there exists the limited maximum value. After the frequency of the maximum, the envelope characteristics gradually decrease and approach to the minimum value.

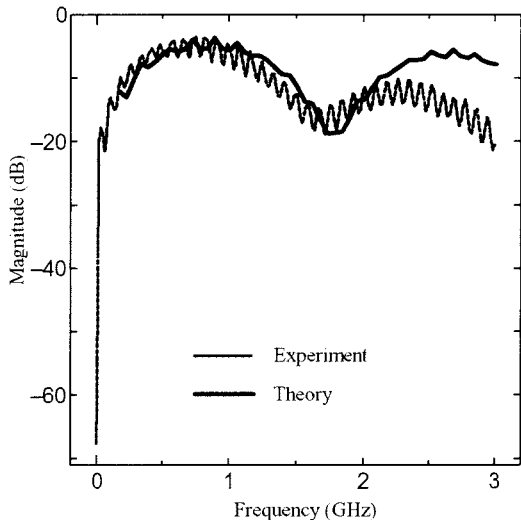
(3) When the envelope of the far-end crosstalk approaches to the maximum, which means that much of the traveling energy goes to the far end and results less energy goes to the through end. Figure 7 (c) shows this fact surely. Therefore, it should be noticed that some risk exists when using long lines, that is, the energy in certain frequency ranges is not transmitted even in the same line, and neighboring lines act as a role of band rejection filter.

(4) One cycle of the envelope of the far-end crosstalk is twice of one of the near-end crosstalk.

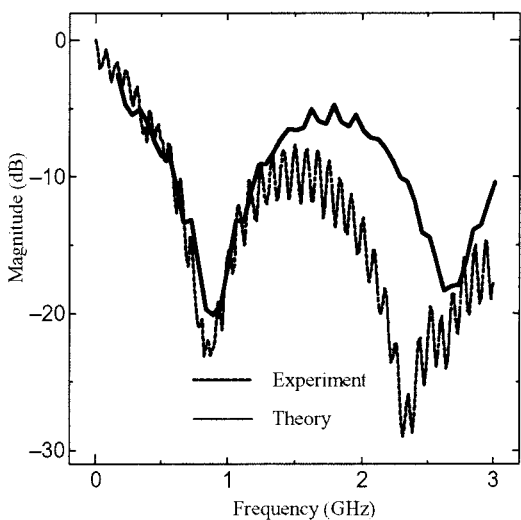
It is also noted that the aforementioned characteristics do not appear for transmission lines in homogeneous medium, we did not mention here though. Therefore the phenomena shown here appear in a long line embedded in plural dielectric materials, where the velocities or phase constants of the independent mode are not coincident.



(a) Near-end crosstalk



(b) Far-end crosstalk



(c) Through-end transmission

Fig.7 Near-end (a), far-end (b) and through-end (c) characteristics for one-meter-long trace lines.

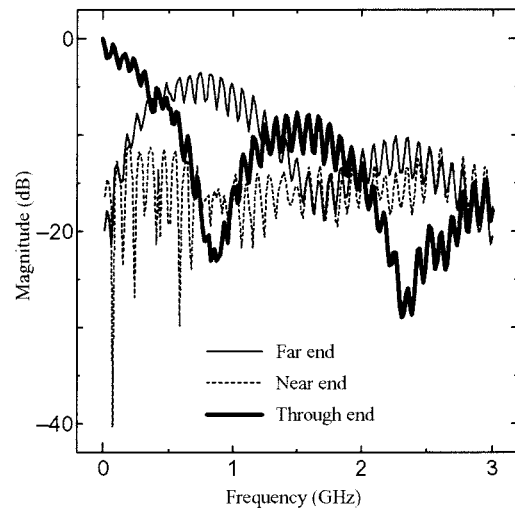


Fig. 8 Comparison between the near-end, far-end and through-end characteristics of experimental results.

4. Conclusions

We investigated crosstalk and throughput transmission phenomena for long parallel lines in an inhomogeneous medium. When the line length is of 10 times wavelength, analyzing transmission-line theory and implementing experiments lead the long line effects, which are quite different from those for short line. The model used here is equivalent to a 10 cm long line on PCB for 30 GHz. As a result of theoretical analysis for the crosstalk in relatively high frequencies, or for long line, we found that the difference of the balanced and unbalanced phase constants, β_b and β_u cause different magnitudes of crosstalk from those for short line as ever known.

In the theoretical analysis, since the dispersion of dielectric constant and resistance of traces are not taken into consideration, we will continue to investigate the phenomena in our further work.

References

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