Antenna in package design and measurement for millimeter-wave applications in fan-out wafer-level package

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Abstract    Due to the advantages of good thermal and electrical performance, lower cost, greater design flexibility, fan-out wafer-level package (FOWLP) has been widely used in millimeter-wave applications. In this letter, a fan-out wafer-level package with the size of 12mm×12mm for the millimeter-wave applications is accomplished by the redistribution layer first (RDL-First) process. The double-sided multiple redistribution layers (RDLs) are used to fan out the signals and to form the antenna-in-package (AiP). An antenna integration scheme for the Ultra Short Range automotive Radar (USRR) chips with four transmit and receive channels was achieved. In addition, a 1×3 series fed aperture-coupled antenna array in the fan-out area was designed. Correspondingly, a probe based antenna measurement setup for FOWLP-AiP working in E band was carried out. The measurement results are in good agreement with the simulation.

key words: Fan-out wafer-level package, antenna in package, 77GHz, automotive radar, probe based antenna measurement setup

Classification: Microwave and millimeter wave devices, circuit, and hardware

1. Introduction

In the millimeter wave band or even the terahertz band, as the application frequency increases, the antenna size keeps getting smaller and the interconnection loss is becoming larger and larger, which makes the integrated antenna possible and necessary. Integrated antennas generally include the antenna-on-chip (AoC) and antenna-in-package (AiP) solutions [1]. When we choose between AoC [2, 3, 4] and AiP, the radiation performance and size of the antenna, the manufacturing cost and the manufacturing accuracy, and the interconnection loss between the antenna and the chip all need to be considered. And, on balance, AiP may be more suitable for most of millimeter-wave applications. AiP based on the multilayered Low-Temperature Co-fired Ceramic technology (LTCC) [3, 4], organic packaging technology [7, 8, 9], and embedded wafer-level ball grid array (eWLB) technology [10, 11, 12, 13, 14] have all been demonstrated for the millimeter wave systems.

Recent years, fan-out wafer-level package (FOWLP) has been a major trend for millimeter-wave applications [15, 16]. Compared with other forms of packaging, such as flip chip and BGA, the FOWLP can ensure a smaller interconnection loss between the antenna and the chip. As shown in [13], the loss is 0.7 dB for the FOWLP, 1.6 dB and 4.9 dB for the C4 bumps and BGA on LTCC substrate at 60 GHz. In addition, there is no need for extra RF substrate for the FOWLP. Correspondingly, AiP solution based on the FOWLP offers more attractive possibilities.

At present, FOWLP are used for most of the 77 GHz automotive radar circuits. However, for the Middle Range Radar (MRR), and Long Range Radar (LRR) [17], due to the high gain requirement, the antennas are generally series fed rectangular microstrip patch arrays [18, 19] or Substrate Integrated Waveguide (SIW) slotted antenna arrays [20] on the substrate. For the Short Range or Ultra Short Range Radars (SRR or USRR), the requirement for gain is relatively low, which makes it possible for the antenna to be integrated in the FOWLP.

In this letter, FOWLP with four RDLs was accomplished. Single aperture-coupled antenna and the series fed aperture-coupled antenna array in the FOWLP were designed and fabricated for the 77 GHz USRR or SRR applications. And a probe based antenna measurement setup for FOWLP-AiP working in E band was carried out to validate the design.

2. Structure and process of the FOWLP

As shown in Fig.1, the FOWLP mainly includes the four RDLs, four dielectric layers, epoxy molding compound (EMC), mega pillars, silicon chip, solder ball arrays. In order to explore a package that can meet the requirements of more I/Os, three RDLs in the front side were utilized. The M4 can be used to design the antennas. The mega pillars were developed for the chips that require vertical interconnection, such as gallium arsenide (GaAs) chips, and it can also be used to optimize the antenna. The FOWLP used in this letter follows the RDL-First process, as shown in Fig.2.

The EMC has a dielectric constant of $\varepsilon_r=3.7$ and a dissipation factor of $\tan\delta=0.009$ measured at 58 GHz. This rel-
atively small dissipation factor can guarantee a relatively good antenna performance. The dielectric constant of the dielectric layers is 3.08 and the dissipation factor is 0.02.

3. Antenna design

3.1 Single aperture-coupled antenna

Considering the interconnection with the ground-signal-ground (GSG) pads in the chip, we use the coplanar waveguide (CPW) fed aperture-coupled antenna[21, 22]. Fig.3(a, c, e) shows the structure of the antenna designed in the FOWLP. It mainly consists of a patch on the M4 and a feeding structure on the M3. The antenna was fed by a 50 Ω CPW transmission line. The feeding structure includes a slot and an open stub. The length of the slot(L_{slot}) was used to adjust the coupling between the patch and the feeding structure, and the length of the open stub(L_{stub}) was designed to modify the impedance matching. The thickness(h) of the EMC can be designed to adjust the bandwidth of the antenna. And the size(L_{GND1}, W_{GND1}) of the ground plane of the antenna can have a great impact on the gain of the antenna.

With proper design of the parameters, the antenna can obtain a large impedance bandwidth. As shown in Fig.4(a), when h = 300um, the simulated bandwidth S11≤-10dB is from 65.4 to 82.9GHz (23.6%). And as h decreases, the return loss of the antenna generally increases.

Considering the height control of the mega pillars and the influence of EMC thickness on warpage, the design value of

\[ R_{\text{max}} = \left( \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^2 S_{\text{min}}} \right)^{\frac{1}{2}} \] (1)

The maximum detection range can be calculated by Eq. (1). And the transmit power of each channel of the radar chip is generally 12dBm. The interconnection loss between the antenna and the chip can be easily controlled within 1dB in FOWLP, and we assume that the actual transmit power \( P_T = 11 \text{dBm} \). For the 77GHz radar antenna, its operating wavelength is about \( \lambda = 3.92\text{mm} \). And the sensitivity of the
receiver is about $S_{\text{min}} = -115\text{dBi}$. The typical value of radar cross-section (RCS, $\sigma$) of people is 0.5 to 2$m^2$, and it is 0.01$m^2$ for the bird. Through calculation, we can know that when the antenna gain is about 6dBi, the birds within 8 meters can be detected, let alone humans or cars. This shows that the antenna gain of 6dBi is feasible for USRR.

In order to better evaluate the performance of the AiP for USRR, a dummy die of 5000*5000*200um was mounted on the RDL. And eight antennas for the radar system with four transmit and four receive channels were fabricated on the RDL, as shown in Fig.5. It can be seen from Fig.6(a) that both the antennas at port 1 and port 2 cover the target frequency band. And for the antenna at port 1, the maximum simulated realized gain is 6.9dBi. The half-power beamwidth (HPBW) angle in E-plane is about 82°, and in H-plane is about 65°.

3.2 Series fed aperture-coupled antenna array

From Eq. (1), we can know that when the antenna has a gain of 10.1dB, objects with a RCS as small as 0.25 $m^2$ within 30 meters can be identified. Here, a 1x3 series fed aperture-coupled antenna array was designed for the 77GHz SRR applications as shown in Fig.3(b, d, e). The distance between the adjacent antenna is $kL_0$, where the $L_0$ is the wavelength in free space at 79GHz. L and W are the length and width of the element antenna respectively. $L_{GND2}$ and $W_{GND2}$ corresponds to the dimensions of the antenna ground plane. The k should be optimized to achieve in-phase feeding for all the antenna elements, and finally we choose 0.6 for k.

By adjusting the parameters and applying the quarter wavelength impedance converter, a well-matched antenna array is obtained. The simulated bandwidth is from 75.9GHz to 82.3GHz, and the simulated gain is 10.6dBi. When the array is integrated in the package, as shown in Fig.7(a), the performance of the array could be affected by the package. Test port 1 is the port we used for the simulation and test. Test port 2 represents an alternate test solution, and we will fan out the input of the antenna to the printed circuit board (PCB). As shown in Fig.7, the S11 of the array is basically the same whether the antenna array is in the package or not, and so is the radiation pattern in E-plane. However, the radiation pattern in H-plane shows some difference. The radiation pattern of the array with package in the H-plane becomes unsymmetrical as a result of the asymmetry of the package structure. Therefore, we should take the effects of the package into account during the design process.

4. Measurement and discussion

4.1 Measurement setup

Usually, the FOWLP samples are soldered on the PCB with a RF substrate for the characterization as in [12, 23]. Then, the antenna could be measured with a vector network analyzer. However, the reflection coefficient and the realized gain at the actual input port of the antenna in the FOWLP cannot be obtained directly and accurately. Additional de-embedding works needs to be introduced.

We have reserved test ports on the RDL. And the antenna can be tested directly through the test pads on the M1 layer. The configuration of the 77-GHz antenna measurement system is shown in Fig.8, but the network analyzer and the high-frequency cables are not shown in it. The antenna in FOWLP is measured as the antenna under test (AUT). The main devices and instruments used in the measurement are the mini anechoic chamber, Kesight PNA5224(10MHz to 43.5GHz) with the OML frequency extender, an E-band standard gain(20dBi) horn antenna, the anti-vibration probe station, Infinity Angled probe(1110-A-GSG-150), the near field test probe designed by FMM for E band, and the six-degree-of-freedom alignment and turntable system.

Fig.9 shows the photos of the practical far-field measurement setup. In the far field test, due to the mutual restriction
Fig. 8: Schematic diagram of the measurement setup for antennas at 77 GHz band

Fig. 9: Photos of the measurement setup for antennas at 77 GHz band

Fig. 10: Photos of the near-field test probe for E band

Fig. 11: Practical block diagram of the near field comparative method for antennas at 77GHz band

Fig. 12: Measured and simulated S11 of the single aperture-coupled antenna and 1×3 antenna array

of the probe station and the robotic arm, only part of the angle can be scanned. We carried out far-field measurement firstly, but the result was not satisfactory. So we used the planar near-field test method[24, 25] instead. Correspondingly, we used a test probe to measure the near-field. The near-field test probe is shown in Fig. 10, and it works from 60GHz to 90GHz. As with the far-field test, we use the comparative method to obtain the realized gain of the antenna.

We carried out planar near-field scanning tests on the AUT and the standard gain horn antenna respectively. The distance between the scan plane and the AUT is about 8.523mm(2.24\(\lambda_0\)). The scanning plane is a square with a side length of 44.318mm. The scan interval is about 1.847mm. Thus the total number of the sampling points is 625. It should be noted that the standard gain horn antenna we used could not be fed with the GSG probe. When feeding the horn antenna, we need to use a waveguide-to-coaxial adapter. And then, the insertion of the probe(IL\(_{probe}\)) and the adapter(IL\(_{adapter}\)) need to be taken into account. As shown in Fig.11, when testing the AUT and the standard gain antenna, except for the difference in the dotted frame, other conditions are the same. So, in fact, the whole of the probe and AUT is compared with the whole of the adapter and the standard gain horn antenna. And then, the realized gain of the AUT can be calculated as

\[
G_{\text{AUT}} = G_{\text{compared}} - IL_{\text{adapter}} + IL_{\text{probe}}
\]  

where \(G_{\text{compared}}\) is the gain calculated from the planar near-field scan data without considering the IL\(_{probe}\) and IL\(_{adapter}\). IL\(_{probe}\) can be obtained through the data sheet. And we got IL\(_{adapter}\) through the S parameters of a pair of direct-connected adapters, as shown in Eq.(3).

\[
IL_{\text{adapter}} = \frac{|S_{21}^{\text{thru}}| + |S_{12}^{\text{thru}}|}{4}
\]

where \(S_{21}^{\text{thru}}, S_{12}^{\text{thru}}\) is the S parameters of a pair of direct-connected adapters.

4.2 Results and discussion

The simulated and measured return loss of the single aperture-coupled antenna and the 1×3 series fed aperture-coupled antenna array are shown in Fig.12. The measured bandwidth of the single antenna is about 75.5 to 86.6GHz. And it is about 76.5 to 84GHz for the antenna array. The simulated and measured results show good consistency.

Fig.13 shows the measured and simulated radiation patterns of the single antenna obtained at 79GHz in Cartesian coordinates, where Co, X represent the co-polarization, cross polarization respectively, and sim, mea1, mea2 represent the results of the simulation, far-field test, near-field test respectively. We can find that the near-field test results are in good agreement with the simulation, but the far-field test results have large errors. Whether it is the E-plane or H-plane pattern, the far-field test has a relatively consistent result in the range of -10° to 10°, but beyond this range, the
Table I: Comparison on the performance of the proposed antennas with previously reported 79-GHz antennas

| Ref    | Antenna type                               | Element number | HPBW (°/°) | Measured Bandwidth (GHz) | Simulated Bandwidth (GHz) | Measured gain (dBi) | Simulated gain (dBi) | Antenna Package size (mm$^3$) | Measurement method          | Feeding and measurement method |
|--------|--------------------------------------------|----------------|------------|--------------------------|---------------------------|--------------------|--------------------|-----------------------------|--------------------------------|--------------------------------|
| [26]   | Patched tri-lobed antenna                  | 1×8            | 8°/8°      | 72.79-81.78 (11.63%)     | 12.57/10.74               | -20                | -20                | 3×4×0.010                     | On the substrate (Roger 4350B)  | End launch connector / NP |
| [27]   | Broadside antenna array                     | 1×2            | 48°/85°    | 76.3-83.5 (10.25%)       | 7.2/0.9                   | 4.79                | 4.79                | 2×15×0.001                    | Hot PC technology                | Probe/Far-field test       |
| [28]   | Dual slot-fed stacked double grid antenna   | 1×4            | 12°/40°    | 75.7-84.8 (11.3%)        | 11.5                      | 10.35/0.001         | 10.35               | 12×15×0.001                   | Integrated in FOWLP          | Probe and waveguide / NP    |
| [29]   | Microstrip-fed aperture-coupled antenna     | 1×3            | NP         | 75.18-80.0 (17.3%)       | 9.0/0.9                   | 2×15×0.001         | 2×15×0.001         | 12×15×0.001                   | Integrated in FOWLP          | Probe/Planar near-field test |
| [30]   | Resonator and cavity-back slot antenna      | 1×3            | 89°/80°    | 75.5-86.6 (13.7%)        | 6.9/5.6                   | 2×12×0.001         | 2×12×0.001         | 3×12×0.001                    | Integrated in FOWLP          | Probe/Planar near-field test |
| This work | CPW-fed aperture-coupled antenna            | 1×3            | 27°/90°    | 76.5-84 (9.35%)          | 10.6/8.8                  | 3×6×0.037×0.021    | 3×6×0.037×0.021 | 12×12×0.038                   | Integrated in FOWLP          | Probe/Planar near-field test |
| This work | Series fed aperture-coupled antenna array   | 1×3            | 27°/90°    | 76.5-84 (9.35%)          | 10.6/8.8                  | 3×6×0.037×0.021    | 3×6×0.037×0.021 | 12×12×0.038                   | Integrated in FOWLP          | Probe/Planar near-field test |

NP: Not provided  
= simulated results  
\*
= calculated from the graph from the referenced paper

Fig. 13: Measured and simulated radiation patterns of the single aperture-coupled antenna obtained at 79GHz

Fig. 14: Measured and simulated radiation patterns of the 1×3 series fed aperture-coupled antenna array obtained at 79GHz

Fig. 14 shows the measured and simulated radiation patterns of the single aperture-coupled antenna obtained at 79GHz. The proposed antenna has a relatively high gain. Compared with designs in [26, 27, 28], the proposed antenna has a higher integration level, a smaller size, and a smaller interconnection distance compared to the antennas in [29, 30]. The proposed CPW series fed aperture-coupled antenna array can reduce the number of metal layers compared to the microstrip-fed aperture-coupled antenna array in [29].

5. Conclusion

In this letter, the FOWLP with four RDLs and the mega pillars was realized. FOWLP-AiP for 77GHz USRR and SRR were proposed and fabricated. Correspondingly, a probe based antenna measurement setup for FOWLP-AiP working in E band was carried out. We performed far-field tests and planar near-field scan tests separately. It turns out that when the far-field test result has a large error, we can choose the near-field scan test as an alternative. The measurement results are in good agreement with the simulation results, which proves the correctness of the simulation and measurement. The experimental and simulation results have shown that both the single antenna and the 1×3 series fed aperture-coupled antenna array cover the working frequency band (77 to 81GHz) of the automotive radar well. At the same time, the simulation also shows how to obtain a much larger impedance bandwidth. The results presented in Fig. 14 show that the 1×3 antenna array has a relatively high gain of 8.8dB, good directivity in the E-plane (HPBW=27°), and large-range coverage in the H-plane (HPBW=90°). These are
expected to provide a complete package solution with integrated antennas for the USRR and even the SRR chips.

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