Effect of Signal Reflection on the Performance of High-density Ceramic Package Transmission Lines

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Abstract—In this paper, the reflection problem caused by the sudden change of characteristic impedance caused by the complex interconnection of laminations and via, pads and interconnects in high-density ceramic package is studied, and the transmission line design optimization is realized. In high-density ceramic package designs, reflections severely affect the performance of the transmission line. Based on the relevant theory of transmission line transmission, the reflection problem is studied by modeling and simulation methods. The transmission line model is constructed by using electromagnetic simulation software, and the obtained return loss represents reflection. The method of controlling variables is used to analyze the factors that affect the reflection. The simulation results show that the anti-pad has a significant impact on the performance of the transmission line, and the influence of via and pads on the performance of the transmission line is second.

1. INTRODUCTION
With the development of high-speed integrated circuits, chip size has been greatly reduced, signal frequency has been continuously improved, and signal reflection has seriously affected circuit interconnection performance during transmission. Therefore, the analysis of ceramic package transmission lines has become a very important part of the design and optimization process. In ceramic package stack design, the effect of reflection on the performance of the transmission line must be considered [1].

Reflection means that a signal generates a reflected signal where the impedance is discontinuous during transmission along the transmission line. The reflected signal and the transmitted signal are superimposed on each other, causing undesired signal distortion [2].

Impedance changes, resulting in impedance mismatch, which is one of the causes of reflection. The degree of change in reflection is expressed using return loss.

2. FUNDAMENTAL
2.1 Principle of Reflection Formation
When the signal is transmitted along the line, a reflection occurs when the sensed instantaneous impedance changes [3]. Interconnects, pads and via of different impedances cause reflections. As shown in Figure 1, when the characteristic impedances of the two parts of the interconnect are not equal, some of the energy is reflected back to produce a reflected signal, and the reflection coefficient is represented by $\rho$ [4].
2.2 Reflection Phenomenon Analysis

In integrated circuit high-density ceramic package design, the main factor that causes reflection is load impedance mismatch. The load categories can be divided into resistive terminal loads, capacitive terminal loads, capacitive middle loads, and inductive loads.

1) Resistive Terminal Load

When the signal is transmitted from the source to the terminal, it is felt that the change of the instantaneous impedance causes reflection, and the reflection coefficient can be obtained by Equation 1. The ringing phenomenon can seriously affect the signal transmission quality, so the transmission line should be kept as uniform as possible in the design.

2) Capacitive Terminal Load

In integrated circuit ceramic packages, structures such as pads and via introduce parasitic capacitance, which is a capacitive discontinuity for the signal. When the signal reaches the terminal, it will reflect due to capacitative discontinuity.

The capacitance impedance can be expressed as:

$$Z_C = Z_0 \left( e^{\frac{t}{\tau}} - 1 \right)$$  \hspace{1cm} (2)

The time constant is $\tau = Z_0 C$. Bring into Equation 1 to get:

$$\rho = 1 - 2 e^{\frac{-t}{\tau}}$$  \hspace{1cm} (3)

3) Capacitive Middle Load

The size of $\rho$ is related to the characteristic impedance of the two parts of the interconnection. The expression is as follows:

$$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$  \hspace{1cm} (1)

Where $Z_1$ and $Z_2$ are the characteristic impedances that interconnect the two parts respectively. If $Z_1 = Z_2$, the signal will not reflect. When $Z_2 > Z_1$, $\rho > 0$, the direction of the reflected signal is the same as the direction of signal transmission, the amplitude of the superimposed signal increases, and overshoot occurs; when $Z_2 < Z_1$, $\rho < 0$, and the direction of the reflected signal is opposite to the direction of signal transmission. The amplitude of the superimposed signal will decrease and undershoot will occur. The phenomenon of repeated overshoot and undershoot in the clock cycle is called ringing, as shown in Figure 2.
In a ceramic package stack structure, the interlayer via is a capacitive load that is equivalent to being at the mid-end of the interconnect. The main difference between the capacitive mid-end load and the capacitive end load is the time constant $\tau$ and the reflection coefficient $\rho$.

If the impedance of the transmission line on both sides of the mid-end capacitive load is $Z_0$, when the signal capacitor is charged, it is equivalent to charging it with an impedance of $\frac{1}{2} Z_0$. Therefore, the circuit charging time constant is $\tau = \frac{1}{2} Z_0 C$.

The capacitance impedance can be expressed as:

$$Z_c = \frac{1}{2} Z_0 \left( e^{\frac{t}{\tau}} - 1 \right)$$  \hspace{1cm} (4)

When the signal is transmitted at the mid-end capacitive load, the perceived impedance is the parallel impedance $Z_p$, which is equal to the parallel connection of capacitive load impedance $Z_c$ and characteristic impedance $Z_0$. Bring $Z_p$ into Equation 1 to get:

$$\rho = -e^{-\frac{t}{\tau}}$$  \hspace{1cm} (5)

4) Inductive Load

In ceramic packages, package interconnects, package leads, via exhibit typical inductive discontinuities.

The inductance impedance can be expressed as:

$$Z_L = \frac{L}{Z_0} \left( e^{\frac{t}{\tau}} - \frac{1}{e^{\frac{t}{\tau}}} \right)^{-1}$$  \hspace{1cm} (6)

The time constant is $\tau = \frac{L}{Z_0}$. Bring into Equation 1 to get:

$$\rho = 2e^{-\frac{t}{\tau}} - 1$$  \hspace{1cm} (7)

3. TRANSMISSION LINE MODEL

In order to study the effect of reflection on high-density ceramic package transmission lines, electromagnetic simulation software was used to construct a transmission line model with various loads for testing. As shown in Figure 3, it is a wire-pad-hole interconnect model. Select the medium as Al$_2$O$_3$, the dielectric constant is 9.8; set the micro strip line and strip line parameters to match 50 $\Omega$; the via radius is 0.075mm, the height is 0.515mm; the pad radius is 0.3mm, the thickness is 0.015mm The anti-pad radius is 0.61mm.

![Figure 3. Transmission line model](image-url)
4. SIMULATION ANALYSIS USING CONTROL VARIABLES

Characteristic impedance $Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$. Under high frequency signal, $j\omega L \gg R$, $j\omega C \gg G$, so

$$Z_0 = \sqrt{\frac{L}{C}}.$$  

Change $L$ and $C$ so that $Z_0$ changes. According to the formulas (2), (4), (6), the impedance of the capacitor and the impedance of the inductor change, resulting in impedance mismatch and reflection. Therefore, the pad, the anti-pad and the via are selected as the changed parameters, and $Z_0$ is changed so that the reflection coefficient $\rho$ changes. The smaller $|\rho|$, the smaller the reflection.

Under the condition that the model determines the specific parameters, the excitation port is loaded, the solution option is set, and the simulation is performed. Using the S parameter, by changing the single parameter by the method of controlling the variable, the return loss $S_{11}$ is obtained. Return loss is a parameter that describes the reflection performance of a transmission line. The smaller the reflection, the smaller $S_{11}$.

The signal frequency range is selected from 1 to 15 GHz, and other parameters are kept unchanged. The return loss of the transmission line interconnection model changes with the frequency. As shown in Figure 4.

![Figure 4](image)

Figure 4. Return loss varies with frequency

Under the condition of considering the crafts achievability, the range of variation of the selected parameters is smaller than the size of the model built, and the amount of change of each parameter varies according to the crafts achievability.

4.1 Effect of Pad Thickness on Return Loss

When analyzing the influence of the pad thickness on $S_{11}$, the other parameters and their characteristic impedances are kept unchanged, and only the pad thickness is changed. The parameters of the pad thickness change are as follows: 0.011mm, 0.012mm, 0.013mm, 0.014mm. Four models of the corresponding parameters were respectively established, and the return loss of the four models was analyzed to obtain the simulation results of the return loss $S_{11}$ at 10 GHz, as shown in Table 1 and Figure 5.

| TABLE 1. Pad Thickness Change Table |
|-----------------------------------|
| $D$/mm | 0.011 | 0.012 | 0.013 | 0.014 |
| $S_{11}$/dB | -39.9506 | -38.2482 | -37.9628 | -37.7494 |
According to the results shown in Table 1, the return loss increases as the thickness of the pad increases while keeping other parameters and their characteristic impedance constant.

4.2 Effect of Pad Radius on Return Loss

When analyzing the influence of the pad radius on $S_{11}$, the other parameters and their characteristic impedances are kept unchanged, and only the pad radius is changed. The parameters of the pad radius are changed as follows: 0.22mm, 0.24mm, 0.26mm, 0.28mm. Four models of the corresponding parameters were established, and the return loss of the four models was analyzed to obtain the simulation results of the return loss $S_{11}$ at 10 GHz, as shown in Table 2 and Figure 6.

| $R_1$/mm | 0.22 | 0.24 | 0.26 | 0.28 |
|----------|------|------|------|------|
| $S_{11}$/dB | -34.5037 | -35.0765 | -35.5360 | -36.5613 |

According to the results shown in Table 2, the return loss decreases as the pad radius increases while keeping other parameters and their characteristic impedance constant.

4.3 Effect of Anti-pad Radius on Return Loss

When analyzing the effect of the anti-pad radius on $S_{11}$, the other parameters and their characteristic impedances are kept unchanged, and only the anti-pad radius is changed. The parameters of the anti-pad radius change are as follows: 0.53mm, 0.55mm, 0.57mm, 0.59mm. Four models of the corresponding parameters were respectively established, and the return loss of the four models was analyzed to obtain the simulation results of the return loss $S_{11}$ at 10 GHz, as shown in Table 3 and Figure 7.

| $R_2$/mm | 0.53 | 0.55 | 0.57 | 0.59 |
|----------|------|------|------|------|
| $S_{11}$/dB | -30.7327 | -32.3411 | -34.6458 | -35.0674 |
According to the results shown in Table 3, the return loss decreases as the radius of the anti-pad increases, while keeping other parameters and their characteristic impedance constant.

4.4 Effect of Via Radius on Return Loss
When analyzing the effect of the via radius on $S_{11}$, the other parameters and their characteristic impedances are keeping unchanged, and only the via radius is changed. The parameters of the via radius are changed as follows: 0.067mm, 0.069mm, 0.071mm, 0.073mm. Four models of the corresponding parameters were respectively established, and the return loss of the four models was analyzed to obtain the simulation results of the return loss $S_{11}$ at 10 GHz, as shown in Table 4 and Figure 8.

| R/mm  | 0.067  | 0.069  | 0.071  | 0.073  |
|-------|--------|--------|--------|--------|
| $S_{11}$/dB | -41.4109 | -39.4934 | -38.9148 | -38.7349 |

According to the results shown in Table 4, the return loss increases as the via radius increases, while keeping other parameters and their characteristic impedance constant.

4.5 Effect of Ground Via on Return Loss
When analyzing the effect of the ground via on $S_{11}$, keep the other parameters and their characteristic impedances unchanged, and just add a ground via, as shown in Figure 3. Models with grounded via and ungrounded via were established, and the return loss of the two models was analyzed to obtain the simulation results of the return loss $S_{11}$ at 10 GHz, as shown in Table 5 and Figure 9.

| Ground via | via     | no via   |
|------------|---------|----------|
| $S_{11}$/dB| -37.0729| -36.7802 |
Figure 9. Return loss varies with grounded via and ungrounded via

According to the results shown in Table 5, the return loss is improved by increasing the ground via, while keeping the other parameters and their characteristic impedance constant.

4.6 Impact Factor $\delta$

Set the impact factor $\delta$, which represents the ratio of the maximum change in return loss to the maximum percentage change in the parameter change. The larger $\delta$, the greater the effect of the parameter, the unit is dB/%. The expression is as follows:

$$\delta = \frac{S_{1 \text{max}} - S_{1 \text{min}}}{\left( \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{min}}} \right) * 100\%}$$

(8)

According to the data in the tables in 3.1, 3.2, 3.3 and 3.4, available, $\delta_{\text{Pad thickness}} = 0.0807$, $\delta_{\text{Pad radius}} = 0.0755$, $\delta_{\text{Anti-pad radius}} = 0.3829$, $\delta_{\text{Via radius}} = 0.2987$.

5. CONCLUSION

According to the impact factor, the anti-pad radius has a significant influence on the reflection performance, and the influence of the via radius on the reflection performance is second, and the pad thickness and radius have the least influence on the reflection performance. That is, the anti-pad has the highest impact on the performance of the transmission line, followed by pads and via. From the above simulation analysis results, it can be seen that for high-density ceramic packaging, the influence of reflection on the performance of the transmission line is inevitable and significant.

The reflection problem of high-speed signals is a complex problem involving multiple influencing factors. In order to analyze the influence of various factors, modeling and simulation is particularly important. Through the simulation results, the settings of each parameter are adjusted, such as appropriately increasing the anti-pad radius and the pad radius, and reducing the pad thickness and the via radius, thereby reducing the influence of reflection on the performance of the transmission line.

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