LETTER

Mitigating differential skew by rotating meshed ground for high-density layout in flexible printed circuits

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Abstract  Asymmetry of differential transmission lines over a meshed ground plane causes differential skew, which leads to signal integrity issues. We measured to evaluate how the angle between the differential transmission lines and meshed ground (the rotation angle) affected differential skew. We also investigated the effect of the lines' position on characteristic impedance and the feasibility of high-density layout of the differential transmission lines, including the bend structure. We found that the differential skew and characteristic impedance are not significantly affected by the position of the differential transmission lines and meshed ground when the rotation angle is set to 30°, a relatively small value. Measurements showed that our design is effective.

key words: Differential transmission lines, Differential skew, Phase difference, Rotation-angle dependence

Classification: Circuits and modules for electronic instrumentation

1. Introduction

In recent years, flexible printed circuit (FPC) boards have been increasingly used in electronic devices as these devices become smaller and lighter [1, 2]. The dielectric of an FPC is very thin, and the characteristic impedance of its differential transmission lines is lower than the designated value, so the ground (i.e. the return path of the differential transmission lines) is formed into a mesh structure to increase the characteristic impedance without changing the line width [3, 4, 5, 6, 7, 8, 9]. In general, as shown in Fig. 1, the meshed ground is rotated by 45° relative to the differential transmission lines (ϕ = 45°). The ground is also arranged such that the intersection position of the meshes are on the axis of symmetry of the differential transmission lines [10, 11]. When the design emphasizes symmetry in this manner, the interval between the adjacent differential transmission lines becomes dependent on the pitch of the meshed ground, making it difficult to set an arbitrary wiring interval. Considering the characteristic impedance, it is necessary to make the mesh pitch rough to cope with thinning of the dielectric, which results in lower packaging density. To improve the wiring density, the structure of the mesh must be changed; to do so, the wiring design of the lines must be redone first [12]. In addition, it is challenging to arrange the lines and the meshed ground completely symmetrically in actual production [13]. If the two are even slightly asymmetrical, the characteristic impedance changes [14, 15, 16], causing mode conversion and differential skew [17, 18, 19].

The effect of line position on the effective characteristic impedance of a single-ended line has been investigated in detail using full-wave simulation. When the angle between the wiring and the meshed ground (i.e. the rotation angle) is 0 or 45°, the characteristic impedance is heavily affected by the arrangement, but the effect is slight in the range of 10 to 40°, and around 22.5°, the effective characteristic impedance is unaffected by the wiring position [14]. Based on this, this study focuses on the differential transmission lines and discusses the phase delay difference (differential skew) between two lines.

There is known a problem with the differential skew, such as the differential skew occurring in the differential transmission lines on a printed circuit board because of dielectric problems with the board’s glass cloth [20, 21, 22, 23]. It has been reported that the differential skew becomes a relatively small value when the angle between the trace of the differential transmission lines and the thread of the glass cloth is around 40° [24]. Therefore, this study focuses on the an-
angle between the trace of the differential transmission lines and the meshed ground plane and investigates the angle dependence of the differential skew, taking into account phase delay between two lines with propagation to find low differential skew at the angle other than 45°. And, a simple model was proposed for reducing the calculation time but is found to be able to evaluate the angle dependence of the differential skew at a similar accuracy to the 3D electromagnetic simulation [25, 26]. Then, by setting the angle between the differential transmission lines and the meshed ground (the rotation angle) to between 30 and 40°, we found that the differential skew is not significantly affected by the position of the differential transmission lines and the meshed ground, and it becomes a relatively small value [25, 26].

We evaluated the differential skew caused by the meshed ground in detail using the simple model and 3D electromagnetic simulation [25, 26]. In this paper, we built two sets of FPC test boards. Our first set of test boards were built to examine differential skew and characteristic impedance. Our second set of test boards were built to evaluate the transmission characteristics of the differential transmission lines, including bending, to test the feasibility of high-density layout.

2. Differential-skew test structures and methods

2.1 FPC test board for measurement

Fig. 1 shows the configuration of the FPC test board used in this paper; \( w \) is the line width, \( s \) is the distance between the lines \( L1 \) and \( L2 \), and \( a \) and \( b \) indicate the width of the mesh and the separating space between meshes, respectively. The dimensions \( w \), \( s \), \( a \), and \( b \) shown in Fig. 1 are the structural parameters used in this paper. These metal widths and spaces are generally easy for FPC manufacturers to make. Table I shows the thickness, relative dielectric constant (\( Dk \)), and dielectric loss (\( Df \)) of each layer material in our FPC test board. Using the above parameters, the differential-mode characteristic impedance was close to 100 \( \Omega \).

In asymmetric structures, when the rotation angle \( \phi \) is 0 or 45° (Fig. 1), and a phase difference between \( L1 \) and \( L2 \) exists at every mesh pitch, differential skew \( \Delta T \) increases monotonically with line length \( l \). This is because the same phase difference accumulates at each mesh pitch. This is also true when \( \phi \) is 26.5° [26]. However, at any other angle, the phase difference at the first mesh pitch is different from that at the next mesh pitch. This is because the different lines pass relatively randomly over the mesh and the separating space between meshes with different effective relative dielectric constants. Therefore, \( \Delta T \) increases and decreases periodically with \( l \). As \( \phi \) becomes larger, the magnitude of the periodic increase and decrease becomes smaller [26].

With this in mind, our first set of test boards, depicted in Fig. 2, was built to study the differential skew induced by the meshed ground. To measure how the rotation angle affected the differential skew \( \Delta T \), we measured seven different rotation angles \( \phi \), 0, 10, 22.5, 26.5, 30, 40, and 45°. To measure how line length affected \( \Delta T \), we measured three different line lengths \( l \), 9.6, 30, and 60 mm. We also wanted to evaluate the effects of line position, but although the relationship between meshed ground and line position can be controlled at the time of fabrication, the worst positions for differential skew and characteristic impedance are different. For this reason, to evaluate how line position affects differential skew and characteristic impedance, at least 3 positions are required including the best (symmetrical) position. Therefore, the 60-mm long differential transmission lines have patterns of three different positions, and the 9.6- and 30-mm long
differential transmission lines have patterns of seven different positions including additional four positions in the first set of test boards.

Our second set of test boards, depicted in Fig. 3, was built to investigate whether or not high-density layout is possible when the rotation angle is set to 30°. However, the 45° bend that is usually used in wiring does not always keep the angle of the meshed ground in relation to the lines at 30°. A 90° bend, however, can always keep the angle at 30°. Therefore, the bend angles of 90° were used for the rotation angle of 30°.

Fig. 3(a) shows a general board design with 45°-bend differential transmission lines and a meshed ground. With this design, all lines can be placed symmetrically. However, the wiring density is still dependent on the mesh structure. With the dimensions in Fig. 1, the minimum distance between adjacent differential transmission lines is 0.47 mm in FPC1. Fig. 3(b) shows our proposed design. First, the meshed ground is rotated by 30°, and a 90° bend is used for the reasons given above. In this design, as shown in FPC2, the minimum distance between adjacent differential transmission lines is reduced to 0.3 mm. Note that optimizing the interval between adjacent differential transmission lines is not the purpose of this study, but generally, the interval is set to about three times the value of s to suppress crosstalk. The length of all the differential transmission lines in FPC1 and FPC2 was set to 37 mm. The red arrows indicate the lines used for measurement; all the unmeasured lines were matched by chip resistance of 51 Ω.

2.2 Measurement method
We use mixed-mode S parameters to evaluate differential skew, characteristic impedance, and transmission characteristics. To obtain mixed-mode S parameters, we conducted 4-port measurement using a vector network analyzer (KEYSIGHT E5071C). We also used a pair of 200-μm-pitched GSGSG microprobes (Cascade Microtech ACP-40-D-GSGSG), with which the propagation characteristics of the test boards were measured at frequencies ranging from 0.1 to 20 GHz.

3. Measurement results of differential skew and characteristic impedance

3.1 Effect of rotation angle on differential skew
To evaluate the differential skew, the differential-to-common mode-conversion amount of mixed-mode S parameters \( S_{cd21} \) are generally utilized. Assuming a lossless transmission, the relationship between the differential skew \( \Delta T \) and \( S_{cd21} \) was derived

\[
\Delta T = \frac{2}{\omega} \sin^{-1} |S_{cd21}|.
\]

where \( \omega \) is the angular frequency [21, 27, 28].

Then, using the measurements from our first set of the test boards, we obtained \( S_{cd21} \) for all patterns. \( \Delta T \) is calculated from \( S_{cd21} \) using (1). Figure 4 shows the effect of the angle between the trace of the differential transmission lines and the meshed ground (rotation angle) \( \phi \) on \( \Delta T \), obtained by calculating the arithmetic average of \( \Delta T \) for the whole frequency of 0.1 to 10 GHz.

Figs. 4(a), (b), and (c) show the effect of \( \phi \) on \( \Delta T \) in the range from 0 to 45°, when the line length \( l \) is 9.6, 30, and 60 mm, respectively. In Fig. 4(a), the red square and the rhombus represent the simulation and measurement values, respectively. The simulation values correspond to the case when \( \Delta T \) takes the largest value (the worst case) when the position of the differential transmission lines over the meshed ground plane is changed. The figure indicates that \( \Delta T \) decreases with \( \phi \) and that it takes its smallest value at around \( \phi = 30° \).
3.2 Effect of line length on differential skew
Fig. 5 shows how the differential skew $\Delta T$ is affected by the line length $l$, ranging from 9.6 to 60 mm, for four different rotation angles, 22.5, 26.5, 30, and 45°. We evaluated $\Delta T$ occurring at $l$ of 9.6, 30, and 60 mm using the positional relationship of the differential transmission lines and the meshed ground in the previously described worst case. In particular, at 26.5 and 45°, the differential transmission lines of three different lengths are placed in the position shown in Fig. 5.

At 26.5 and 45°, $\Delta T$ monotonically increases with $l$. This increasing tendency is caused by the accumulation of the same phase difference. For an integer $\nu$ that is greater than or equal to 1, this increasing trend manifests at rotation angle given by

$$\phi = \tan^{-1} \left( \frac{a + b}{\nu(a + b)} \right) = \tan^{-1} \left( \frac{1}{\nu} \right).$$

As shown in Fig. 5, $\phi = 45^\circ$ when $\nu = 1$, and $\phi = 26.5^\circ$ when $\nu = 2$.

At 22.5 and 30°, $\Delta T$ fluctuates but does not increase. This is because the change is not exactly periodic, so $\Delta T$ takes a random value in every portion. The average value approaches 0, so $\Delta T$ does not increase even if $l$ is extended.

3.3 Relationship between rotation angle and characteristic impedance
In our analysis, we focus only on the differential-mode characteristic impedance. The effective differential-mode characteristic impedance $Z_{\text{diff}}$ was calculated using the S parameters and mixed-mode ABCD parameters [29, 30].

First, S parameters are obtained from the 9.6-mm differential transmission lines in our first set of test boards. Then, the mixed-mode ABCD parameters of this structure can be determined using S parameters [30].

The effective differential-mode characteristic impedance $Z_{\text{diff}}$ of the differential transmission lines can be calculated from its mixed-mode ABCD parameters

$$Z_{\text{diff}} = \sqrt{\frac{B_d}{C_d}},$$ (3)

where $B_d$ is differential-mode B-parameter and $C_d$ is differential-mode C-parameter.

Then, using the maximum and minimum values of $Z_{\text{diff}}$ obtained from different line positions, the relationship between the rotation angle and amount that the characteristic impedance changes is evaluated. Fig. 6 shows the maximum and minimum values of measured $Z_{\text{diff}}$ for seven rotation angles. When the rotation angle is 0 or 45°, the characteristic impedance changes significantly depending on the arrangement of the wiring and meshed ground, but the change is small in the range of 10 to 40°. Further, around 30°, $Z_{\text{diff}}$ was scarcely affected by the wiring-and-ground position.

4. Evaluation of differential transmission lines including bends for high-density layout
In the previous section, the differential skew $\Delta T$ and the effective differential-mode characteristic impedance $Z_{\text{diff}}$ were evaluated. Here, we evaluate our second set of test boards, shown in Fig. 3. Our second set of test boards was built to investigate whether or not high-density layout is possible when the rotation angle is set to 30°. With the dimensions in Fig. 1, the minimum distance between adjacent differential transmission lines is 0.47 mm in FPC1, as shown in Fig. 3(a). FPC2 shows our proposed design, as shown in Fig. 3(b). Using our design, the distance between adjacent differential transmission lines is reduced to 0.3 mm. And, we have confirmed from the 3D electromagnetic simulation that the crosstalk (near- and far-end crosstalk) between the adjacent differential transmission lines is negligibly small in the above setup.

Figs. 7 and 8 show the differential-to-common mode conversion $|S_{\text{cd}21}|$ and differential-mode characteristics of $|S_{\text{dd}11}|$ and $|S_{\text{dd}21}|$ as a function of frequency for test boards FPC1 and FPC2.

The following three points are clear from Figs. 7 and 8. First, $|S_{\text{cd}21}|$ of FPC1 and FPC2 became less than -20 dB when frequency below 20 GHz. This shows that $|S_{\text{cd}21}|$ for FPC2 is
not dependent on the position of the differential transmission lines relative to the pattern of the meshed ground and comparable to that for FPC1. Second, the position dependence of the differential-mode reflection $|S_{dd11}|$ for FPC2 is small compared to FPC1 when frequency below 15 GHz. This is because FPC1 demands high symmetry, and it is challenging to arrange the wiring and the meshed ground completely symmetrically in actual production. Third, FPC2 is better for the differential-mode transmission coefficient than FPC2 when frequency below 15 GHz. This is the same reason as $|S_{dd11}|$, that is the small position dependence in FPC2.

This means that differential transmission lines in FPC2 (our proposed design) is unaffected by the position of the lines relative to the meshed ground, enabling improved wiring density.

Fig. 7. Differential-mode transmission characteristics as a function of frequency for test boards FPC1.

Fig. 8. Differential-mode transmission characteristics as a function of frequency for test boards FPC2.

5. Conclusion

We achieved very low levels of differential skew by rotating the meshed ground. We found that the differential skew is not affected by the position of the differential lines relative to the pattern of the meshed ground and that it takes its minimum value when the rotation angle is around 30°.

When the angle between the differential transmission lines and the meshed ground is 0 or 45°, the effective differential-mode characteristic impedance is heavily affected by the arrangement, but the effect is slight in the range of 10 to 40°, and around 30°, the effective differential-mode characteristic impedance is unaffected by the wiring position.

We also proposed a design wherein the meshed ground is rotated by 30° with a 90° bend in the differential transmission
lines. We compared this design with a general design that has 45°-bend differential transmission lines and meshed ground. Our proposed design is unaffected by the position of the lines relative to the meshed ground, enabling improved wiring density. Further, our design is better for the differential-mode transmission characteristics than the general design, which demands high symmetry.

Acknowledgments

This study was partially supported by Grant-in-Aid for Scientific Research (B) 16H04318.

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