Design for Reduction of Far-end Crosstalk in Four-channel Differential Transmission Line using Per-unit-length Parameters

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***Abstract*—Modal analysis of a multi-channel differential transmission line is discussed for estimation of far-end crosstalk. A simple formula to evaluate the far-end crosstalk was derived using eigenmode and mixed mode S parameter. The accuracy of the proposed formula was verified by comparison with a full wave simulation. The far-end crosstalk of test four-channel differential lines was calculated by the derived formula. These results were in good agreement with that obtained by full-wave simulation. In addition, position of the differential transmission line with low crosstalk was determined using the proposed method.**

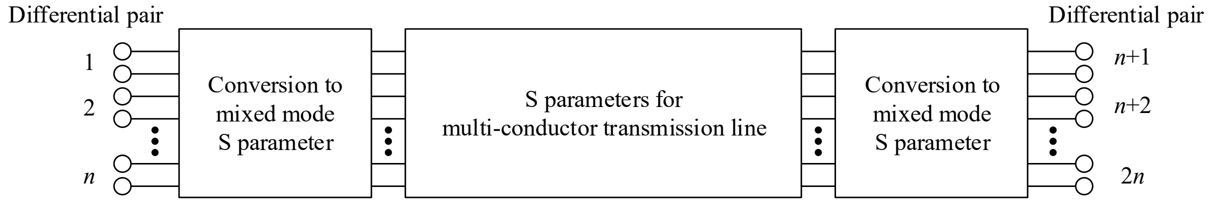
Keywords—crosstalk; differential transmission lines; modal analysis; mixed-mode S parameter

I. INTRODUCTION

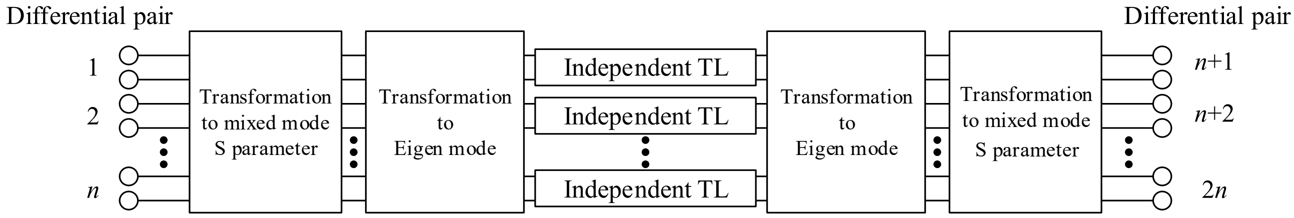
For further high-speed transmission, a multi-channel differential transmission line is adopted. In a differential line having a signal line in proximity, crosstalk occurs and causes deterioration of signal integrity. Mixed mode S parameter [1] is used for the characteristic evaluation of the differential line. It is studied that the differential mode is converted to the common mode by line bent and/or lack of the signal ground [2][3]. Another differential line placed in proximity also affects to the conversion to the common mode [4][5][6].

In order to reduce the crosstalk and common-mode conversion, it is enough to place the differential line far from the other differential line. However, in order to design how much distance should be separated, it is necessary to perform time-consuming electromagnetic field analysis.

In this report, focusing on the mode analysis [7] of the transmission line, the authors derive an equation that can easily calculate the far-end crosstalk between the differential



(a) Commonly used mixed mode S parameter.



(b) Proposed estimation method.

Fig. 1: Analysis for Far-end Crosstalk.

transmission lines. In addition, the design method of the differential line with low crosstalk is discussed.

II. Estimation Method of Far-end Crosstalk

A. Modal Expression of Transmission Line

Multi-conductor transmission line including multi-pair differential transmission lines can be expressed by par-unit-length parameters, *L*, *R*, *G*, *C*. If we assume loss less transmission line, voltages and currents are described as follows,

$$\frac{\partial}{\partial z}\boldsymbol{V} = \mathrm{j}\omega \boldsymbol{L}\frac{\partial}{\partial t}\boldsymbol{I}, \tag{1}$$

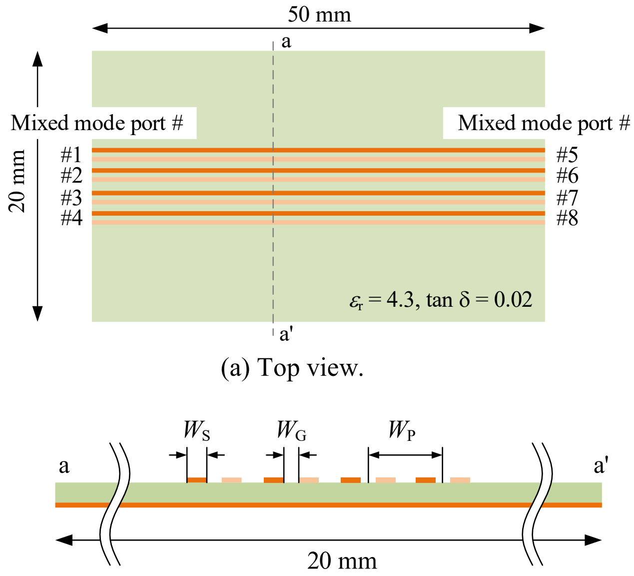
$$\frac{\partial}{\partial z}\boldsymbol{I} = \mathrm{j}\omega \boldsymbol{C}\frac{\partial}{\partial t}\boldsymbol{V}, \tag{2}$$

where $\boldsymbol{V}$ and $\boldsymbol{I}$ represents a voltage vector and a current vector, respectively, $\boldsymbol{L}$ and $\boldsymbol{C}$ represents inductance and capacitance matrices, respectively, as per-unit-length parameters of the transmission line. In many cases, the inductance and capacitance matrices are dense. Therefore, crosstalk can be occurred in the transmission line because of its inductive and/or capacitive coupling between the lines. In multi-pair differential line, the crosstalk is also occurred due to these coupling, and it causes degradation of signal integrity.

As well known, we use a mixed-mode S parameter for the evaluation of the differential transmission line as shown in Fig.1 (a). The S parameter of the transmission line can be converted to the mixed-mode S parameters, $\dot{\boldsymbol{S}}_{\mathrm{mix}}$, using transformation matrices, $\dot{\boldsymbol{T}}_{\mathrm{V}}$ and $\dot{\boldsymbol{T}}_{\mathrm{I}}$,

$$\dot{\boldsymbol{S}}_{\mathrm{mix}} = \begin{pmatrix} \dot{\boldsymbol{S}}_{\mathrm{mix,11}} & \dot{\boldsymbol{S}}_{\mathrm{mix,12}} \\ \dot{\boldsymbol{S}}_{\mathrm{mix,21}} & \dot{\boldsymbol{S}}_{\mathrm{mix,22}} \end{pmatrix} = \dot{\boldsymbol{T}}_{\mathrm{V}}^{-1}\boldsymbol{S}\dot{\boldsymbol{T}}_{\mathrm{I}}. \tag{3}$$

If we assume the one-pair differential transmission line, the transformation matrices are represented as



(a) Top view.

(b) Cross-sectional view.

Fig. 2: Test board structure.

$$\dot{\boldsymbol{T}}_{\mathrm{V}} = \begin{pmatrix} 1/2 & 1 \\ -1/2 & 1 \end{pmatrix}, \dot{\boldsymbol{T}}_{\mathrm{I}} = \begin{pmatrix} 1 & 1/2 \\ -1 & 1/2 \end{pmatrix}, \tag{4}$$

respectively. The first column indicates the transposition factor for differential mode, and the second one is for common mode. It is easy to extend it to applying multi-pair differential transmission line.

In in-homogenous media, however, the differential mode and common mode do not propagate as eigenmode of the transmission line. The eigenmode can be determined the following discussion. From Eqs. (1) and (2), we obtain the wave equations as follows:

$$\frac{\partial^2}{\partial z^2}\boldsymbol{V} = -\omega^2 \boldsymbol{LC}\frac{\partial^2}{\partial t^2}\boldsymbol{V}, \tag{5}$$

$$\frac{\partial^2}{\partial z^2}\boldsymbol{I} = -\omega^2 \boldsymbol{CL}\frac{\partial^2}{\partial t^2}\boldsymbol{I}. \tag{6}$$

Eigenmode of the transmission line can be obtained by diagonalizations of $\boldsymbol{LC}$ and $\boldsymbol{CL}$. Namely, $\boldsymbol{LC}$ and $\boldsymbol{CL}$ can be diagonalized by the matrices, $\boldsymbol{T}_{\mathrm{V}}$ and $\boldsymbol{T}_{\mathrm{I}}$. These matrices which contain the eigenvectors are different from transformation matrices $\dot{\boldsymbol{T}}_{\mathrm{V}}$ and $\dot{\boldsymbol{T}}_{\mathrm{I}}$, respectively, except in the case of transmission line in homogenous media.

Transmission part of modal $\boldsymbol{S}$ parameter defined as $\boldsymbol{S}_{\mathrm{m}} = \boldsymbol{T}_{\mathrm{V}}^{-1}\boldsymbol{S}_{\mathrm{TL}}\boldsymbol{T}_{\mathrm{I}}$ becomes a sparse matrix. The cross term between eigenmodes is eliminated. Therefore, the modal transmission line can be expressed by independent transmission lines as shown in Fig. 1 (b).

B. Equation for Estimation of Far-end Crosstalk

Now, we focus on only far-end crosstalk. Because the modal transmission line in Fig. 1(b) is represented by modal S parameters, a transmission coefficient of each modal transmission line can be described by $e^{-\mathrm{j}\beta_i l}$ where l represents the length of the transmission line, and β_i indicates a phase constant of the mode i. This phase constant can be determined by the modal propagation velocity which obtained by the eigen analysis. Namely, the S parameter of the independent transmission lines are represented a diagonalized matrix whose diagonal elements are $e^{-\mathrm{j}\beta_i l}$.

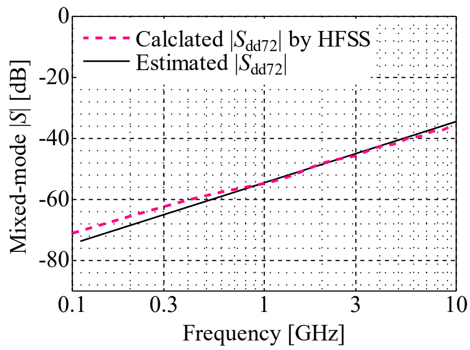


Fig. 3: Comparison of far-end crosstalks which are calculated by HFSS and estimated by proposed method.

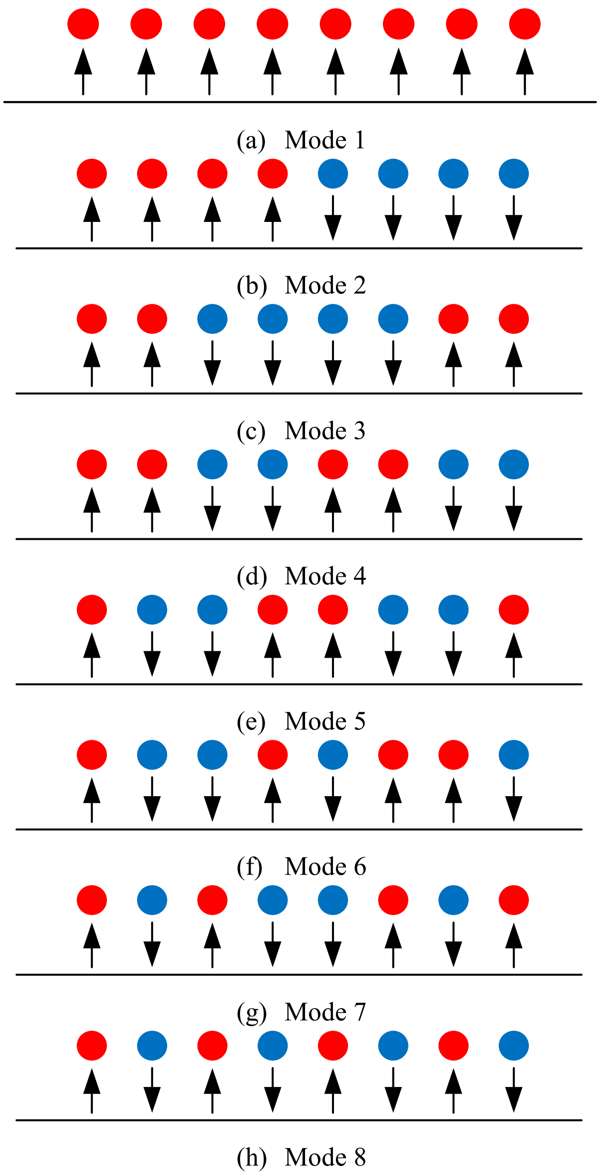


Fig. 4: Eigenmodes of 8-conductor and ground transmission line.

The crosstalk of differential modes and/or common modes in the multi-conductor transmission line can be calculated by two transformation matrices. One is for transformation from S parameter of the ideal and independent transmission lines, $\boldsymbol{S}_{\mathrm{TL}}$, to the modal S parameter $\boldsymbol{S}_{\mathrm{m}}$. Another is for transformation from the modal S parameter, $\boldsymbol{S}_{\mathrm{m}}$, to the mixed-mode S parameter, $\dot{\boldsymbol{S}}_{\mathrm{mix}}$. In addition, we need to consider the mixed-mode port impedance. If we use the transformation matrices shown in Eq. (4), the mixed-mode port impedances are determined as follows: differential mode impedance is fixed to 100 Ω, and common mode impedance is fixed to 25 Ω.

Summarizing the above, we can obtain the transmission coefficient, $\dot{\boldsymbol{S}}_{\mathrm{mix}}$, representing the far-end crosstalk in multi-channel differential transmission line as follows:

$$\dot{\boldsymbol{S}}_{\mathrm{mix21}} = \sqrt{\dot{\boldsymbol{Y}}_0}\dot{\boldsymbol{T}}_{\mathrm{V}}^{-1}\boldsymbol{T}_{\mathrm{V}}\sqrt{\boldsymbol{Z}_0}\boldsymbol{S}_{\mathrm{TL}}\sqrt{\boldsymbol{Y}_0}\boldsymbol{T}_{\mathrm{V}}^{-1}\dot{\boldsymbol{T}}_{\mathrm{V}}\sqrt{\dot{\boldsymbol{Z}}_0} \quad (7)$$

where and represents model port impedance and admittance matrices, respectively, and these are diagonalized matrices. The dot mark in Eq. (7) indicates that the matrix represents mixed-mode (differential and common mode). The matrix without a dot mark indicates that the matrix represents eigenmode.

III. Four-Channel Differential Transmission Line

A. *Test board structure*

Now we focus on the four-channel differential transmission line shown in Fig. 2. The far-end crosstalks of differential mode are calculated by using Eq. (7). The test structure shown in Fig. 2 consists of two layers. Top layer has 8 lines and bottom layer has an ideal ground plane. Therefore, the test board has 4 differential lines. The width, W_{S}, and thickness of the line are fixed to 75 μm and 35 μm, respectively. The gap W_{G} of the differential pair is fixed to 100 μm. The interval, W_{P}, of the differential pair is changed in this report.

B. *Full Wave Simulations*

The far-end crosstalk of the test board is calculated by full wave simulator, HFSS. When the interval of the transmission line is fixed to 1.0 mm, the differential-mode crosstalk from mixed mode port #2 to #7 is shown in Fig. 3. The interest frequencies are from 0.1 to 10 GHz. Particularly, maximum crosstalk appears at 10 GHz, and it is about −36 dB.

We can image that the crosstalk can be larger when the interval of the differential line becomes closer. In order to quantitatively evaluate the crosstalk, however, the full wave simulation should be carried out. The proposed estimation method using Eq. (7) needs to only quasi static simulation of the cross-sectional structure of transmission line. Therefore, the crosstalk can be obtained in extremely short time by the proposed method.

IV. Modal Analysis

A. *Eigenmode and Propagation Velocity*

We discuss the modal analysis when the interval of the differential line is fixed to 1.0 mm. The quasi static simulator gives the inductance and capacitance matrices of the transmission line shown in Fig. 2. Using the results, we obtain eigenvectors and eigenvalues. Calculated eigenvectors are listed as matrix formation as follows:

$$\boldsymbol{T}_{\mathrm{V}} = \begin{pmatrix} 0.28 & 0.43 & 0.42 & 0.26 & 0.28 & 0.43 & 0.24 & 0.42 \\ 0.30 & 0.44 & 0.40 & 0.24 & -0.26 & -0.42 & -0.44 & -0.27 \\ 0.40 & 0.27 & -0.27 & -0.44 & -0.43 & -0.23 & 0.30 & 0.41 \\ 0.41 & 0.23 & -0.31 & -0.43 & 0.28 & 0.28 & -0.25 & -0.43 \\ 0.41 & -0.23 & -0.31 & 0.43 & 0.28 & -0.28 & -0.25 & 0.43 \\ 0.40 & -0.27 & -0.27 & 0.44 & -0.24 & 0.24 & 0.30 & -0.41 \\ 0.30 & -0.44 & 0.40 & -0.24 & -0.44 & 0.43 & -0.44 & 0.27 \\ 0.28 & -0.43 & 0.42 & -0.26 & 0.44 & -0.44 & 0.24 & -0.42 \end{pmatrix}.$$

The eigenmodes are illustrated in Fig. 4. In mode 1, phase of each line is the same as that of other line. This mode is common-mode-like mode. However, amplitude of each line is different from that of other line.

Table 1: Propagation velocity of eigenmode.

Mode #	Velocity [m/s]	Mode #	Velocity [m/s]
1	1.707×10^8	5	1.905×10^8
2	1.731×10^8	6	1.903×10^8
3	1.749×10^8	7	1.910×10^8
4	1.760×10^8	8	1.908×10^8

Propagation velocity of each mode, which can be obtained by eigenvalue, is listed in Table I. Due to the dielectric, propagation velocities of all modes are slower than light speed.

B. Estimation of Far-end Crosstalk

In this subsection, we discuss the far-end crosstalk in the test boards. Firstly, the frequency dependency of the far-end crosstalk is estimated using Eq. (7). In this report, we focus on the far-end crosstalk between adjacent differential lines, particularly, the transmission coefficient from mixed mode port #2 to #7 in Fig. 2(a). When the interval of the differential lines, W_P, is set to 1.0 mm, the results of the estimation is shown as black solid line in Fig. 3. The results are in good agreement with results calculated by the full wave simulation described in the previous section.

Using the proposed Eq. (7), interval dependency of the crosstalk is calculated and is illustrated in Fig. 5. Five frequency, 1, 10, 100 MHz and 1, 10 GHz, are selected from this calculation. Figure 5 mentions that the closer interval of the differential line increases the far-end crosstalk, and amount of the far-end crosstalk can be evaluated quantitatively. For example, when the interval of the differential line is changed from 1.0 to 0.5 mm, the crosstalk increases about 20 dB in all frequencies which we calculated.

In addition, the red marks in Fig. 5 indicate the results calculated by the full wave simulator. These are also in good agreement with the results of the proposed method. The proposed method uses the per-unit-length parameter obtained by the quasi-static simulation. The time of the simulation is shorter than that of the full wave simulation.

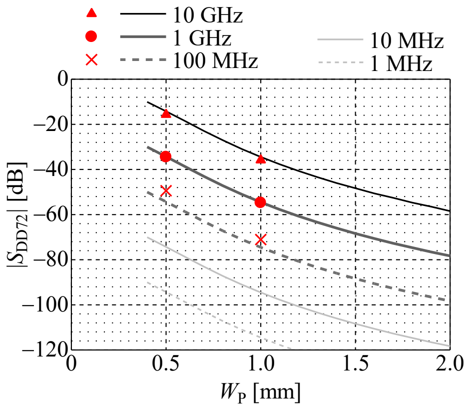


Fig. 5: Far-end crosstalk changing interval of differential pairs.

V. CONCLUSION

In this report, estimation method of the far-end crosstalk in the multi-channel differential transmission lines is discussed. In addition, location dependency of the differential pair for reduction of crosstalk is calculated.

The proposed calculation method is based on the multi-conductor transmission theory and modal analysis. The eigenvectors and eigenvalues of the transmission line give the far-end crosstalk using the simple formula derived in this report. Because these eigenvectors and eigenvalues are obtained by the quasi-static simulation, calculation time for the far-end crosstalk is extremely shorter than that of full wave simulation. Therefore, optimized location of the transmission line is obtained by comprehensive calculation.

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