Tackling the Issues of Millimeter-wave On-chip Antenna Measurements

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***Abstract*— On-chip antennas are becoming more and more important due to the high level of integration and lower costs they offer as part of System-on-Chip solutions. However, the accurate characterization of mm-wave on-chip antenna is difficult because the probe-based measurement is easily influenced by the coupling and interference effects from the integrated circuits and the probe itself. In this paper, the measurement of a monopole on-chip antenna is reported. Then the reasons for the discrepancies in return loss and radiation pattern measurements are analyzed through modified simulation model. Furthermore, we characterize the probe self-radiation pattern and then propose the method of covering the probe with an absorber to improve the measurement accuracy.**

***Index Terms*—on-chip antenna, mm-wave, measurement, return loss, radiation pattern**

I. Introduction

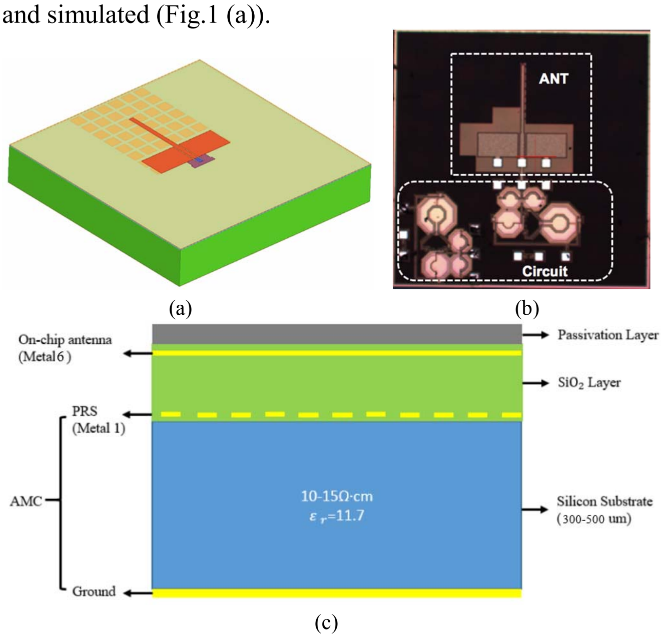
Recently, the millimeter-wave frequencies have attracted enormous research interests because it can fulfill the requirements for high data rates wireless system applications, such as automotive radar systems and imaging systems. Due to the relatively smaller wavelengths at such high frequencies, the standard CMOS processes provide a suitable platform for integrating the mm-wave antennas on chip, which has the advantages of high level of integration, robustness due to no external bonding wires and lower fabrication cost. An Antenna-on-Chip (AoC) can overcome the last barrier to true RF System-on-Chip (SoC) solutions [1].

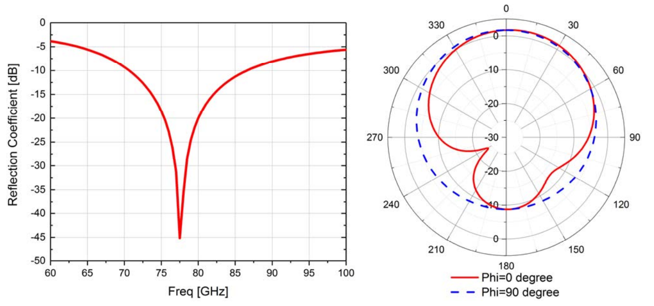
In addition to the numerous design and implementation challenges of AoC, characterization of such tiny antennas in a complex environment is also not easy. The reliable and accurate characterization of mm-wave AoC performance is an important issue because of the short EM wavelength and the possible reflection and interference in the measurement environment. Typically, there are two main error sources in the AoC measurements. The first error source is the chip itself. The SoC does not only have the AoC, but also some relevant circuits and floating conductors according to the CMOS process rules, which leads to mutual coupling effects between the antenna and other parts on the chip. The other error source comes from the measurement setup. The mm-wave AoC has to be characterized by landing the probe on the chip to feed the antenna. However, the probe has self-radiation, as well as the bulk conductor body of the probe reflects part of the antenna radiation.

Several approaches have been investigated to improve the reliability and accuracy of the on-chip antenna characterization. In [2][3], the superposition and S-parameter techniques are investigated to de-embed the effects of probe tip self-radiation. Besides, the probe ABCD matrix and probe radiation can be obtained by modeling the probe in simulation software for de-embedding the probe influence [4]. Furthermore, the probe structure is modified by extending the coaxial probe tip to increase the distance between the probe and the antenna [5]. In this paper, a 77GHz AoC is designed, fabricated and measured. A modified simulation model of the on-chip antenna is proposed, and the two error sources-chip itself and measurement setup have been studied to improve the reliability and precision of the measurement results. Eventually, the probe self-radiation is characterized. And the method of covering the probe with absorber is proposed to improve the measurement accuracy.

II. On-Chip Antenna Design and Fabrication

In order to investigate the circuit and measurement environment that affects the AoC characterization, a coplanar waveguide (CPW) fed monopole on-chip antenna is designed and simulated (Fig.1 (a)).





(d) (e)

Fig. 1. (a) HFSS simulation model of CPW-fed monopole on-chip antenna (b) Microscope view of the chip (c) standard 0.18μm stack-up (d) simulation result of the reflection coefficient (e) simulation result of radiation pattern

Fig. 1(c) shows the standard 0.18μm CMOS stack-up. The antenna is a standard λ/4 monopole antenna designed on the top metal layer. Since the on-chip antennas typically suffer from low gain due to the lossy silicon substrate [6], a 6*8 artificial magnetic conductor (AMC) surface is placed on the bottom metal layer to increase the antenna gain. The antenna has been simulated in Ansys HFSS. The simulated resonant frequency of the AoC is 76.5GHz and it is shown in Fig. 1(c). Fig. 1(d) presents the simulation result of the radiation pattern, showing the maximum gain of 1.7dBi.

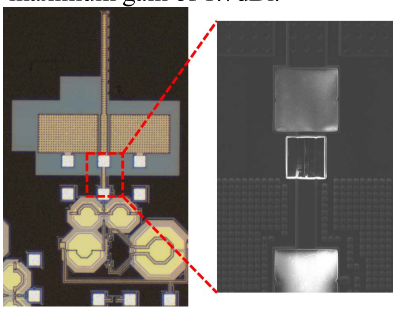


Fig. 2. Transmission line cut by FIB

The chip has been fabricated in TSMC 0.18μm CMOS process, and the microscopic view of the fabricated chip is shown in Fig. 1(b). The fabricated chip consists of the antenna part and the driving circuit part. The driving circuit provides a 77GHz source for feeding the on-chip antenna via a transmission line between the contact pads of the circuit output and the antenna input (highlighted in Fig. 2). Before the characterization of the on-chip antenna, this transmission line is cutoff by focus ion beam (FIB), as shown in the zoomed in version of that part in Fig. 2. This is done for independent testing of the AoC without the loading effects of the circuits.

III. Measurement

A. Measurement Setup

The compact mm-wave anechoic chamber shown in Fig. 3 is used for characterizing the reflection coefficient and the radiation performance of the proposed on-chip antenna.

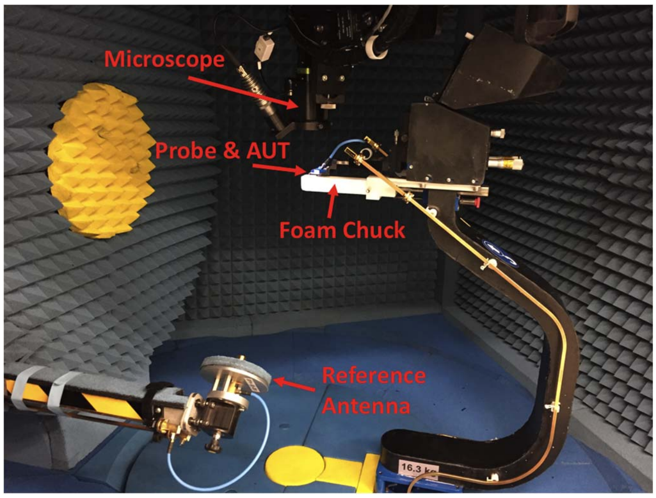


Fig. 3. μ-Lab mm-wave anechoic chamber

The chamber, fully covered with EM absorber, is designed and built for measuring the mm-wave antennas in the range from 18 to 110 GHz. The antenna under test (AUT) is placed in the center of the chamber on top of the foam chuck. The AUT is connected to the Power Network Analyzer (PNA) through the probe and the waveguide. The reference antenna is a horn antenna with a gain of 16dBi at 77GHz. It is connected to the scanning arm and aligns its boresight to the AUT. The microscope and the vision system are used to assist the alignment and landing of the probe with respect to the AUT. Before the radiation pattern measurement, the path loss in this measurement setup is calibrated by directly connecting the two ports with a known cable. For the return loss measurement, the probe is calibrated by landing it on the short, open, load of the impedance standard substrate (ISS) prior to the S_{11} measurement.

B. Measurement Results

Fig. 4 shows the comparison of measurement result and simulation result of the antenna return loss. It shows an obvious discrepancy between the measurement result and the simulation result. The antenna is well matched at 76.5 GHz in the simulation. However, the measured antenna is barely matched at 92GHz, and it has the return loss of -6.8dB at 77GHz.

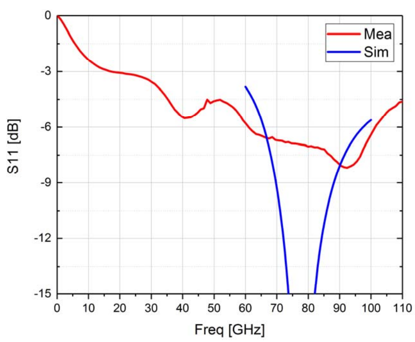


Fig. 4. Measurement result and simulation result of antenna return loss

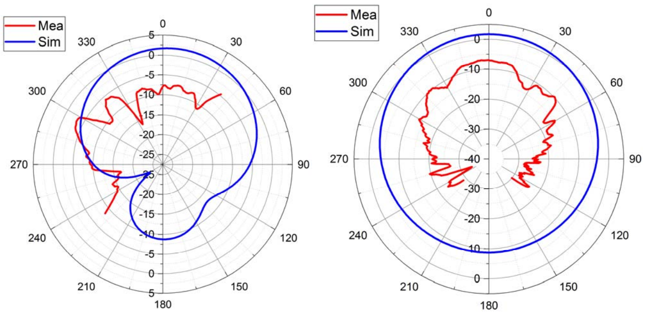


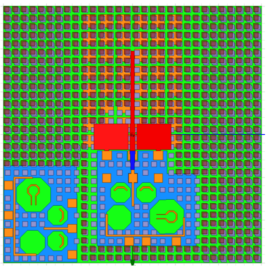
Fig. 5. Measurement results and simulation results of radiation patterns (a) E-plane (b) H-plane

The blue curve in Fig. 5(a)(b) shows the measurement results of the antenna radiation patterns which have a large discrepancy compared with the simulation results shown as the red curve.

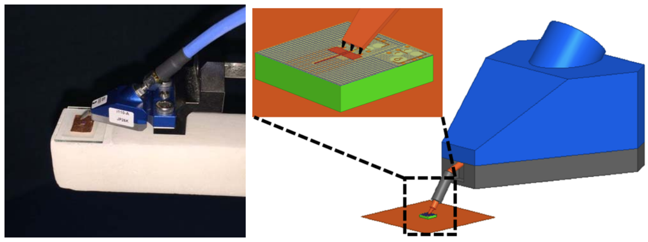
IV. Analysis of Return Loss Discrepancy

As it is shown above, the return loss in the measurement and simulation have a large discrepancy. There are three main reasons causing the discrepancy:

- Coupling effects between the on-chip antenna and the driving circuits. The single chip shown in Fig. 1(b) is integrated with both the antenna and the corresponding driving circuit which are close to each other. The circuit contains many inductors, capacitors, and long interconnection lines which lead to electromagnetic coupling when the antenna is excited.
- Coupling effects between the on-chip antenna and the dummy metal fill. The dummy metal fills are some floating metal sheets with size around 10mm*10mm, placed in each metal layer for fulfilling the metal density constraint according to the standard CMOS layout rules. It also causes the coupling effect if the dummies are placed close to the antenna.
- Probe effect. Although the probe inner impedance has been de-embedded through the calibration, the large conductor body of the probe still behaves as an extra conductor load for the antenna. Besides, the probe tip isn't completely covered with absorber resulting in unwanted coupling between the probe tip and the circuit under the probe.



(a)



(b) (c)

Fig. 6. (a) Modified chip simulation model (b) Probe landed on the antenna pads (c) Probe simulation model

As what is shown in Fig. 7, by including the circuit part and probe model in the post-simulation, it shows a good matching between the measurement and the post-simulation in the range from 60-110GHz which verifies that the discrepancy is caused by the coupling effects between the antenna and the components in the circuit and the probe. So, in order to avoid the discrepancy, all the circuit components, the dummy metal fills, and the probe model should be taken into consideration in the stage of on-chip antenna design and simulation.

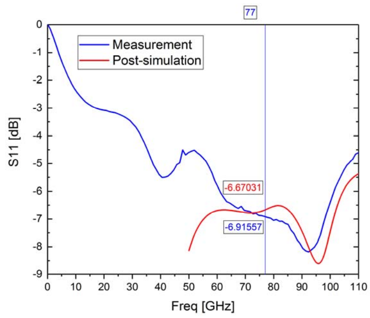


Fig. 7. Reflection coefficients of measurement and post-simulation

V. Analysis of Radiation Pattern Discrepancy

There are also three main reasons for the discrepancy between the measurement and simulation results of the antenna radiation patterns.

- Coupling effects between the on-chip antenna and the driving circuits. As the coupling happens between the circuit and the antenna, the coupled fields result in the generation of coupled currents in the conductors in circuit part, which degrades the antenna radiation performance.
- Probe tip self-radiation. The probe tip itself would radiate, so the measured radiation patterns are actually the superposition of probe self-radiation and antenna radiation. This is an issue especially for the low gain antennas because the probe self-radiation can be as larger as the antenna radiation.
- Reflection from the probe conductor body. The probe body is a close-by conductor for the antenna. It could reflect the EM radiated by the antenna and cause interference at certain angles. As what is shown in the blue curve of Fig. 10(a), the reflection and interference

results in ripples in the E-plane. The probe reflection has less influence on the H-plane because the H-plane is perpendicular to the plane where the reflection happens.

A. Probe Tip Self-radiation

The measurement of the probe tip self-radiation is quite important, especially for the low gain antenna. The probe radiation would define the gain sensitivity of the measurement system. In order to measure the probe radiation, the probe radiation is measured when the probe is landed on the 50Ω load of the calibration substrate shown as the load in Fig. 8. The reason of landing the probe on a 50Ω load is that this load represents an antenna that is matched a 50Ω system. So it is assumed that the probe tip on this load would radiate the same way as it does when it is landed on an impedance matched antenna. Besides, the 50Ω load isn't a radiating element, so minor radiation happens on the 50Ω load which can be ignored.

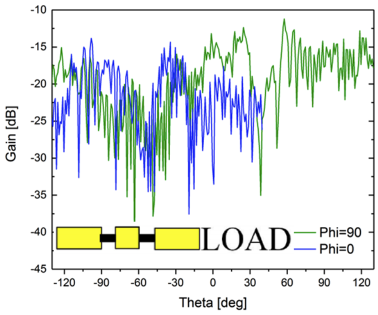
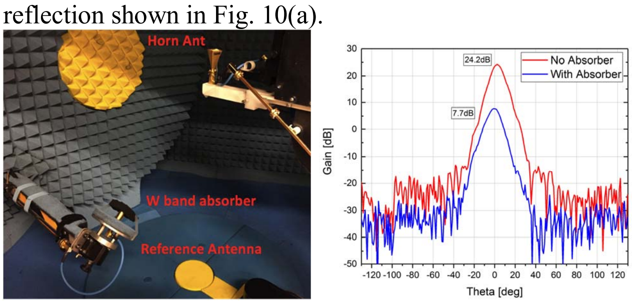


Fig. 8. Probe tip radiation (50 Ω loaded)

According to the probe radiation shown in Fig. 8, the maximum gain of the probe radiation is -12dB which is also defined as the gain sensitivity of this measurement system.

B. EM Reflection from the Probe

Since the probe has a large conductor body close to the antenna, it would cause EM reflection when the antenna is excited. Eventually, the reflected wave from the probe body and the directly radiated wave from the antenna would have interference at certain angles, resulting in the ripples (ripples in E-plane can be seen for this particular case in Fig. 5 (a)). All the reflection and interference influence the measured radiation pattern. The solution proposed in this paper is to cover the probe conductor body with the absorber to avoid the reflection shown in Fig. 10(a).

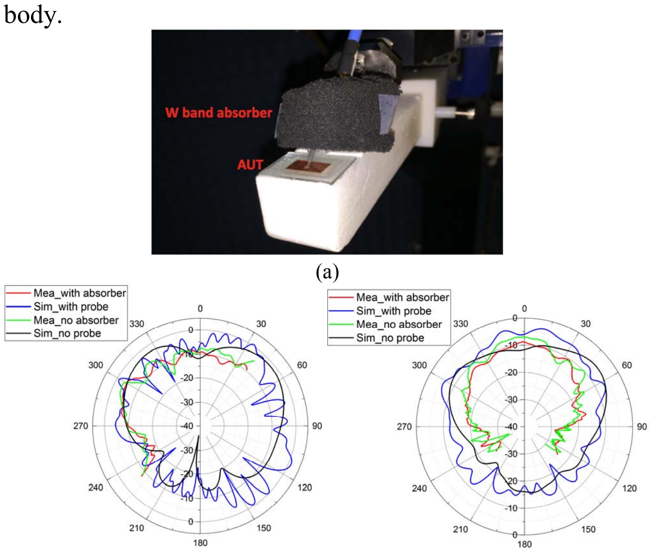


(a) (b)

Fig. 9. (a) Absorber performance measurement setup (b) Absorber performance measurement results

The absorber performance at 77GHz should be studied prior to the measurement. Fig. 9(a) shows the measurement setup of the absorber performance, where a 24dBi horn antenna is placed in the center of the chamber, then the reference antenna is covered with the W-band absorber. It is shown in Fig. 9(b) that the absorber has 24.2-7.7=16.5dB absorption at 77GHz, which indicates a good absorption. Then the probe body is covered with the absorber. The antenna is measured again, and the measurement results are shown in Fig. 10(b)(c).

As it is shown in Fig. 10(b)(c), the original measurement results (green curve) show a better matching with the simulation results (blue curve) when the probe model is included in the simulation. When the probe is covered with the absorber, the measurement results (red curve) present a slight lower gain compared with the original measurement results (green curve), and the reason is that the absorber is thick so that it partly influences the antenna boresight radiation. For this method to be successful, it is recommended that a very thin and conformal absorber is applied to the probe metallic body.



(b) (c)

Fig. 10. (a) Probe body covered with the absorber (b) Radiation patterns at E-plane (c) Radiation patterns at H-plane

VI. CONCLUSION

The reliable and accurate characterization of the mm-wave on-chip antenna is a challenge. The probes are commonly used to contact and characterize on-chip antennas, but the coupling and reflection effects from the bulk metal probe body degrade the radiation pattern and return loss measurement accuracy. This paper presented several methods for studying and removing the effects of probe radiation and scattering. These include post-simulation and covering the probe body with the absorber. We also showed how the circuit part and the dummy metal fill distort the pattern of on-chip antennas. Further investigations of these approaches are being conducted.

REFERENCES

[1] H. M. Cheema and A. Shamim, "The last barrier: on-chip antennas," IEEE Microwave Magazine, vol. 14, no. 1, pp.79-91, Jan.-Feb. 2013

[2] J. Murdock, E. Ben-Dor, F. Gutierrez, and T.S. Rappaport, “Challenges and approaches to on-chip millimeter wave antenna pattern measurements”, IEEE International Microwave Symposium (MTT-S), Baltimore, MA, June 2011

[3] S. Ranvier, M. Kyrö, C. Luxey, C. Icheln, R. Staraj, and P. Vainikainen, “Compact 3-D on-wafer radiation pattern measurement system for 60 GHz antennas”, Microwave and Optical Technology Letters, vol. 51, pp. 319-324, February 2009.

[4] M. Seyyedesfahlan and I. Tekin, ‘‘ACP probe measurement of on-chip strip dipole antennas at W band,’’ IEEE Trans. Antennas Propag., vol. 64, no. 4, pp. 1270–1278, Apr. 2016

[5] L. Boehm, M. Hitzler, F. Roos, and C. Waldschmidt, “Probe influence on integrated antenna measurements at frequencies above 100 GHz,” in Proc. European Microwave Conf. (EuMC), London, U.K., Oct. 2016.

[6] M. Nafe, A. Syed, A. Shamim, "Gain Enhanced On-Chip Folded Dipole Antenna Utilizing Artificial Magnetic Conductor at 94 GHz ", IEEE Antennas and Wireless Propagation Letters , vol. 16, 2844 – 2847, 2017.