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Electromagnetic Emissions from the IC Packaging

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Abstract—The EMC and EMI of the IC packaging are becoming increasingly important to modern electronics. Its EMC, SI, and PI have been broadly attested. But electromagnetic radiations from IC packaging and the corresponding EMI were seldom studied. In this paper, the fundamental principles and properties of the electromagnetic radiations caused by vias and traces in IC packagings are carefully investigated. Various radiation mechanisms are analyzed for different representative scenarios. Numerical simulations are employed to support the analyzing results.

Index Terms—EMC/EMI, radiated emission, IC packaging, trace radiation, via radiation, cavity modes

I. INTRODUCTION

In recent decades, continuous advances in semiconductor technology pushes for improvements in integrated circuit (IC) packaging. Packaging’s increasing capacities and shrinking dimensions lead to a complex electromagnetic environment. Hence, advanced modeling and optimization for multilayer packaging are needed to solve for signal/power integrity (SI/PI) and electromagnetic compatibility/interference (EMC/EMI) issues. However, most recent works have been focused on SI/PI [1]–[3]. EMI on IC packaging has become increasingly important for EMC/EMI regulations. But it was focused on SI/PI [1]–[3]. EMI on IC packaging has become increasingly important to modern electronics. Its EMC, SI, PI technology pushes for improvements in integrated circuit (IC) packaging. Packaging’s increasing capacities and shrinking dimensions lead to a complex electromagnetic environment. Hence, advanced modeling and optimization for multilayer packaging are needed to solve for signal/power integrity (SI/PI) and electromagnetic compatibility/interference (EMC/EMI) issues. However, most recent works have been focused on SI/PI [1]–[3]. EMI on IC packaging has become increasingly important for EMC/EMI regulations. But it was focused on SI/PI [1]–[3]. EMI on IC packaging has become increasingly important to modern electronics. Its EMC, SI, PI

II. THE EFFECTS OF VIA STRUCTURES

The importance of fundamental via effects has been discussed in [4]. In this paper, further investigations on via structures along with a trace and a heatsink are studied.

A. The Effects of Frequency

For each via, suppose it has the current $I$. Its current moment is $P = I_d dl a$. Even though there are top and bottom ground planes, the via can still be treated as a Hertzian dipole as Fig. 1(a) when the frequency is low. Its radiated field (when placed at the origin) is

$$E_\theta = j \omega \mu I_d dl a \cdot \frac{e^{-j\beta r}}{r} \cdot \sin \theta$$

(1)

Hence, $E_\theta \sim O(\omega)$. When there are two vias with opposite currents (see Fig. 1(b)), the total E-field is the result of multiplication of an array factor. At low frequencies,

$$E_\theta \approx j \frac{\omega^2 \mu d I_d dl a}{c} \cdot \frac{e^{-j\beta r}}{r} \cdot \sin \theta \cos \varphi$$

(2)

Hence, $E_\theta \sim O(\omega^2)$. When there are four GND vias symmetrically surrounding the signal via in Fig. 1(c), four GND vias are assumed to share the return current. At low frequencies,

$$E_\theta \approx j \frac{\omega^3 \mu d^3 I_d dl a}{c^2} \cdot \frac{e^{-j\beta r}}{r} \cdot \sin \theta \cdot \frac{d^2}{8} \cos^2 (\varphi)$$

(3)

Hence, $E_\theta \sim O(\omega^3)$. In general, the total E-field will increase by 20, 40, and 60 dB for one order of frequency increase for one, two, and five vias, respectively.

The above analysis is only valid for low frequencies. If $d \approx 2 \ mm$, $\beta d \ll 1$, $\lambda_0 = 20 \pi d$, we have $f_0 = c/\lambda_0 \approx 2.39 \ GHz$. Hence, this analysis is invalid above 2.4 GHz. Beyond this frequency, the approximated dipole radiation mechanism
is not accurate anymore. The effects of the top and bottom ground planes have to be considered. Plus, the parallel metal plates form cavities that support the cavity modes excited by vias.

The emission tests at 3 meters are shown in Fig. 2(a). It is observed that the radiated emissions are increasing approximately at the rate of 20 dB for one via, at the rate of 40 dB for two vias, and at the rate of 60 dB for five vias at frequencies below 2.39 GHz. It proved the low frequency radiation models for vias in packaging. When vias are placed irregularly, the return currents will make the effective via configuration close to one of these three cases. Hence, at low frequencies, the increasing rate of the radiation shall be below 60 dB. More frequently, we shall see 20 dB in practical implementations.

At high frequencies, the metallic cavity with dielectrics is dominated by cavity modes: $TE_z$ and $TM_z$ modes. $TM_z$ modes’ cutoff frequencies can be estimated by:

$$f_{TM_{np}} = \frac{1}{2\pi\sqrt\mu}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{c}\right)^2}$$

where $m = 0, 1, 2, \cdots; n = 1, 2, 3, \cdots; p = 0, 1, 2, \cdots$. Similar equations can be obtained for $TE_z$ modes. Physically $TM_z$ modes shall be dominant in the layered packaging structure. Mathematically the lowest $TE_z$ cutoff frequency is calculated to be above 100 GHz for the target structure, which is much higher than that of the first $TM_z$ mode. The cutoff frequencies of $TM_z$ modes when $p = 0$ are calculated and shown in Fig. 2(b). It reveals many correlations between the cutoff frequencies of cavity modes and the peak radiation of the packaging at frequencies from 3.5 to 20.5 GHz. It is also observed that the estimated cavity cutoff frequencies are not necessarily at the resonance. There are some other radiation peaks that need further study and understanding.

B. The Position of the Stripline in the Package Layers

The position of a stripline is an important factor to the contribution of EMI. It is interesting to find out how it affects the IC packaging EMI.

Figure 3 illustrates a stripline structure with different po-

Fig. 2. 3-m emission tests (a) for short vias and (b) cavity modes at high frequencies.

3-m Emission Tests on Short Via Position

3-m Emission Tests on Cavity Modes at High Frequencies

Fig. 3. A stripline structure. (a) Cross sectional view of the signal path with the trace $h$ below the top plate. Only one ground via is used at the right of the load. (b) The signal path at height of $H/5$ when there are two ground vias. (c) The signal path at height of $H/2$ when there are two ground vias. (d) The signal path at height of $3H/4$ when there are two ground vias.

Fig. 4. 3-m emission tests for (a) 1 GND via case and (b) 2 GND vias case.
Fig. 5. A microstrip line structure with a heatsink on top of it.

Fig. 6. 3-m emission tests on the microstrip line and the heatsink.

Fig. 7. A differential traces structure. (a) top view. (b) cross-sectional view.

A. Differential Traces

Two differential traces structures are studied and compared. The first one is shown in Fig. 7 with four GND vias surrounding each signal via. The second case is when there are only four GND vias and they are placed at the four corners of the packaging, far away from signal vias. The 3-m measurement position is taken to obtain the maximum emission tests shown in Fig. 8.

From the results of the first case, the differential mode of differential traces has higher radiated emissions than the common mode at low frequencies below 0.4 GHz. Above 0.4 GHz, the differential mode has lower radiations than the common mode, and this is expected. The reasons for the low frequency distortion is due to the location of the GND vias. At the common mode, the two signal vias on the one side act as one signal via and the surrounding four GND vias are the path to share the return current. As a result, it increases by 60 dB for one order of frequency increase [4]. At the differential mode, the two vias have the opposite currents, and the surrounding GND vias join one of the signal vias to share the current path. Therefore, the radiation increases by 40 dB for one order of frequency increase. This is only valid at low frequencies.

The illustration of Fig. 8 shows a reasonable result that the differential mode has lower radiations than the common mode overall. The differential mode can be explained in similar details in last case. For the common mode, at frequencies below 300 MHz, the two signal vias on one side are acting as one signal via, so the radiated emission increases by 20 dB for one order of frequency increase. For frequencies above 300 MHz, the four GND vias in the corner come in to play an
important factor to make the radiated emission increase at 60 dB for one order of frequency increase. At higher frequencies, the metallic cavity modes dominate the radiation.

B. The Study between Trace and No Trace

To understand the relative contribution importance of traces and vias in packaging structures, two cases are studied and compared. Fig. 9(a) shows a trace in-between two shorted parallel plates. Both signal via and load via are surrounded by 4 GND vias that short top and bottom ground planes. In the second case shown in Fig. 9(b), the trace is removed. The vias are extended to shorted plates. To maintain the same current on two vias, in Ansys HFSS the top surface of the via is used as the wave port, and the bottom surface of the via is used as the load. To compensate the phase shift due to the length of the trace, the excitation current phase of the right via in Fig. 9(b) has a phase delay equal to the phase shift of trace in Fig. 9(a) at each frequency. Both vias in Fig. 9(b) are extended by one time to enable reasonable port and load setups.

The simulated 3-meter radiated emissions of both cases at all frequencies are shown in Fig. 10. Two emissions are almost identical except a difference of around 6 dB. It means the radiated field magnitude of Fig. 9(b) is almost exactly doubled than that of Fig. 9(a). Considering the fact that the current length of vias are doubled in Fig. 9(b), it can be seen that the trace radiation is trivial compared to that of vias.

The phenomena can be explained with several reasons. First, the TEM mode propagated along the stripline trace does not radiate. Secondly, $TM_z$ modes are dominant in this type of packaging structures. But the horizontal traces are not good excitation sources for these modes. Thirdly, most guided modes by traces are absorbed by matched loads. Hence, the via EMI effects are more critical. Under this scenario, both vias and traces will work together to increase the radiated emissions of IC packaging.

IV. CONCLUSION

This paper studied the fundamental via and trace radiating principles of IC packaging for electromagnetic interference issues. This research area was seldom addressed but is increasingly important for today’s EMI qualification and regulation. The radiation mechanisms of vias, traces, current loops, and heat sinks are carefully investigated under different scenario. It provides helpful guidance for optimal low emission IC packaging designs.

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