A compact Ka-band antenna-in-package for system-in-package application

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Abstract: This paper presents an improved quarter-wave patch antenna assembled in a quad-flat-no-lead (QFN) package for system-in-package (SiP) application. An improved short method is proposed to reduce the size of antenna. Moreover, the influence of the package and the wire-bond has been taken into account in the antenna optimization. It has been found that the length of the bonding wire has an obvious effect on the antenna reflection coefficient. According to the simulation results, a bonding wire length of less than 600 μm is suggested in the antenna assembly. The experimental results show that the proposed antenna operates from 34.3 GHz to 38.8 GHz, and has a gain of 4.1 dBi at 37 GHz. The size of the patch antenna is only $1.1 \times 2.0 \text{ mm}^2$ ($0.034\lambda_0^2$), and it is very suitable for the wire-bond based SiP application.

Keywords: SiP, bond-wire, patch antenna

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

System-in-package has been proposed as a competitive solution for the wireless system miniaturization in recent years. In this technology, the antenna besides with the RF integrated circuit (IC) is integrated into a single package. Then, only the DC, control signals and baseband signals have to be connected with the RF IC through the board-to-package interconnections and thus the interconnections influence on the performance of the system can be significantly reduced, because the RF signals no longer need to be transmitted between the package and the printed circuit board (PCB) [1, 2, 3, 4, 5].

The design of an antenna-in-package (AiP) plays a key role in the SiP implementation, as it will greatly affect the performance of the whole system. Several technologies have been used for the AiP realization. In [6], a differential microstrip patch antenna is implemented based on the low-temperature co-fired ceramics (LTCC) process. A measured gain of 3.2 dBi and a simulated radiation efficiency of 90% are achieved by this antenna. However, the bandwidth is only 2.2%. An E-band dual-patch antenna driven by differential signals is realized in the redistribution layer of an embedded wafer level ball grid array (eWLB) package [7]. With a dielectric rod lens, this antenna has an average gain of 13.7 dBi from 71 GHz to 82 GHz. But the lens occupies a large space. The dimensions of the whole antenna are 10 mm × 10 mm × 10.5 mm, which is over $2.5\lambda_0 \times 2.5\lambda_0 \times 2.6\lambda_0$ (λ_0 is the free space wavelength).

In this work, a Ka-band compact microstrip patch antenna is designed and measured in a QFN ceramic package. The antenna is proposed to meet the typical SiP application, which is based on the technology of wire-bond as illustrated in Fig. 1 [8, 9]. To reduce the size of antenna, an improved quarter-wave patch antenna is implemented in this design. A shorted metal sheet, rather than the

Fig. 1. A typical architecture of the SiP, which is based on wire-bond.

traditional shorted metal vias, is proposed to realize the antenna shorted. Additionally, a slot is designed in this antenna to further decrease its size. Compared with the traditional quarter-wave patch antenna [10], the area of the proposed antenna is much more compact. Furthermore, the wire-bond is taken into account in the antenna design and the influence of the wire-bond length on the antenna performance has been investigated in detail in this paper. The proposed antenna has a measured -10 dB impedance bandwidth from 34.3 GHz to 38.8 GHz, and a measured gain of 4.1 dBi at 37 GHz.

2 Antenna design and simulation results

For the design of an AiP, the one important issue is that the package itself will affect the antenna performance obviously. Accordingly, antenna design needs to be based on a package model as accurately as possible. A QFN ceramic package with the size of $7 \times 7 \times 1.24$ mm³ is used in this work. It is manufactured by the KYOCERA Corporation. The cavity in the package for assembling RFIC and antenna is $4 \times 4 \times 0.74$ mm³. The walls and the lid of the package are made of ceramic material, which has the dielectric properties of $\epsilon_r = 8.5$ and $\tan \sigma = 0.0021$. The simulation model of this QFN package is built and is shown in Fig. 2(a). The following design is developed based on this package model.

In addition to build a package model, in the design of AiP, another important criterion is to make antenna having a small size, in order to reserve enough space for the RFIC in the package. So in this work, a “30”-shape improved quarter-wave patch antenna is proposed. The 3-D and 2-D models of the proposed antenna are presented in Fig. 2. As is shown that, a PCB with a material of Ro4350B ($\epsilon_r = 3.66$, $\tan \sigma = 0.0037$, $h = 0.338$ mm) is used to fabricate this antenna. The antenna is shorted by a sheet of metal at the edge of the PCB to form a quarter-wave patch. Compared with the traditional vias-shortened quarter-wave patch antenna, as depicted in Fig. 2(c), the proposed structure has a much more compact size at a certain frequency. This is due to that the minimum diameter of metal vias that can be manufactured by the common commercial PCB process is around 0.2 mm. That means at least 0.2 mm in length can be reduced by the proposed sheet-shortened quarter-wave patch antenna, when compared to the vias-shortened one. This is an attractive improvement especially when the antenna operating at millimeter-wave band and the total length of antenna is less than 2 mm. To further decrease the antenna size, a slot is manufactured in this antenna for the purpose of increasing the electrical length of the antenna. To achieve good impedance matching, another two slots are etched around the antenna feed line, which makes the proposed antenna look like an Arabia number “30”.

Fig. 2. (a) Simulation model of the antenna in a QFN package. The influence of the gold wire has been taken into account in the design of antenna. (b) Configuration and parameters of the proposed “30”-shape improved quarter-wave patch antenna, which has a length of $\lambda_g/5$ (λ_g is the guided wavelength). (c) A traditional quarter-wave patch antenna with the length of more than $\lambda_g/4$ due to the shored vias. It shows that the proposed antenna has much more compact size than the traditional one. (d) Simulated current distribution of the antenna at 37 GHz.

It should be mentioned that for the convenience of testing, the antenna is placed at the left side of the package. A gold wire with a diameter of $25.4 \mu\text{m}$ and a length of $400 \mu\text{m}$ (typical values) is applied as a bonding wire for the interconnection between the antenna and the signal input pad of the package. A 50Ω lumped port is added on one side of the gold wire to excite the antenna in simulations. As a result, the effects of the bonding wire and the package have been taken into account in the antenna design. Using the high frequency structure simulator (HFSS), the simulated current distribution of the proposed antenna is depicted in Fig. 2(d) and the optimal dimensions of the antenna are obtained as follow: $L_1 = 0.9 \text{ mm}$, $L_2 = 0.52 \text{ mm}$, $L_3 = 0.12 \text{ mm}$, $L_4 = 0.2 \text{ mm}$, $W_1 = 2 \text{ mm}$, $W_2 = 0.5 \text{ mm}$, $W_3 = 1.1 \text{ mm}$, $W_4 = 1.2 \text{ mm}$, $L_5 = 0.2 \text{ mm}$ and $S = 0.12 \text{ mm}$.

Among above parameters, L_1 has a significant influence on the antenna resonant frequency while the size of the slot ($L_3 \times W_3$) is critical to both of the bandwidth and the resonant frequency of the antenna. In Fig. 3, the reflection coefficient of the proposed antenna with different L_1 and L_3 is presented respectively when other dimensions are fixed (W_3 has the same effect on the antenna performance as L_3 , so here we analyze L_3 only). It is shown from Fig. 3(a) that, antenna resonant frequency will decrease with the increase of L_1 , and vice versa. But, when L_1 is increased to 1 mm and 1.1 mm , a poor impedance matching is observed. So changing the value of L_1 , the size of the antenna feed line need to be redesigned to obtain a good impedance matching performance.

Fig. 3. (a) Simulated reflection coefficient with different L_1 . (b) Simulated reflection coefficient with different L_3 . (c) Simulated reflection coefficient with different L_{wire} . (d) Simulated patterns with different L_{wire} at 37 GHz.

Furthermore, one can observe from Fig. 3(b) that increasing the size of the slot, the center frequency of the antenna will be reduced correspondingly. Accordingly, a more compact antenna can be obtained with this slot. However, it is also shown that this reduction in the size of the antenna is at the cost of the bandwidth of the antenna. Therefore, when designing the size of the slot, it is necessary to compromise the size and bandwidth of the antenna.

Additionally, it is also should be noted that the influence of gold wire length (L_{wire}) on antenna performance cannot be negligible. The simulated reflection coefficient and radiation patterns of the proposed antenna with different length of wire are depicted in Fig. 3. It is obviously seen from Fig. 3(c) that, the -10 dB bandwidth of the antenna is shifted from 5.4 GHz to 1.3 GHz, when the L_{wire} is changed from 300 μm to 1000 μm . If the L_{wire} is limited to less than 600 μm , the antenna will have a -10 dB bandwidth of more than 12.5%. However, if the L_{wire} is longer than 800 μm , a -10 dB bandwidth of less than 10% will be achieved by the antenna. Accordingly, for this antenna, the length of bond-wire must be controlled within 600 μm when it is assembled in the package.

As illustrated in Fig. 3(d), the proposed antenna has a simulated gain of 4.95 dBi at 37 GHz with the $L_{\text{wire}} = 400 \mu\text{m}$. It has also shown that the gold wire length has a few influences on the pattern of antenna and this effect can be ignored when the wire length is less than 800 μm .

3 Measurement results

The proposed AiP is fabricated and assembled, and then is mounted on a carrier board for test. Fig. 4(a) shows the photograph of the AiP. The reflection coefficient of the AiP is tested using an Aglient vector network analyzer. As exhibited in Fig. 4(b), the measured -10 dB impedance bandwidth is 12%, from 34.3 GHz to

Fig. 4. Photograph of the fabricated AiP and the comparisons of the simulated and measured results. (a) AiP assembled on a test fixture. (b) Comparisons of reflection coefficient. (c) Comparisons of radiation patterns (at 37 GHz).

38.8 GHz. Compared with the simulation result, a bandwidth deviation of 1.5% and a frequency deviation of 1.2 GHz can be observed. This may be due to the fabrication tolerances, and the length of the bonding wire, as shown in Fig. 3. Additionally, the radiation patterns are measured in an anechoic chamber. The E-plane and H-plane of the patterns at 37 GHz are presented in Fig. 4(c). It shows that, a measured peak gain of 4.1 dBi is obtained at $\theta = -10^\circ$, while the measured 3-dB beam width is about 65° and 110° in the E-plane and H-plane respectively. It can be seen that, there is a good agreement between the measured and simulated patterns results, except when $\theta > 60^\circ$ because of the existence of the metal connector.

4 Conclusion

A Ka-band quarter-wave patch antenna is fabricated and assembled in a QFN package in this work. A shorted metal sheet and a slot are proposed in this design to reduce the antenna size. According to the simulation, the length of bonding wire is critical to the antenna impedance matching and a significant deterioration of antenna bandwidth has been observed when the wire length is more than $800 \mu m$. With a compact size of $1.1 \times 2.0 \text{ mm}^2$, a measured gain of 4.1 dBi is achieved at 37 GHz by the proposed antenna and this antenna is suitable for the SiP applications.