Circuit Model and Analysis of Antenna-in-Package

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***Abstract*—This letter presents a circuit model of the antenna-in-package (AiP) employing the via holes to connect the antenna ground and the system ground. A closed-form expression for the inductance of ground via is provided in case that two ground vias are arranged under the non-radiating edge of the AiP. The new expression takes account of the radius and length of the vias, the relative positions of the vias and the distances between the vias and the feed point of the antenna. Then, the influences of the vias on the performance of the AiP are analyzed using the model. It is found that the bandwidth of the AiP can be improved effectively by properly arranging two via holes under the non-radiating edge of antenna. The simulated results agree with the modeled results.**

***Index Terms*—Antenna-in-package, equivalent circuit, RF transceiver, via holes**

I. INTRODUCTION

HIGHER levels of integration are driven by technological advancements in electrical performance requirements. The antenna-in-package (AiP) provides an advanced solution to the system architect. Lots of research about AiP were been done [1-6]. In AiPs, the multiple via holes are used to connect the antenna ground with the system ground. The influences of the number and positions of the ground vias on the performance of the antenna and package were studied in [7-8]. In this letter, the circuit model of the investigated AiP is presented. A closed-form expression for the inductance of the ground via arranged under the non-radiating edge of the AiP is deduced. The new formula takes account of not only the radius and length of the vias, the relative positions of the vias, but also the distances between the via holes and the feed point of the antenna. Based on this circuit model, the influences of the positions of the vias on the AiP are studied. The results indicate the bandwidth of the investigated AiP can be effectively improved by arranging two via holes properly.

II. THE CIRCUIT MODEL OF THE AIP

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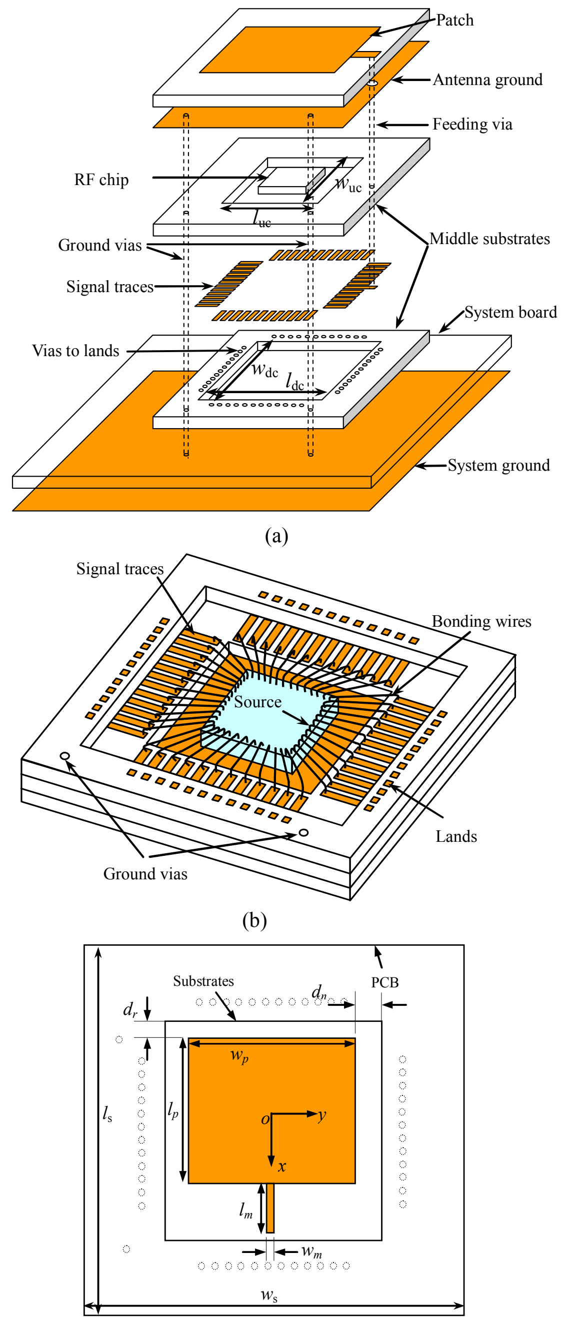


Fig. 1. Architecture of the investigated AiP: (a) explored view, (b) bottom view, (c) top view.

Fig. 1 (a) shows the explored view of the investigated AiP. It consists of three substrate layers and three metallization layers.

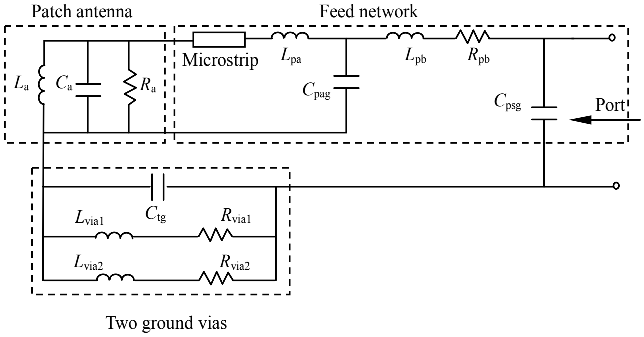


Fig. 2. Equivalent circuit model of the AiP.

TABLE I
PARAMETERS IN THE CIRCUIT MODEL

R_a(Ohm)	L_a(nH)	C_a(pF)	L_{pa}(nH)	R_{pb}(Ohm)
130.5	0.225	4.95	0.44	0.2
L_{pb}(nH)	C_{pag}(pF)	C_{psg}(pF)	C_{tg}(pF)	
0.87	0.38	0.1	3.6	

The top metallization layer is the radiator of the antenna, while the second and third metallization layer is used for the antenna ground and the signal traces, respectively. Under the antenna ground, a stepped cavity is formed in the second and third substrate layers. The RF chip can be packaged in the cavity then connected to the system board. Two vias called ground vias are used to connect the antenna ground with the system ground. Fig. 1 (b) shows the bottom view of the AiP. The RF chip is attached facing downwords to the antenna ground plane with conductive adhesive. Through the bond wires the chip is connected to the inner ends of the signal traces, then connected to the lands through the vias. Finally, the whole packaged module can be connected with the system board by the lands. The dimensions of AiP are l_p=13.5 mm, w_p=15 mm, l_m=3.5 mm, w_m=0.5 mm, l_s=w_s=20 mm, d_n =2 mm, d_r=2.5 mm, l_{uc}=w_{uc}=10 mm, and l_{dc}=w_{dc}=14 mm respectively. The size of the system board is 40 $\times$ 40 mm^2. All substrate layers are with the thickness of 0.8 mm, relative dielectric constant of 4.4 and loss tangent of 0.02.

The equivalent circuit model of the investigated AiP is shown in Fig. 2 and it comprises three subcircuits which represent the patch antenna, the feed network and two ground vias, respectively. For the microstrip patch antenna, it is usually modeled as a simple parallel resonant *RLC* circuit according to the cavity theory. The *RLC* values are given as follows [6],

$$R_a = \frac{Q_{total} H}{\pi f \varepsilon_{dyn} W L_{eff}} \cos^2\left(\frac{\pi X_{eff}}{L_{eff}}\right) \tag{1}$$

$$L_a = \frac{R_a}{2\pi f_r Q_{total}} \tag{2}$$

$$C_a = \frac{Q_{total}}{2\pi f_r R_a} \tag{3}$$

The feed network consists of the microstrip line and the feeding via. The feeding via above the antenna ground plane is represented by an inductance L_{pa}. L_{pb} and R_{pb} are the inductance and the resistance of the feeding via below the antenna ground [6]. C_{pag} and C_{psg} are the capacitances between the feeding probe and two ground planes, respectively.

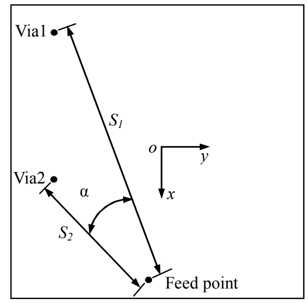


Fig. 3. Relative positions of the feed point and two vias.

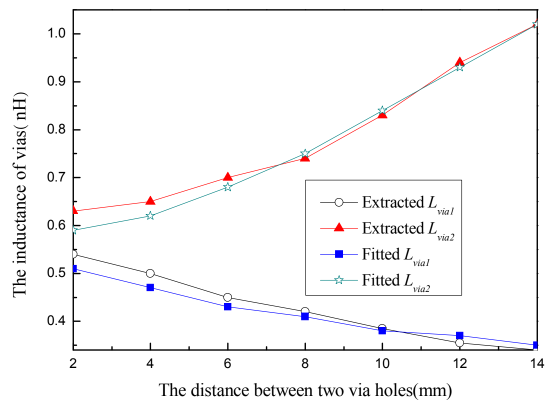


Fig. 4. Inductances of two ground vias when the first via hole is placed at (-8, -8) and the second via hole shifts along the positive direction of x axis.

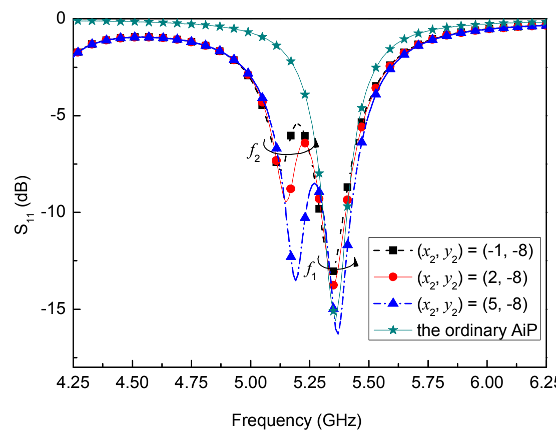


Fig. 5. S parameters calculated by the circuit model.

The via holes connect two ground planes and each one offers a route for the current to the system ground, so it is represented with a series branch of an inductance L_{viai} and a resistance R_{viai}. L_{viai} depends on the positions of two vias because the portion of the current on the antenna ground plane crowds down to each via hole and it contributes to the magnetic flux wrapping it. Further, L_{viai} is related to the distances between the via holes and the feed point, the separation of two ground planes and so on. R_{viai} represents the loss and is highly dependent on the fabrication process. They can be extracted from 3D EM full-wave field solver. C_{tg} represents the capacitance between

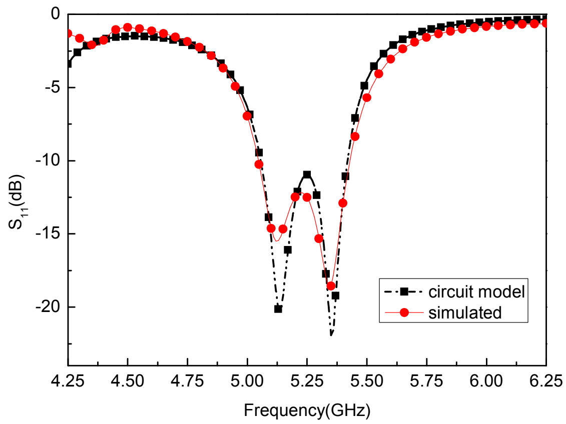


Fig. 6. Input impedances for the AiP placed two vias at (-8, -8) and (6, -8).

two ground planes and is calculated by the method of moments. The calculated parameters in Fig. 2 are shown in Table I.

When two via holes are arranged under the non-radiating edge, as is shown in Fig. 3, the closed-form expression for L_{viai} can be obtained by the nonlinear curve fitting. Firstly, extract the parameters for the different dimensions from 3D EM full-wave field solver. Then, find the appropriate function to fit the parameters. An expression for the inductance of a cylinder via, $h \cdot \ln(h/r)$, is selected as the basis of the function, where h and r are the length and radius of the via. Considering the effect of the relative positions between two vias and the feed point, an item with regard to (S_j/S_i) (S_i, S_j (i=1, j=2 or i=2, j=1) are the distances between two vias and the feed point) is added. Also, a natural exponential function of α (the angle between two lines connecting the vias and the feed point) is supplemented to introduce the influences of the relative positions of the vias. The final expression for L_{viai} can be got as,

$$L_{viai} = \frac{Exp(-0.4\alpha/\pi)\mu h}{4\pi}[\ln(\frac{h}{r}) + 1.65(\frac{S_j}{S_i})^{0.85}\ln\frac{S_j}{S_i}] \quad (4)$$

Fig. 4 shows L_{viai} extracted from 3D EM full-wave field solver and calculated by the expression (4). It indicates the expression (4) can fit L_{viai} well.

III. Influence of Vias

The influences of the via holes on the performance of the investigated AiP will be analyzed in this section.

Fig. 5 shows the S parameters calculated by the circuit model when the first via hole is placed at (-8, -8) and the second via hole shifts along the x-axis. It indicates for the ordinary AiP with one ground via at (-8, -8), there is a main resonant frequency at f_1 = 5.23 GHz and f_1 is determined by the patch of the antenna. When another via hole is added, a new resonant frequency f_2 around 5 GHz occurs and f_2 is related with the patch and the positions of the vias. By properly adjusting the positions of the ground vias, f_2 can be close to f_1 that the bandwidth of the AiP can be improved.

According to the above analysis, an AiP operating at the center frequency of 5.2 GHz is realized. In order to obtain a wider bandwidth, two resonant frequencies of 5.14 GHz and 5.35 GHz are expected to appear. In this case, two vias are arranged at (-8, -8) and (6, -8).

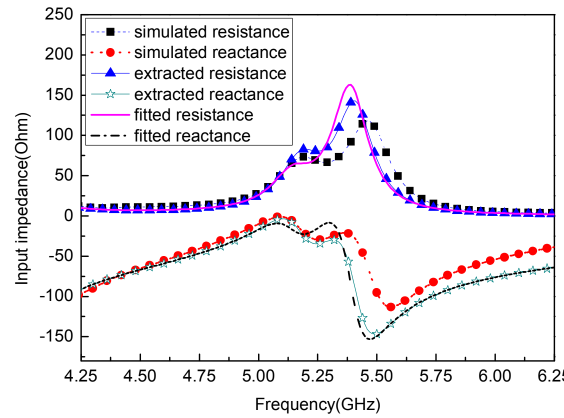
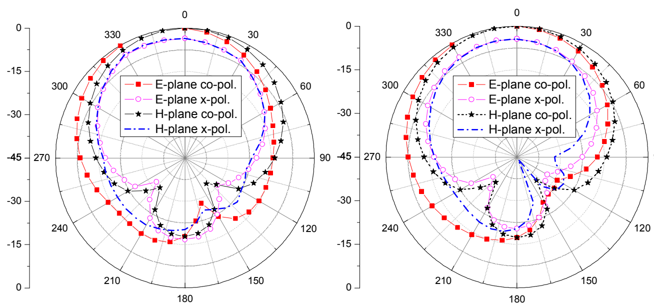


Fig. 7. S_{11} for the AiP placing two via holes at (-8, -8) and (6, -8).



(a) (b)

Fig. 8. Simulated radiation patterns at two operating frequencies: (a) 5.14 GHz, (b) 5.35 GHz.

IV. Validation of Circuit Model

Fig. 6 presents the modeled, and simulated S_{11} of the AiP with two via holes at (-8, -8) and (6, -8). The simulated resonant frequencies are 5.12 GHz and 5.34 GHz, respectively. The simulated bandwidth is 370 MHz. Fig. 7 shows the input impedances of the AiP. It is obvious that there are two resonant frequencies around 5.2 GHz. The impedances calculated by the closed-form expression agree with the simulated. Also, it can be seen that the circuit model is valid around the operation frequency (from 4.5GHz to 6.25GHz).

The simulated radiation patterns at two resonant frequencies are also plotted in Fig. 8. It is noted that the same polarization planes and similar radiation characteristics are obtained at two frequencies. Due to the influences of the ground vias on the current distribution on the patch, the cross-polar levels are higher. Moreover the simulated peak gains are 3.2 dBi and 4.1 dBi, respectively.

V. Conclusion

In this paper, an equivalent circuit model of the AiP with two via holes connecting the antenna and the system ground planes is proposed. When two ground vias are arranged under the non-radiating edge of the AiP, a closed-form expression for the inductance of the ground via is further provided as a function of the via radius and length, the via relative positions and the distances between the via holes and the feed point. Based on the model, the influences of the positions of the via holes on the performance of the AiP are investigated. It is found that the positions of the via holes will affect the performance of the AiP. Moreover, the bandwidth of the investigated AiP can be effectively improved by arranging two via holes properly. The modeled results agree with the simulated results.

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