CST Analysis and Simulation of Signal Integrity of Differential Transmission Lines

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Abstract. The differential transmission line has been widely used in the field of high-speed signals with its unique transmission characteristics, and it will be affected by many factors during the transmission process. In this paper, the differential transmission line is taken as the research object, and a three-dimensional electromagnetic simulation software CST is used to study its signal integrity performance parameters including characteristic impedance, loss, and crosstalk. It is found through simulation that increasing the spacing between differential pairs will reduce the crosstalk. The smaller the differential pair length, the greater the value of the insertion loss. This will improve the quality of signal transmission.

Keywords: Signal integrity parameters; Differential transmission line; CST simulation.

1. Introduction
In the low-speed era of signal transmission, the signal can be correctly transmitted from the sending end to the receiving end. However, as the rising edge of the high-speed signal becomes smaller and the frequency gradually increases, the signal will change during the transmission process of the interconnected device. The receiving end cannot obtain a true and reliable signal value, so problems of signal integrity occur. When the frequency exceeds 50MHz or the signal rise time is less than 6 times the transmission line delay [1], the system design needs to face the signal integrity problems of high-speed transmission lines such as crosstalk and transmission line effects.

Broadly speaking, signal integrity refers to all the problems [2] caused by interconnects in high-speed products. It mainly studies the different effects caused by the electrical properties of interconnects on digital signal waveforms [3]. S-parameters and impedance are all common signal integrity issues. High-speed transmission systems often use differential signal lines for data transmission. Differential signal lines use a two-wire coupling structure to form a transmission channel. While transmitting signals, they provide a return path by themselves, which can effectively suppress ground bounce noise [4-5]. Compared with ordinary single-ended signals, the advantages of differential signals are reflected in the following aspects. First, the differential signal has strong anti-interference ability. Secondly, it can effectively suppress electromagnetic interference (EMI). Furthermore, its time sequence location is more accurate. The strip differential transmission line is often used in the field of transmission lines such as antennas, high-speed PCBs, and connectors.

This paper takes two pairs of strip differential transmission lines as the research object. By establishing a simulation model in CST (Computer Simulation Technology) software, the signal integrity parameters are analyzed, and the structure and size of the differential pair are studied.
2. Simulation Model

The simulation model of the coplanar strip differential transmission line is shown in Figure 1. The model has a differential impedance of 100\(\Omega\) and a single-ended impedance of 50\(\Omega\). The left of Figure 1 is the differential pair model, and the right figure is the overall model after adding the coaxial port. The differential transmission line is formed by partially overlapping the left and right sides, and a contact area is formed in the middle to simulate the mating of the connector plug and the socket. The specific dimensions and material parameters of the analysis model are shown in Table 1.

Table 1. Dimensions and material parameters of the differential pair model

| Related parts          | Length×width×height (mm) | Spacing (mm) | Materials and parameters                      |
|------------------------|--------------------------|--------------|-----------------------------------------------|
| Upper / lower ground plate | 19×12.6×0.1             | 2.2          | copper; Conductivity: \(\sigma=5.8\times10^7\) (S/m), Thermal Conductivity: \(\lambda=401\) (W/m·K); |
| Unilateral differential reed (blue) | 10×0.45×0.2 | internal spacing is 1; pair spacing is 2 | |
| Unilateral differential reed (yellow) | 10×0.4×0.2 | the spacing between the differential reed and the ground reed is 0.8 | |
| Contact zone           | 1×0.45×0.4               | /            | |
| Ground pile            | 0.5×0.4×0.8/1.0/1.2      | 7.4          | FR-4; Dielectric constant: \(\varepsilon_r=4.3\) |
| Dielectric layer       | 19×12.6×2.2              | /            | |

When performing CST simulation on high frequency connectors, coaxial ports can be added to both ends of the male and female connectors. The details of the coaxial port are shown in Figure 2. The dielectric layer of the coaxial port is air, and the relative dielectric constant is 1. The diameter \(d\) of the inner conductor is 0.45mm, which is equal to the width of the differential signal pin. The inner diameter \(D\) of the outer conductor is 1.035mm and the length is 0.1mm. The material of coaxial port is copper. The highest frequency of CST simulation is 12GHz, so the simulation frequency range is 0-12GHz.

Figure 1. Diagram of the differential pair model (left) and model diagram after adding the coaxial port (right)

Figure 2. Calculation of the coaxial ports (left) and coaxial ports in the model (right)
3. Results and Analysis

3.1. Signal Integrity Parameters

The return loss, insertion loss, near end crosstalk NEXT, and far end crosstalk FEXT of the strip differential transmission line are shown in Figure 3 to Figure 6 respectively.

Return loss exhibits periodic arch changes, as shown in Figure 3. There are 3 resonance peaks in 0-12GHz frequency. When the frequency is close to 0, the return loss is -43.7dB. When the frequency is 8.38GHz, the return loss reaches the maximum value, which is -16.1dB. When the frequency is 11.1GHz, the return loss reaches a minimum value of -54.9dB. When the frequency is between 7.12 and 9.7 GHz, the return loss value is greater than -20dB.

Insertion loss shows a tendency to decrease with increasing frequency, as shown in Figure 4. The maximum insertion loss is -0.07dB at zero frequency. When the frequency is 12GHz, the minimum insertion loss is -1.14dB. The insertion loss of differential transmission line is generally greater than -3dB, that is, 70% of the energy can reach the output through the transmission line. Through calculation, the output signal is degraded by approximately 2.1ps compared to the rising edge of the input signal. When the transmission line length is 19mm, the rising edge degradation of the output signal is less than the allowable 10%.

NEXT also exhibits periodic arch changes, as shown in Figure 5. When there are three resonances in the frequency range of 0-12GHz, the frequencies at resonance are 2.0GHz, 5.8GHz and 9.9GHz respectively. The maximum value of NEXT is about -37.2dB. In this case, the distance between the differential pairs is 2mm, which is 4.5 times of the transmission line width of 0.45mm. The distance between the two differential pairs is far, so the influence of near-end crosstalk can be ignored.

FEXT shows a tendency to increase with increasing frequency, as shown in Figure 6. When the frequency is 0, the minimum value of FEXT is -67dB. When the frequency is 12GHz, the maximum value of FEXT is -41.9dB.

In high-speed circuits, the return loss is usually required to be less than -20dB, which means that less than 10% of the signal energy can reflect to the source. The insertion loss is usually required to be greater than -3dB, that is, more than 70% of the signal energy is transmitted to the receiving end. NEXT and FEXT usually required to be less than -30dB, that is, less than 3% of the signal energy is coupled to the adjacent transmission line. Except for return loss, all other parameters of the strip differential transmission line studied in this paper meet the requirements.
3.2. TDR Impedance
CST usually uses the time domain reflectometry (TDR) [6] method to measure the impedance value along the transmission line, which is called as TDR impedance [7-8]. TDR impedance ($\Omega$) versus transmission time (ns) of the differential transmission lines is shown in Figure 7.

The formula of signal propagation speed in the dielectric is as follows.

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

The dielectric constant of FR4 is 4.3, so the propagation speed of the signal in FR4 is 144.6mm/ns. When the transmission time is 0.275ns, the TDR impedance decreases from 100 $\Omega$ to 89 $\Omega$, which corresponds to the overlap area of the transmission lines. The thickness and cross-sectional area of the overlap area of the transmission lines are increased, so the impedance value is reduced.

![Figure 7. TDR impedance curve (right) of a differential transmission line model (left)](image)

4. Influencing Factors

4.1. The Distance between the Differential Pairs
Let the distance between the differential pairs be the variable $x$ and take the value from 1.2mm to 1.4, 1.6, 1.8, 2.0 mm respectively. When the distance between differential pairs changes, the return loss, insertion loss, and TDR impedance are basically unchanged, indicating that only changing the spacing between pairs of differential pairs has little effect on them. The effect of the distance between differential pairs on crosstalk is more obvious, as shown in Figure 8.

![Figure 8. NEXT (dB, left) and FEXT (dB, right) versus frequency (GHz) at different distance](image)

The smaller the distance between the differential pairs, the greater the NEXT and FEXT. When the spacing increases from 1.2mm to 1.4mm and 2mm, the NEXT maximum value decreases from -27.6dB to -30dB and -36.9dB, and the FEXT maximum value decreases from -34.9dB to -36.5dB and -41.7dB. The hazard of NEXT is more serious than FEXT. In order to make the crosstalk value less than -30dB, the differential pair spacing should be greater than 1.4mm, which is more than three times of the transmission line width of 0.45mm.
4.2. The Length of the Differential Pair
The length of the strip difference line is 19 mm. The length $l_1$ of the male head is now expanded to 20 mm and 30 mm, the female head remains unchanged at 10 mm. The length of the middle contact area is 1 mm, that is, the total length is 29 mm and 39 mm respectively. The simulation results are shown below.

![Figure 9. Return loss (dB)](image)

![Figure 10. Insertion loss (dB)](image)

![Figure 11. NEXT (dB)](image)

![Figure 12. FEXT (dB)](image)

![Figure 13. TDR impedance](image)

When the total length is 39mm and 29mm, there are more bridge arches on the return loss curve than when the total length is 19mm, indicating that there are more frequency points where resonance occurs, as shown in Figure 9. The overall insertion loss decreases with increasing frequency. When the frequency is 12GHz, the minimum insertion loss of the total length of 39mm is -2.34dB, and the minimum insertion loss of the total length of 29mm is -1.78dB, as shown in Figure 10. Compared with the previous minimum insertion loss of -1.14dB, it is reduced by 1.20dB and 0.64dB respectively. The longer the length, the smaller the insertion loss.

When the total length is changed, the maximum value of the NEXT does not change much, but resonance occurs more often. The maximum value of NEXT is about -38dB, as shown in Figure 11. The maximum value of FEXT is -41.9dB, as shown in Figure 12. The value of TDR impedance does not change much, the minimum value is $89\Omega$. Because the length of the male head $l_1$ changes, while the female head is still 10mm, the impedance curve on the horizontal axis increases with the length of the male head, as shown in Figure 13.
5. Conclusion

The strip differential transmission lines meet the requirements except the return loss. The overlapping area of the differential transmission line makes the impedance fail to meet the matching requirement of $100 \Omega \pm 10 \Omega$, and increases the return loss of the signal. Compared with the proposed $100 \Omega$, the impedance is less than the proposed value and it can be made close to the proposed value by changing the physical structure or some material parameters. As the return loss does not meet the requirements, the bandwidth of the differential pair is reduced from 12GHz to 7GHz.

For the factors affecting signal integrity, the conclusions are shown as follows. The distance between the differential pairs affects NEXT and FEXT value. The smaller the spacing, the greater the impact of crosstalk. In order to make the crosstalk value less than -30dB, the differential pair spacing should be greater than 1.4mm, which is more than three times of the transmission line width of 0.45mm. The longer the differential pair, the more resonance the return loss and NEXT, and the insertion loss is also smaller. In order to make the insertion loss of transmission line meet the requirement of less than -2dB, the total length of transmission line should be less than 35mm.

The main reason of impedance mismatch and reflection loss not meeting the requirements is the difference pair overlapping area, which must be carefully designed.

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