Pulse Propagation Characteristics of a Multi-layered Printed Circuit Board with a Via and a Bump

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In this paper, we numerically analyze the transient response of pulse propagation in a multi-layered printed circuit board with a via and a bump. FDTD method is used for our models. It is found from numerical results that; (1) Even if the lengths of the striplines are equal, pulse waveforms passed through a via and a bump are different according to the direction of the striplines. (2) The propagating pulses are influenced by the pad size connecting the bump rather than the bump size. (3) For the model consisted of a via and a bump pulse distortion of responses are substantially improved, if the smaller bump part (including pads) can be designed.

Keywords : via, bump, multi-layered printed circuit board, pulse response

1. Introduction

The interconnects in printed-circuit-boards (PCB) are of considerable importance for high density packing and high speed signal transmission. For example, a clock frequency is greater than 1GHz and input-output terminals exceed 2000⁽¹⁾.

A via is one of the most commonly used interconnections in the multi-layered printed boards⁽²⁾⁻⁽⁵⁾. Recently the wiring structures are composed of multi-layered striplines combined with a ball grid (bump)⁽¹⁾⁽⁶⁾. The accurate characterization for pulse propagation is an important issue in the successful design of high speed circuits implemented on multi-layered PCB constructed by vias and bumps.

In this paper, pulse propagation characteristics are investigated for the fundamental multi-layered printed circuit model with a via and a bump as shown in Fig.1. The via is connected to the circular pads of conductor (labeled pad-2 and pad-3 in Fig.1) through the hole of conductor-2. The bump is put between pad-1 and pad-2. Pad-1 is connected to the transmission line labeled line-1.

Numerical results for pulse propagation are compared a bump-via connected structures with a via connected structures without a bump. The finite-difference time-domain (FDTD) method⁽⁷⁾⁽⁸⁾ has been successfully used for the analysis of our problem. FDTD method can analyze the pulse propagation characteristics as the boundary value problem for Maxwell equations. Numerical simulation can provide quantitative and accurate results which are difficult to measure directly. For printed circuit designers, it is desirable to predict the pulse waveforms in circuit segment of via-bump structure rather than to evaluate the equivalent circuits⁽¹⁾.

2. Analysis

2.1 Analysis Models The coordinate system and the structures of a multi-layered PCB with a bump and a via are

shown in Figs.1,2, and 3. Fig.2 shows the cross section on x - z plane of the bump-via model (BV model) whose striplines separated by dielectric layers are connected by both a via and a bump. BV model is a fundamental model throughout this paper and a part of structure in the practical PCB taken as BV model. BV model is consisted of five layered structures of three dimensions. Layer-1, layer-3, and layer 4 are dielectric substrates of the relative permittivity $\epsilon_r = 3.4$. Layer-2 and layer 5 are the air ($\epsilon_r = 1.0$). The detail of striplines, pads, and conductors placed into each layer are as follows.

- (1) Layer-1 : The layer is composed of a dielectric sheet on the conductor1. The stripline (line1) of width w_d and the pad (pad1) of radius a_{bp} are put on the dielectric sheet.
- (2) Layer-3 : The layer which is put on a bump is composed of a dielectric sheet of thickness c_3 . The conductor2 with a through hole is out on the sheet.
- (3) Layer 4 : The layer is a dielectric sheet on which the line2, pad3 and line3 are put. A via perpendicularly passes through the layer.

Fig. 1. Configuration of a via and a bump

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Fig. 2. Cross section of the bump-via model (BV model)

Fig. 3. Cross section of the via model (V model)

The conductor (conductor-2) with the clearance hole of radius a_{clr} is placed between layer-3 and layer 4. Pad-1 and pad-2 are connected by the bump of radius a_b , and pad-2 and pad-3 are connected by the via passing through a clearance hole of conductor-2.

Fig.3 shows the cross section on x - z plane for the via model (V model) whose striplines separated by dielectric layers are connected by only a via. V model is the structure prepared in order to discuss the influence to pulse response due to the bump of BV model. Pad-2 and the bump are removed and pad-1 and pad-3 of radius a_{vp} are directly connected by the via. The relative permittivity of layer-2 is $\epsilon_r=3.4$.

In Figs.1,2, and 3, line-1 ~ line-3, pad-1 ~ pad-3, conductor-1, conductor-2, a via, and a bump are the perfect conductor of thickness h_m . All dielectric sheets are lossless.

2.2 Analysis Method A transient analysis of a pulse propagation for BV model and V model is computed by FDTD method⁽⁷⁾⁽⁸⁾. The cell size Δ is defined as $\Delta=\Delta x=\Delta y=\Delta z$. The time step Δt is determined so as to satisfy the stability condition of Courant⁽⁹⁾. Ten layered PML⁽⁸⁾⁽⁹⁾ is imposed as the absorbing

Fig. 4. Incident excitation pulse form and its spectrum

Table 1. The size of each part of the analysis model (μm)

$a=300$	$c_5=30$	$l_{vx}=100$
$b=140$	$a_v=15$	$l_{vy}=70$
$c_1=25$	$a_{vp}=30$	$h_m=10$
$c_2=25$	$a_b=35$	$l_{im}=250$
$c_3=25$	$a_{bp}=50$	$w_d=20$
$c_4=25$	$a_{clr}=30$	

boundary condition around the each model. An incident excitation pulse is a Gaussian pulse defined as :

$$E_z^{inc} = \exp\left\{-\frac{(t-3T)^2}{T^2}\right\} \dots\dots\dots (1)$$

where $T=0.5\text{ps}$. The pulse form and the spectrum of E_z^{inc} are shown in Fig.4. E_z^{inc} is uniformly excited under line-1 at $x=l_{im}$ in Figs.2 and 3.

3. Numerical Results

The sizes of BV model and V model in Figs.2 and 3 are denoted in Table.1. These data are practical values which are used for the printed circuit board⁽¹⁾. We set three observation points (OP-1, OP-2, and OP-3 in Figs.2 and 3) for clarifying the status of pulse propagating from line-1 to line-2 and line-3. OP-1 (at $x=250\mu\text{m}$ and $y=70\mu\text{m}$) is just under line-1. OP-2 (at $x=25\mu\text{m}$ and $y=70\mu\text{m}$) and OP-3 (at $x=175\mu\text{m}$ and $y=70\mu\text{m}$) is just under line-2 and line-3, respectively. The distance from OP-2 to the center of the via is same as that from OP-3 to the center of the via.

Fig.5 shows a convergence test of the amplitude of E_z against the cell size Δ of FDTD on OP-1 for BV model. From Fig.2, it is found that the relative error to the extrapolated true value of the amplitude of E_z can be kept less than 5% by taking Δ in the range of $\Delta \leq 2.5\mu\text{m}$. In the following numerical analysis, the relative error of the amplitude of E_z is always kept below 5% by selecting Δ carefully.

Fig.6 shows pulse responses observed on OP-1. The results of the BV model and V model are indicated by the solid line and the broken line, respectively. b_i (as labels of BV model) and v_i (as labels of V model) at the response waveforms are utilized as a help of the considerations throughout numerical results. In Fig.6, b_1 and v_1 are the excited pulse. b_1 has a larger peak value of response than the peak value of v_1 . This is because the permittivity of each model in layer-2 is different. b_2 and v_2 are the reflection wave from a bumps and/or a via. The response after b_2 and v_2 is continued decreasing by a multiple reflection generating in the substrate.

Fig.7 shows pulse responses observed on OP-2. In the case of V model, v_2 due to the influence of multiple reflection is continued

Fig. 5. Convergence test of a pulse response against the cell size

Fig. 6. Pulse responses on OP-1 for BV model and V model

Fig. 7. Pulse responses at OP-2 for BV model and V model

Fig. 8. Pulse responses at OP-3 for BV model and V model

Fig. 9. Pulse responses at OP-2 for BV model when varying a clearance hole radius a_{clr}

Fig. 10. Pulse responses at OP-3 for BV model when varying a clearance hole radius a_{clr}

Fig. 11. Pulse responses at OP-2 for V model when varying a clearance hole radius a_{clr}

Fig. 12. Pulse responses at OP-3 for V model when varying a clearance hole radius a_{clr}

after v_1 which the excited pulse is arrived on OP-2 by propagating through the via. BV model also has a similar response. However, a large distortion of waveform is observed for BV model, thus having a complicated structure with a bump.

Fig.8 shows pulse responses observed on OP-3. In the case of BV model, b_1 at OP-3 is larger than that at OP-2, and b_2 of OP-3 is smaller than that at OP-2. In the case of V model, these results become reverse relations. Whereas the response time at the peak value at b_1 and v_1 for OP-2 is same, the peak value at b_1 for OP-3 is later than that at v_1 .

In Figs.6,7 and 8, a clearance hole of radius a_{clr} made into conductor-2 had been fixed at $a_{clr}=30\mu\text{m}$. Next, we will study on the effect and the influence to pulse response when varying a_{clr} in BV model and V model. To compare with the responses in Figs.7 and 8 we computed the responses when a_{clr} is $30\mu\text{m}$, $40\mu\text{m}$, and $50\mu\text{m}$.

For BV model, Figs.9 and 10 show pulse responses observed on OP-2 and OP-3, respectively. The following results are found from the figures.

- (1) b_1 at OP-2 increases as a_{clr} is increased, on the other hand b_1 at OP-2 does not change.
- (2) When varying a_{clr} is changed from $30\mu\text{m}$ to $50\mu\text{m}$, the modification of b_1 at OP-3 is smaller than that at OP-2.
- (3) For OP-3, b_2 decreases as a_{clr} is increased. Then, the new distortion b_3 is arisen by larger a_{clr} . b_3 increases as a_{clr} is increased.
- (4) The rise of response on OP-2 is not almost influenced by

the size of a_{clr} . But, the rise of response on OP-3 becomes quick as a_{clr} is increased.

For V model, Figs.11 and 12 show pulse response observed on OP-2 and OP-3, respectively. The results from the figures are summarized as follows.

- (1) For OP-2, v_1 increases and v_2 decreases as a_{clr} is increased. For OP-3, v_1 and v_2 decrease and v_3 increases as a_{clr} is increased. The change for v_1 on OP-3 is smaller than that at OP-2.
- (2) The large pulse distortion by varying a_{clr} is not observed.

When the pulse excited from OP-1 was arrived to OP-2 or OP-3, the large pulse distortion was observed in BV model. If the clearance hole radius was set up larger, the pulse distortions on OP-2 were improved. But the pulse on OP-3 produced a new distortion. This means that less distortion of the pulse responses on OP-2 and OP-3 is trade-off for the size of the clearance hole. From these results, it is necessary to find out fundamental causes of the pulse distortion arising in BV model. We discuss the influence of the bump which is put between pad-1 and pad-2 of bump surface. The bump radius is a_b and the radiuses of pad-1 and pad-2 are equally a_{bp} . Firstly, the size of a bump radius is examined. When the bump radius a_b is reduced from $a_b=35\mu\text{m}$ (original size in Table.1) to $a_b=15\mu\text{m}$ (same size as via radius a_v), pulse responses on OP-2 and OP-3 are shown by solid lines ($a_b=a_v$) in Figs.13 and 14, respectively. For comparison, responses of the original bump radius ($a_b=35\mu\text{m}$) for BV model in Figs.7 and 8 are also indicated by broken lines ($a_b \neq a_v$). The radius of

Fig. 13. A comparison of a pulse response (solid line) in the case with a small bump radius ($a_b=a_v=15\mu\text{m}$) and a pulse response (broken line) in the case with an original bump radius ($a_b=35\mu\text{m}$) for BV model at OP-2

Fig. 14. A comparison of a pulse response (solid line) in the case with a small bump radius ($a_b=a_v=15\mu\text{m}$) and a pulse response (broken line) in the case with an original bump radius ($a_b=35\mu\text{m}$) for BV model at OP-2

Fig. 15. A comparison of a pulse response (solid line) of BV model and a pulse response (broken line) of V model at OP-2. a_b and a_{bp} of BV model is set up similarly to a_v and a_{pp} of V model, respectively

Fig. 16. A comparison of a pulse response (solid line) of BV model and a pulse response (broken line) of V model at OP-3. a_b and a_{bp} of BV model is set up similarly to a_v and a_{pp} of V model, respectively

clearance hole a_{clr} is $30\mu\text{m}$ and a_{bp} is kept at $50\mu\text{m}$. In Figs.13 and 13, pulse responses of solid line ($a_b = a_v$) almost agree with pulse responses of broken line ($a_b \neq a_v$). From Figs.13 and 14, it is drawn that the waveforms of pulse on OP-2 and OP-3 are not influenced by the size of bump. Secondly, the size of bump pads (pad-1 and pad-2) is examined keeping $a_b = a_v = 15\mu\text{m}$ on the basis of results from Figs.13 and 14. When radius a_{bp} of pad-1 and pad-2 is reduced from $a_{bp} = 50\mu\text{m}$ (original size in Table.1) to $a_b = 30\mu\text{m}$ (same size as the via pad (pad-3) with radius a_{vp}), pulse responses at OP-2 and OP-3 are shown by solid lines ($a_{bp} = a_{vp}$) in Figs.15 and 16, respectively. The responses of V model in Figs.7 and 8 are also indicated by broken lines ($a_b \neq a_v$). a_{clr} is $30\mu\text{m}$. The rise time in BV model becomes slightly earlier than that in V model. The large pulse distortion in BV model is not almost observed. As a result, it is concluded that the pulse distortion on OP-2 and OP-3 is depended on the radius of the pads added to the bump. From above results, it is found that the pulse distortion on a stripline after propagating the bump part can be minimized if the bump pad radius can be small (as much as the via pad radius) by designing the bump radius as small as possible.

4. Conclusions

In this paper, pulse propagation characteristics in multi-layered PCB with a via and a bump were investigated. We proposed BV model (with a via and a bumps) and V model (with a via). V model was prepared as a comparison model to discuss the influence of a bump. The main results are as follows.

(1) It is found for BV model that the pulse distortion on a stripline after propagating the bump can be minimized if the bump pad radius is nearly equal to the via pad radius.

(2) In BV model, although the radius a_{clr} of a clearance hole located into conductor plate can be controlled (in the the range of $30 \leq a_{clr} \leq 50\mu\text{m}$), an improvement effect to a pulse response is trade-off by the propagation direction of pulse.

(3) It is found for BV model that the pulse distortion on a stripline after propagating the bump can be minimized if the bump pad radius is nearly equal to the via pad radius.

In the design of high speed circuit for multi-layered PCB, studies of numerical simulation of pulse propagation characteristics are a very important. In this paper, the responses of a pulse propagating through the fundamental structure combined with a bump and a via were numerically analyzed by FDTD method. The accuracy of a pulse response was also discussed fully. In the future, we will also study on a pulse propagation characteristics for more complicated structures with bumps and vias on the basis of results obtained in this paper.

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