Imbalance Control by Open Stub for Reduction of Common-Mode Conversion at Differential Transmission Line Bend

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***Abstract*—At a differential transmission line bend, a differential mode propagated in a differential transmission line is converted to a common mode due to asymmetry of the transmission line. The common mode conversion leads to problems with signal integrity. We propose a method to improve electric symmetry of the transmission line bend and thus reduce the common mode conversion. The self-capacitance and inductance of one line are different from those of another. In order to fit those parameters, the narrowing signal line for increasing self-inductance and placing a conductor shape which is like a stub are used to reduce the imbalance degree of the transmission line bend. We obtained a 20-dB reduction of common mode excitation by optimizing the signal line width and stub length. In addition, an equivalent circuit model for the transmission line bend is proposed to evaluate the reduction. The simulation results using the proposed equivalent circuit model are in good agreement with the results obtained by the 3D electromagnetic solver.**

I. INTRODUCTION

A differential transmission line is used for high-speed signal devices. The signal voltage of the differential signaling system is smaller than that of a single-ended transmission line because the differential transmission line has a high immunity to a coupling noise from the external field [1], [2]. We can ignore common mode excitation in the differential transmission line if the total system with a driver and a receiver is completely symmetric.

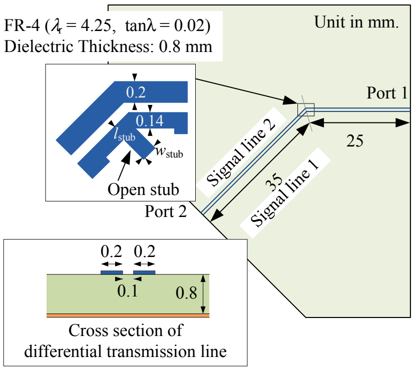

Fig. 1. Structure of differential transmission line bend.

The transmission line on a printed circuit board (PCB) should maintain a symmetric layout. In a practical PCB, however, the transmission lines need several bends in order to connect a driver LSI and a receiver LSI which are placed on various locations on a PCB. The common mode is thus excited from the differential mode, and it leads to problems with signal integrity [3].

Isometric wiring is a conventional technique for improving signal integrity. However, it does not reduce common-mode generation which causes large radiated emission[4]. The other groups have proposed methods to reduce and eliminate the common mode in the differential transmission line. A periodically defected ground structure (DGF) has been proposed for reduction of common mode propagation [5], [6]. The periodic DGF can filter out the common-mode noise without disturbing the differential signal transmission. In this method, the layout requires complete symmetry, and the common-mode may be produced due to a lack of its symmetry.

Our group proposed an imbalance difference model for evaluation of the common-mode excitation of the single-ended and differential transmission lines [7], [8]. This model expresses how the common mode is excited from the differential mode at the discontinuities of the transmission line due to a mismatch of the imbalance of the transmission line. In order to reduce the common-mode excitation, our group proposed a design strategy of the low common-mode transmission line by controlling the imbalance.

The imbalance difference model is applied to a transmission line corner bend as shown in Fig. 1. A method to reduce the common-mode excitation is proposed for improving the signal integrity. According to [9], narrowing the signal line to increase of the self inductance of inner line and placing the stub in a way that increases the self capacitance of inner line improved the imbalance degree of the transmission line bend. As described in the results of reference [9], a reduction of 15-dB of common mode excitation was obtained. Another method to control the degree of imbalance of the transmission line bend is proposed here. Attaching a conductor such as a stub to the inner line can increase self-capacitance. If the width of the stub is narrow enough to ignore current flow, only the self inductance of the inner line increases, and the symmetric property at the line bend can be improved. In addition, an equivalent circuit model using ideal transformers is proposed for estimation and prediction of common-mode excitation at the transmission line bend.

II. REDUCTION OF COMMON-MODE EXCITATION

A. Electrical Symmetry of Transmission Line Bend

At the straight section in Fig. 2, the transmission line is structurally and electrically symmetric. On the other hand, the bent section has structural and electrical asymmetry. It causes common-mode excitation from the differential mode. Designing the electrically symmetric transmission line at the bent section can eliminate the excitation of the common mode.

At the bent section in Fig. 2, the inductance of the inner line, L_{11}, is smaller than that of the outer line, L_{22} because the inner line is shorter than the outer one. Additionally, the capacitance between the inner line and the ground plane, C_{11}, is smaller than that of the outer line, as follows,

$$C_{11} < C_{22}, \quad L_{11} < L_{22}. \tag{1}$$

We expect that the decrease of these differences, $C_{22} - C_{11}$ and $L_{22} - L_{11}$, can reduce the common-mode excitation. In order to increase the inductance of the inner line, L_{11}, width of the inner line is narrowed at the bent section. In addition, a conductor shape of which is like a stub is connected to the inner line at bend section to enlarge the self capacitance, C_{11}. The stub is short enough to enable stub resonance to be ignored. In addition, the width of the stub is also narrow enough to ignore the current flowing on the stub. By adjusting the width of the inner line and length of the stub, we can control the self inductance and self capacitance of the inner line and can improve electrical symmetry of the bent section and eliminate the common-mode excitation.

B. Test board structure

In order to verify the proposed method to reduce the common-mode excitation, we prepared four test boards[1] as shown in Fig. 1. All of the test boards have a differential signal line, with a length of 60 mm, and which is routed on the top layer and the ground plane, which is large enough to be assumed as the system ground, is placed on the bottom layer. The transmission line is bent at the middle of the line.

One test board has only the bent differential transmission line on the top layer, and is called the original test board. The three other test boards have narrow signal line and stub at the line bend to control the electrical symmetry. The length of the stub is different in each test board.

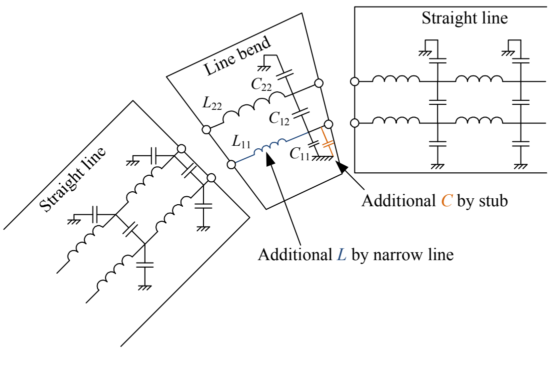

Fig. 2. Equivalent circuit of transmission line bend using ladder circuits.

C. Common-mode Reduction at Bent Section

The calculation results of the conversion from the differential mode to the common mode, $|S_{\mathrm{cd21}}|$, are plotted in Fig.3. In Fig. 3, the solid lines are obtained by the three-dimensional electromagnetic solver, HFSS, and the broken lines are obtained by circuit simulation using the equivalent circuits described in the next section. In the electromagnetic simulation, the wave ports are placed at both ends of the transmission line, and we calculate mixed-mode S parameters. Now, we focus on comparison of four test boards. The result was the narrow signal line and the stub length of which 0.9 mm gave a reduction of about 20 dB of common-mode excitation because of the improved electrical symmetry at the bent section. In the test board with the 0.6- or 1.2- mm stub, reductions of about 5 dB of common-mode excitation were observed. It suggests the optimal solution of length of the stub is present around the $\ell_{\mathrm{stub}} = 0.9$ mm.

The characteristics of the differential-mode propagation, $|S_{\mathrm{dd21}}|$ and $|S_{\mathrm{dd11}}|$, of the test boards are shown in Fig. 4. The reflection coefficients, $|S_{\mathrm{dd11}}|$, of all test boards are less than -20 dB. In addition, there is no difference between the transmission characteristics of the test boards. These results indicate that the narrowing signal line and placing the stub exert little effect on the propagation of differential mode on these test boards. In other words, the characteristic impedance of the differential mode at the bent section is not changed by the narrowed signal line and the stub. As would be expected the stub can resonate and act as a short in the frequency range of 150 GHz or more. However, we focus on the frequency range below 10 GHz. Therefore, we regard the stub as only an additional capacitor.

In the next section, an equivalent circuit at the bent section of the transmission line will be explained to evaluate the reduction of the common mode.

III. EQUIVALENT CIRCUIT MODEL OF TRANSMISSION LINE BEND

A. Equivalent Circuit Model Using Ideal Transformer

We developed an equivalent circuit model for mode conversion due to the line bend [9]. The bent transmission line can be separated in to three parts: two straight ones and one bent one. Since the two straight sections are completely symmetric, the differential mode excited at one terminal of the transmission line does not couple to the common mode in those sections. In addition, we assume that these lines are long enough to be

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[1] The material of the conductor patterns is copper and FR-4 (relative permittivity is about 4.25) is used for insulating material in the test boards.

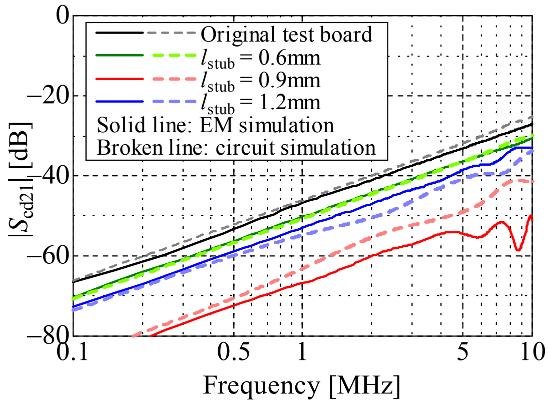

Fig. 3. Conversion of common mode from differential mode and reduction effect of narrow signal line and stub.

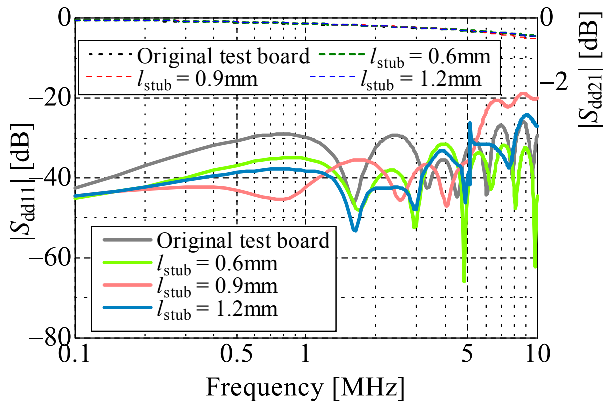

Fig. 4. Transmission and reflection characteristics of differential mode.

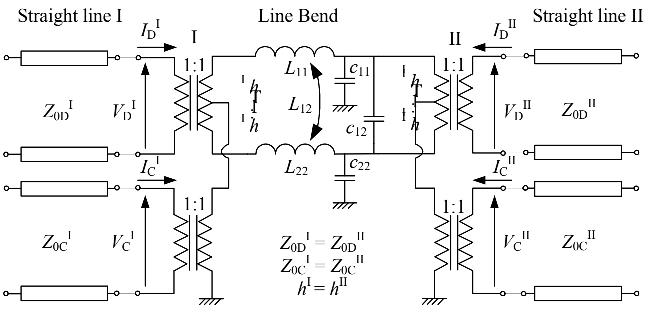

Fig. 5. Equivalent circuit using ideal transformers for estimation of common-mode excitation.

expressed by the transmission line model as shown in Fig. 5. The transmission models at both sides shown in the Fig. 5 can express the characteristics of the differential-mode and common-mode propagations separately. When we regard the differential mode and the common mode as orthogonal modes, there is no coupling between two transmission lines.

We now discuss a model of the bent section. Since the bent section is very short, a lumped-constant circuit expresses the characteristics of the bent section. We use an LC circuit shown in the center of Fig. 5 because of the assumption of a loss-less circuit.

In this model, while the transmission lines are not actual ones, each of them expresses a differential-mode or common-mode propagation as a virtual modal line. L_{11} and L_{22} are self inductances of two bent lines, and L_{12} is a mutual inductance between two lines. C_{11} and C_{22} are self capacitances between each of the lines and the ground plane. C_{12} is the capacitance between two lines. These parameters can be calculated by electromagnetic solver with a quasi-static assumption.

As described elsewhere, [9], we can express the cascade connection between the modal lines and the actual lines using ideal transformers. Because of the symmetrical property of the straight transmission line, all of the tap ratios of the transformers are 1/2.

The fundamental matrix of the equivalent circuit is calculated by using the cascade arrangement of fundamental matrices of the LC circuit and the tap transformers, as follows,

$$\begin{bmatrix} V_{\mathrm{D}}^{\mathrm{I}} \\ V_{\mathrm{C}}^{\mathrm{I}} \\ I_{\mathrm{D}}^{\mathrm{I}} \\ I_{\mathrm{C}}^{\mathrm{I}} \end{bmatrix} = \left[\begin{array}{cc|cc} A_{\mathrm{DD}} & A_{\mathrm{DC}} & B_{\mathrm{DD}} & B_{\mathrm{DC}} \\ A_{\mathrm{CD}} & A_{\mathrm{CC}} & B_{\mathrm{CD}} & B_{\mathrm{CC}} \\ \hline C_{\mathrm{DD}} & C_{\mathrm{DC}} & D_{\mathrm{DD}} & D_{\mathrm{DC}} \\ C_{\mathrm{CD}} & C_{\mathrm{CC}} & D_{\mathrm{CD}} & D_{\mathrm{CC}} \end{array}\right] \begin{bmatrix} V_{\mathrm{D}}^{\mathrm{II}} \\ V_{\mathrm{C}}^{\mathrm{II}} \\ I_{\mathrm{D}}^{\mathrm{II}} \\ I_{\mathrm{C}}^{\mathrm{II}} \end{bmatrix}, \tag{2}$$

$$A_{\mathrm{DC}} = \omega^2 (h_{\mathrm{C}} - h_{\mathrm{L}})(C_{11} + C_{22})(L_{11} + L_{22} - 2L_{12}), \tag{3}$$

$$\begin{aligned} A_{\mathrm{CD}} = {} & \omega^2 \left[h(1-h)\left\{C_{22}L_{22} - C_{11}L_{11}\right\}\right. \\ & + L_{12}\left\{h^2 C_{22} - (1-h)^2 C_{11}\right\} \\ & \left. - C_{12}(h - h_{\mathrm{L}})(L_{11} + L_{22} - 2L_{12})\right], \end{aligned} \tag{4}$$

$$B_{\mathrm{DC}} = -\mathrm{j}\omega \left\{h - (1 - h_{\mathrm{L}})\right\}(L_{11} + L_{22} - 2L_{12}), \tag{5}$$

$$B_{\mathrm{CD}} = \mathrm{j}\omega \left(h - h_{\mathrm{L}}\right)(L_{11} + L_{22} - 2L_{12}), \tag{6}$$

$$C_{\mathrm{DC}} = \mathrm{j}\omega \left\{h - (1 - h_{\mathrm{C}})\right\}, \tag{7}$$

$$C_{\mathrm{CD}} = -\mathrm{j}\omega \left(h - h_{\mathrm{C}}\right), \tag{8}$$

$$D_{\mathrm{DC}} = D_{\mathrm{CD}} = 0, \tag{9}$$

where

$$h_{\mathrm{L}} \equiv \frac{L_{22} - L_{12}}{L_{11} + L_{22} - 2L_{12}}, \tag{10}$$

$$h_{\mathrm{C}} \equiv \frac{C_{11}}{C_{11} + C_{22}}. \tag{11}$$

Only the factors of mode conversion are described in Eq. (3) ~ (9). By using these equations, we can calculate and predict the common-mode excitation at the bent transmission line.

By using the fundamental matrix of the equivalent circuit in Fig. 5, we calculate a mixed-mode S matrix. The broken lines in Fig. 3 are obtained by a calculation using the equivalent circuit. The calculation results by the circuit simulation are in good agreement with those gained by the three-dimensional electromagnetic solver.

B. Control of imbalance at line bend

We can design the transmission line with low common-mode excitation by modifying the structure of transmission line bend. In order to eliminate the common-mode excitation, components of the fundamental matrix, Eq. (3) $\sim$ (9), should be equal to 0. The trivial solution for elimination of common-mode excitation is

$$C_{11} = C_{22}, \quad L_{11} = L_{22}. \tag{12}$$

This condition means the transmission line bend is electrically symmetric.

Modifying the structure of the line bend, however, can change the characteristic impedance of the differential mode, and reflection of incident signal at the line bend becomes large. The differential-mode characteristic impedance is defined as follows,

$$Z_{0\mathrm{D}} = \sqrt{\frac{L_{11} + L_{22} - 2L_{12}}{C_{12} + \frac{C_{11}C_{22}}{C_{11}+C_{22}}}}. \tag{13}$$

The capacitance between two lines, C_{12} is the dominant factor of the differential-mode characteristic impedance because the self capacitances, C_{11} and C_{22}, are connected in series, and the total capacitance is smaller than C_{12}. On the other hand, the self capacitances, C_{11} and C_{22}, are dominant in the imbalance at the line bend, h_C, as shown in Eq. (11). In order to control the h_C with insignificant change of the differential-mode characteristic impedance, the stub is connected to inner signal line # 1 to increase the self capacitance, C_{11}, because the stub has insignificant effect on the self-capacitance of the outer line #2, C_{22}, and mutual capacitance between two lines, C_{12} depends on the separation between two lines.

C. Calculation results

In this case, we assume the line length of the bend section is equal to 2 mm. The parameters of the equivalent circuit model at the line bend were extracted by the electromagnetic simulator with quasi-static assumption. The calculation results of these parameters are listed in Table I. As shown by these results, narrowing the signal line #1 and placing the stub improves the imbalance of the line bend at the line bend without changing the characteristic impedance of the differential mode.

TABLE I

RESULTS FROM EXTRACTION OF LUMPED ELEMENT MODEL.

	original	ℓ_stub=0.6	ℓ_stub=0.9	ℓ_stub=1.2
C_{11} [fF]	89.50	94.13	110.09	127.75
C_{22} [fF]	103.80	103.74	102.78	102.33
C_{12} [fF]	86.20	85.36	86.41	86.96
L_{11} [nH]	1.68	1.76	1.75	1.75
L_{22} [nH]	1.85	1.85	1.85	1.85
L_{12} [nH]	1.02	1.04	1.04	1.03
h_C	0.46	0.48	0.52	0.56
h_L	0.56	0.53	0.53	0.53
$Z_{0\mathrm{D}}$ [Ω]	105	106	104	103
$Z_{0\mathrm{C}}$ [Ω]	85	85	82	78

Finally, the calculation results of the mixed mode S parameters using the proposed equivalent circuits model are shown in Fig, 3. In the low frequency range, the calculation results expressed by broken lines are in good agreement with the calculation results by 3-D electromagnetic simulator, which is expressed by the solid lines. On the other hand, the differences between results of two simulations are large because the length of the bent section cannot be ignored. Therefore, the equivalent circuit parameter needs to be further divided to express the characteristics at the line bend.

IV. CONCLUSION

We proposed a reduction method of common-mode excitation at a differential transmission line bend. The common mode is converted from the differential due to a lack of symmetric property of the transmission line. Narrowing the signal line and placing the stub on the inner signal line at the line bend are effective ways to reduce the common mode conversion. The simulation results by 3D electromagnetic simulator showed a 20-dB reduction. In addition, we discussed an equivalent circuit model for estimation of the common-mode generation at the line bend. The simulation results using the proposed model were in good agreement with the results obtained by using a 3D electromagnetic simulator.

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