High-gain low-cost broadband 60 GHz differential integrated patch array antennas with wire-bonding packaging and on-board compensation network

Tao Zhang\(^1\), Lianming Li\(^1\)\(\ddagger\), Dixian Zhao\(^1\), Haiyang Xia\(^1\), Yuan Chai\(^1\), Jian Guo\(^1\), Chen Qian\(^1\), Fu-Chun Zheng\(^1\), Tie Jun Cui\(^1\)

\(^1\)School of Information Science and Engineering, Southeast University, Nanjing 210096, People’s Republic of China
\(\ddagger\) E-mail: Lianming.Li@seu.edu.cn

Abstract: Two high-gain broadband 60 GHz integrated planar patch array antennas, without and with air cavity, are designed and implemented on Rogers 5880 substrate. The differential antenna structure is used to improve the signal integrity at millimetre-wave frequencies. The antennas are co-designed with bonding wires of which the parasitic effect is compensated using a passive network. The proposed antennas have the advantages of symmetrical radiation pattern, wide bandwidth and low insertion loss. In the measurement, a differential transmission line based de-embedding structure is developed on silicon, mimicking the real chip packaging environment and providing reliable terminations for antennas. The measured fractional bandwidths (|S\(_{11}\)| < −10 dB) are 13.8 and 26.2%, respectively, for the two structures without and with air cavity, including the effect of a waveguide-to-microstrip line transition and a branch-line balun. Both antennas have measured gain of about 12 dBi. After de-embedding the return loss, the measured insertion loss of the bond wire compensation network is only 0.07 dBi at 61 GHz.

1 Introduction

The 60 GHz band is a good candidate for future high data-rate communication applications because of its wideband nature (i.e. 9 GHz unlicensed band). Recent advances in complementary metal–oxide–semiconductor (CMOS) process enable the realisation of fully integrated 60 GHz CMOS transceivers [1, 2]. To deal with the relatively high path loss at 60 GHz, a high-gain (> 10dBi) and high-efficiency antenna is needed in order to achieve the desired effectively isotropic radiation power and thus relax the requirement of PA output power.

For millimetre-wave (mm-wave) applications, the planar antenna is widely used for its small size and low cost advantages [3–12]. Moreover, it allows straightforward and low-cost integration with the radio-frequency (RF) front-end. In [13–15], high-gain Yagi-Uda antennas for 60 GHz communications have been reported, but their end-fire radiations are undesirable for nearly all applications [16]. In [17, 18], stacked patch antennas fabricated in multi-layers demonstrate high-gain and broadband performance, with the penalty of high fabrication cost and complicated packaging process.

In this paper, two 60 GHz planar integrated patch array antennas, without and with air cavity, are designed and implemented on Rogers 5880 substrate. To reduce the large-volume fabrication cost and enhance the performance, the antennas and interconnects are improved in multiple manners. First, the differential structure is deployed to achieve symmetrical radiation patterns and relax the grounding requirements. Second, based on the traditional wire-bonding technique, the integrated patch array antennas are co-designed with the bond wire compensation network (BWCN) using aluminum wires. In particular, the bond wire dimensions are optimised to achieve repeatable packaging process with the automatic wire bonder. Third, the differential transmission line based de-embedding structure is developed on silicon to provide reliable terminations for antennas, easing the design of chip-to-antenna interconnects.

The antennas, without and with the air cavity, have measured relative bandwidths of 13.8 and 26.2% for |S\(_{11}\)| < −10 dB, including the effect of a waveguide-to-microstrip line (WG-to-MSL) transition and a branch-line balun. These results meet the requirements of 60 GHz applications and prove the effectiveness of the air cavity on the antenna bandwidth. Both antennas have measured gains of about 12 dBi and simulated radiation efficiencies of more than 90%. The measured insertion loss of the compensation network is only 0.07 dBi at 61 GHz.

2 Antenna and interconnects design

2.1 60 GHz integrated array antenna without air cavity

Considering the trade-off between radiation efficiency and bandwidth, the Rogers 5880 substrate with the thickness of 0.254 mm and the permittivity of 2.2 is used. In this way, the antenna bandwidth can be guaranteed and the radiation efficiency can be improved by suppressing the surface wave power. In addition, the thickness of the substrate is close to that of the chip die (i.e. 300 μm), which helps to reduce the bond wire length.

At mm-wave frequencies, differential circuits are widely used for their advantages in common-mode noise suppression, gain and stability. As a result, the differential antenna structure is preferred. Simulations prove that the radiation symmetry can be ensured and the ground issues can be relaxed a lot due to the differential virtual ground effect. This case the assembly process and allows simple interconnects between the antenna and the differential RF front-end circuits.

Fig. 1 shows the structure of the implemented integrated array antennas with and without air cavity, which consist of four rectangular patch elements on the top side. Four pairs of parasitic strips are used to enhance the antenna bandwidth and gain. Besides, a differential microstrip line and a matched T-junction are used to divide the input power and feed it to each element. On the bottom side, the antenna without air cavity has a continuous ground plane in Fig. 2a, whereas the antenna with air cavity has a partially etched ground in Fig. 2c. With electromagnetic simulations, the dimensions of both antennas are optimised, and their values are listed in Tables 1 and 2.
2.2 BWCN-based interconnects

At 60 GHz, the parasitics of interconnects introduced by the packaging will cause impedance mismatch, degrading the overall performance. To solve these issues, flip-chip packaging is preferred because of its reduced parasitic effects [19]. As an alternative solution, the wire-bonding technique is still widely used because of its reliability and low cost [20]. In [9, 21, 22], an etched cavity having a depth equal to the height of the die is introduced to reduce the bond wire length, which needs additional process and increases the cost. Additionally, the BWCN is needed to alleviate the mismatch caused by the bond wire inductance. In [23], with the manual bonder, an L–C–L impedance matching network is realised to compensate the bond wire inductance. However, from the large-volume and low-cost fabrication perspective, it is preferred to realise such compensating network in an automatic process.

To tackle the above issues, several improvements are made in this design, from the chip and antenna assembly to the chip bonding. Fig. 2 shows the interconnects structure in this design. The aluminium bond wire with a diameter of 25 μm is adopted to further reduce the cost. As the height of the chip die is close to the thickness of the substrate, no cavity is needed. To ensure the mechanical stability, both the chip die and antenna are glued automatically on a FR4 board, further easing the assembly process.

For a repeatable auto-bonding process, the performance of the integrated antenna with BWCN interconnects should not suffer too much from a certain bonding wire length error, which can be caused by the assembly and auto-bonding process. In this design, the optimised length (‘BL’) and loop height (‘BH’) of the bond wire are 0.3 and 0.2 mm, respectively (see Fig. 2). The off-chip pad length (‘L’ and ‘W’) are 0.35 and 0.4 mm, respectively.

Fig. 1 Structure of the integrated array antennas
(a) Top view of both antennas, (b) Bottom view of the antenna without air cavity, (c) Bottom view of the antenna with air cavity

Table 1 Optimised dimensions of the array antenna without air cavity

| Parameter | Value, mm | Parameter | Value, mm |
|-----------|-----------|-----------|-----------|
| L_f       | 0.50      | S_f       | 0.15      |
| L_1       | 2.10      | W_1       | 0.70      |
| L_2       | 5.00      | W_2       | 0.35      |
| L_p       | 1.45      | W_p       | 2.34      |
| L_s       | 1.20      | W_s       | 0.20      |
| S_x       | 1.14      | S_y       | 1.36      |
| S_1       | 0.10      | S_2       | 0.20      |

Table 2 Optimised dimensions of the array antenna with air cavity

| Parameter | Value, mm | Parameter | Value, mm |
|-----------|-----------|-----------|-----------|
| L_f       | 0.50      | S_f       | 0.15      |
| L_1       | 2.23      | W_1       | 0.70      |
| L_2       | 4.53      | W_2       | 0.35      |
| L_p       | 1.50      | W_p       | 2.20      |
| L_s       | 1.30      | W_s       | 0.20      |
| S_x       | 1.45      | S_y       | 1.50      |
| S_1       | 0.10      | S_2       | 0.25      |

2.3 60 GHz integrated array antenna with air cavity

To further improve the bandwidth of the above antenna, a 7.1 mm × 4.45 mm air cavity with a depth of 0.14 mm is introduced at the back side of the antenna. Accordingly, an equal size of area on the bottom ground plane is etched away right beneath the four patches.

Fig. 2 Interconnects structure with BWCN

Fig. 3 Equivalent circuits of the single-ended compensation network and its matching trace on the Smith chart. In Fig. 3, the bond wires and the off-chip pad are modelled as two identical inductors (0.32 nH) and a lumped capacitor (39.6 fF), respectively. The values of the inductors and capacitor are obtained by fitting the L–C–L model with the simulation results of the single-ended compensation network. To allow co-design of the compensation network and the antenna, the characteristic impedance of the differential feeding line is designed to be 100 Ω.

Table 2 Optimised dimensions of the array antenna with air cavity

| Parameter | Value, mm | Parameter | Value, mm |
|-----------|-----------|-----------|-----------|
| L_f       | 0.50      | S_f       | 0.15      |
| L_1       | 2.23      | W_1       | 0.70      |
| L_2       | 4.53      | W_2       | 0.35      |
| L_p       | 1.50      | W_p       | 2.20      |
| L_s       | 1.30      | W_s       | 0.20      |
| S_x       | 1.45      | S_y       | 1.50      |
| S_1       | 0.10      | S_2       | 0.25      |
Fig. 4 illustrates the top view and cross-section of the antenna with air cavity, which are attached to the aluminium fixture with the air cavity. For comparison, Fig. 4(b) shows the antenna without air cavity, which has a similar structure as the one with air cavity. The air cavity improves the antenna bandwidth substantially, which will be illustrated in Section 3.

3 Simulation and measurement

3.1 Conventional measurement

The measurement of a differential antenna usually requires additional structures (e.g. balun). Since the probe-based measurement of the antenna is not available in our laboratory, the WG-to-MSL transition is added after the balun for measurement. The simulation results are all based on Ansoft HFSS software and the S-parameters are measured by Aglient 67 GHz PNA-X N5247A.

Fig. 5 shows the measurement results of the antennas without and with the air cavity, including the effect of a WG-to-MSL transition and a branch-line balun. Clearly, the bandwidth of the antenna is broadened significantly with the additional air cavity. The measured relative impedance bandwidths ($\left| S_{11} \right| < -10 \text{ dB}$) of the antenna without and with air cavity are 13.8 and 26.2%, respectively.

The radiation patterns and gains of the antennas are measured in an anechoic chamber. After de-embedding the loss of the balun and the WG-to-MSL transition, Fig. 6 illustrates the measured de-embedded gains of all the antennas at reference plane (see Fig. 4), as well as the simulated efficiency at reference plane. In this design, the antennas efficiencies are maintained, as the feeding loss of the differential feeding networks (including the differential line and the matched T-junction), the dielectric loss and the conductor loss are almost stable at the 60 GHz band. In simulations, the antenna model includes the top side ground plane, via fences and bottom fixture. Besides, the WG-to-MSL transition and the branch-line balun are simulated separately to reduce the simulation time. For comparison, the air cavity antenna without and with BWCN are fabricated. Both antennas achieve similar gains of about 12 dB, which shows a quite low loss of the BWCN. Fig. 7 shows the normalised measured and simulated radiation patterns of the antenna with air cavity. The antenna front-to-back ratio is about 25 dB, and the cross-polarisation level is less than $-12 \text{ dB}$. Compared with the E-plane cross-polarisation, the H-plane shows a higher cross-polarisation level, which mainly comes from the radiation of the coplanar strips to microstrip line transition and the T-junctions in the feeding network. Clearly, on the half-power beamwidths of the main lobes, the measurement results agree well with the simulation results.

To derive the BWCN insertion loss, the back-to-back WG-to-MSL transitions without and with BWCN are manufactured and measured. As shown in Fig. 8, the BWCN insertion loss is only 0.07 dB at 61 GHz after de-embedding the return loss.

3.2 De-embedding measurement

The antenna without air cavity is used to connect our 60 GHz transceiver. Before making the chip interconnects to the antenna, it is important to know the differential antenna impedance information at the reference plane (see Fig. 2). However, the measured $S_{11}$ results in Section 3.1 (see Fig. 5) include the effect of...
the WG-to-MSL transition and the branch-line balun, which introduces some uncertainties in generating accurate terminal impedance information. To overcome these issues, as shown in Fig. 9, the WG-to-MSL transition and the branch-line balun are removed, and the differential transmission line based de-embedding structure is developed on silicon, mimicking the real chip packaging environment. The de-embedding process can be divided into three steps. First, the differential silicon transmission line is measured. Third, the measured antenna S-parameters are multiplied with the inverse matrix of the transmission line S-parameters, and the reliable antenna impedance information at the reference plan can be obtained. To investigate the antenna performance against the fabrication and bonding variations, three samples are measured. In Fig. 10, the measured results are compared with the simulated results. Clearly, the measured results show similar trends and agree well with the simulated results, which prove good process tolerances. Additionally, compared with the conventional measurement, the de-embedding measurement shows a more accurate result of the antenna for interconnects.

4 Conclusion

In this work, two 60 GHz differential planar integrated patch array antennas, without and with air cavity, are presented. Improvements are performed from the chip and antenna assembly to the chip bonding. With the differential structure, symmetrical radiation patterns are achieved and the grounding issues are relaxed. By optimisations, the aluminium BWCN interconnects are implemented with the automatic wire bonder. The measured relative bandwidths ($|S_{11}| < -10$ dB) of the antennas (i.e. without and with air cavity) are 13.8 and 26.2%, respectively. The measured gains of the antennas are about 12 dB and the simulated
radiation efficiencies are more than 90% at 60 GHz. Besides, the differential transmission line based de-embedding measurement is developed to provide the reliable antenna port impedance. Last but not least, the integrated planar patch array antennas with BWCN interconnects are tolerant against fabrication inaccuracies.

5 Acknowledgments

The authors acknowledge supports from the National Nature Science Foundation of China (nos. 61306030, 61571117, 61631007), the National High-Tech Project (863Project) of China under grant nos. 2011AA010201 and 2011AA010202 and the Fundamental Research Funds for the Central Universities.

6 References

[1] Natarajan, A., Reynolds, S.K., Tsai, M.-D., et al.: ‘A fully-integrated 16-element phased-array receiver in SiGe BiCMOS for 60-GHz communications’, IEEE J. Solid-State Circuits, 2011, 46 (5), pp. 1059–1075

[2] Babakhani, A., Guan, X., Komijani, A., et al.: ‘A 77-GHz phased-array transceiver with on-chip antennas in silicon: receiver and antennas’, IEEE J. Solid-State Circuits, 2006, 41 (12), pp. 2795–2806

[3] Zhang, T., Li, L., Xia, H., et al.: ‘Low-cost high-gain differential integrated 60 GHz phased array antenna in PCB process’, IEEE Wireless and Microwave Technology Conf. (WAMICON), Tampa, April 2016, pp. 1–4

[4] Bisognin, A., Titz, D., Ferrero, F., et al.: ‘PCB integration of a Vivaldi antenna on IPD technology for 60-GHz communications’, IEEE Antennas Wirel. Propag. Lett., 2014, 13, pp. 678–681

[5] Liao, S., Wu, P., Shum, K.M., et al.: ‘Differentially fed planar aperture antenna with high gain and wide bandwidth for millimeter-wave application’, IEEE Trans. Antennas Propag., 2015, 63 (3), pp. 966–977

[6] Wang, D., Ng, K-H., Chan, C.H., et al.: ‘A novel wideband differentially-fed higher-order mode millimeter-wave patch antenna’, IEEE Trans. Antennas Propag., 2015, 63 (2), pp. 466–473

[7] Li, Y., Lok, K.M.: ‘60-GHz dual-polarized two-dimensional switch-beam wideband antenna array of aperture-coupled magneto-electric dipoles’, IEEE Trans. Antennas Propag., 2016, 64 (2), pp. 554–563

[8] Beer, S., Roach, C., Gulan, H., et al.: ‘An integrated 122-GHz antenna array with wire bond compensation for SMT radar sensors’, IEEE Trans. Antennas Propag., 2013, 61 (12), pp. 5976–5983

[9] Liu, D., Akkermans, J.A., Chen, H.-C., et al.: ‘Packages with integrated 60-GHz aperture-coupled patch antennas’, IEEE Trans. Antennas Propag., 2011, 59 (6), pp. 3607–3616

[10] Pan, H.K., Horine, B.D., Ruberto, M., et al.: ‘Mm-wave phased array antenna and system integration on semi-flex packaging’. 2011 IEEE Proc. of Antennas and Propagation Society Int. Symp. (APSURSI), Washington, July 2011, pp. 2059–2062

[11] Lin, W., Wong, H.: ‘Polarization reconfigurable aperture-fed patch antenna and array’, IEEE Access, 2016, 4 (15), pp. 1510–1517

[12] Jin, H., Chiu, Y.-C., Che, W., et al.: ‘A broadband patch antenna array with planar differential L-shaped feeding structures’, IEEE Antennas Wirel. Propag. Lett., 2015, 14, pp. 127–130

[13] Alhalabi, R., Chiou, Y.-C., Rebeiz, G.M.: ‘Self-shielded high-efficiency Yagi–Uda antennas for 60 GHz communications’, IEEE Trans. Antennas Propag., 2011, 59 (3), pp. 742–750

[14] Kramer, O., Djafari, T., Wu, K.: ‘Very small footprint 60 GHz stacked Yagi antenna array’, IEEE Trans. Antennas Propag., 2011, 59 (9), pp. 3204–3210

[15] Khan, W.T., Lopez, A.L.V., Papapolymerou, J.: ‘Packaging a W-band integrated module with an optimized flip-chip interconnect on an organic substrate’, IEEE Trans. Microw. Theory Tech., 2014, 62 (1), pp. 64–72

[16] Zhang, T., Li, L., Xia, H., et al.: ‘Low-cost aperture-coupled integrated 60 GHz phased array antenna in PCB process’. IEEE Antenna and Propagation Symp. (APSURSI), Puerto Rico, June 2016

[17] Hong, W., Baek, K.-H., Goodelev, A.: ‘Multilayer antenna package for IEEE 802.11 ad employing ultralow-cost FR4’, IEEE Trans. Antennas Propag., 2012, 60 (12), pp. 5932–5938

[18] Rowe, W.S., Waterhouse, R.B.: ‘Investigation into the performance of proximity coupled stacked patches’, IEEE Trans. Antennas Propag., 2006, 54 (6), pp. 1693–1698

[19] Valenta, V., Schumacher, H., Spreng, T., et al.: ‘Experimental evaluation of differential chip-to-antenna bondwire interconnects above 110 GHz’. IEEE European Microwave Conf. (EuMC), Rennes, October 2014, pp. 1008–1011

[20] Li, C.-H., Ko, C.-L., Kuo, C.-N., et al.: ‘A low-cost DC-to-84-GHz broadband bondwire interconnect for SoP heterogeneous system integration’, IEEE Trans. Microw. Theory Tech., 2013, 61 (12), pp. 4345–4352

[21] Bon-Hyun, K., Schinaelenberg, P., Inac, O., et al.: ‘A 77–81 GHz 16-element phased-array receiver with ±10° beam scanning for advanced automotive radars’, IEEE Trans. Microw. Theory Tech., 2014, 62 (11), pp. 2823–2832

[22] Ku, B.-H., Schinaelenberg, P., Kim, S.Y., et al.: ‘A 16-element 77–81 GHz phased array for automotive radars with ±10° beam-scanning capabilities’. IEEE MTT-S Int. Microwave Symp. Digest (IMS), Washington, June 2013, pp. 1–4

[23] Wang, R., Sun, Y., Wipf, C., et al.: ‘An on-board differential patch array antenna and interconnects design for 60 GHz applications’. IEEE Int. Conf. on Microwave, Communications, Antennas and Electronic Systems (COMCAS), Israel, November 2011, pp. 1–5

IET Microw. Antennas Propag., 2017, Vol. 11 Iss. 7, pp. 971-975
This is an open access article published by the IET under the Creative Commons Attribution -NonCommercial License (http://creativecommons.org/licenses/by-nc/3.0/)