Measurement Package for mm-Wave Antennas-on-Chip

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Abstract
The accurate measurement of mm-wave Antennas-on-Chip (AoC) exhibits several challenges. Not only the lossy substrate and the associated low radiation efficiency causes a problem but also the inherently small size of the antenna. We designed a low-cost measurement package that can help to prevent these issues.

1. INTRODUCTION

In the past years there has been an increasing interest in antennas integrated on a chip together with the active RF front-end. Several research groups have studied the behavior of such Antennas-on-Chip (AoCs) using (Bi-)CMOS compatible silicon process technologies (see, e.g., [1 – 4]). One common result of all these studies is the tremendous loss associated with the high-conductivity silicon substrate. In order to take advantage of the benefits of an AoC, e.g., the ability to apply direct matching to the amplifier, but without compromising the overall system performance, this substrate loss needs to be significantly reduced. Therefore, techniques were developed to enhance the radiation efficiency. One measure is micro-machining the silicon bulk to avoid the existence of substrate modes [2]. Though widely used, this method requires a comparably expensive post-processing technique with respect to the overall fabrication costs. In [3] techniques are proposed to reduce the substrate loss for a 60 GHz AoC, which are fairly simple. The silicon wafer was back-grinded from 750 µm to 200 µm. Together with an implementation of a metal plate in the metal stack this results in suppression of transverse electric (TE) modes in the silicon. Additionally, a commercial BiCMOS process with a high substrate resistivity (200 Ωcm) was chosen [4], which further decreases the losses. The simulation results were promising and, hence, a chip design was manufactured for verification purposes (see Fig. 1). During the measurement, however, it turned out that the used setup was inappropriate for the measurement of the AoC’s radiation pattern since the on-wafer probe led to an interference pattern in the H-plane [3]. This pattern is mainly caused by reflections of a portion of the radiated power at the probe’s metal body. It could be verified by implementing a simple model of the probe into the simulation setup. Furthermore, the AoC was initially designed without taking any package into account. Since the silicon substrate was thinned down to 200 µm, which is less than \( \lambda_g/4 \), with \( \lambda_g \) the guided wavelength in silicon, the input impedance is highly sensitive to the material of the support on which the chip is placed.

It is the purpose of this paper to propose and prove the feasibility of a novel concept that overcomes these issues by a low-cost measurement package based on standard PCB technology. This concept can also serve as a basis for the final packaging of the AoC.

2. PACKAGE DESIGN

In order to overcome the problems associated with the close proximity of the probe to the AoC, an extended feed line for the antenna was required. Since the die size should meet the size of the final chip, an extension of the feed line on chip was no option. As a consequence, the feed line had to be extended off chip. Furthermore, the die had to be placed on a defined support to achieve insensitivity of the AoC’s input impedance to its placement in the measurement setup. One way to achieve both goals is the placement of the chip on a printed circuit board (PCB). While the PCB area around the antenna can be designed to modify the radiation pattern and to some extend also the input impedance, the on-chip feed line can be connected to an on-PCB line to
obtain the necessary distance of the probe to the radiating element.

An interconnect from a chip to a PCB at 60 GHz is not a trivial task and a matter of discussion in the mm-wave community [2]. The two standard options for the interconnect are, first, the bond-wiring technique and, second, the flip-chipping technique. Though flip-chipping is seen to be superior to the bond-wiring technique with respect to return loss [2], it requires the chip to be mounted upside down with the antenna facing the PCB on one side and the silicon substrate on the other side. This does not resemble the targeted mounting of the AoC. Therefore, the bond-wire interconnect was chosen. As described in [2], a bond-wire is commonly considered to be a non-negligible inductance at mm-wave frequencies. Instead of looking at the bond-wire as a parasitic element, however, we considered an alternative approach by creating a half-wavelength (λ/2) bond-wire transmission line at 60 GHz. A simulation with the commercial full-wave solver HFSS [5] revealed that a ground-signal-signal-ground (GSSG) configuration of wires with a diameter of 38 μm and a pitch of 200 μm, which are embedded in a glob-top environment (ε_r = 3), exhibits a characteristic impedance of 100 Ω. In order to obtain a λ/2 line, the required wire length is 1.44 mm. Using these values, the simulation setup as depicted in Fig. 2 was made. It shows the bond-wire transmission line that connects a on-chip 100 Ω load to a GSSG on-PCB transmission line with a pitch of also 200 μm. Its length was designed to be λ/2 (= 1.81 mm). The PCB itself has a thickness of 0.5 mm and a relative permittivity of 3. The resulting on-PCB line has a characteristic impedance of 130 Ω. Since the on-chip landing structure has a pitch of 125 μm between the bond-pads, the bond-wire transmission line had to be slightly tapered. The resulting input impedance of the overall structure from Fig. 2 is depicted in Fig. 3. The input impedance at 60 GHz does not exactly show a value of 100 Ω. This difference is seen to be the result of the discontinuity of the on-chip probe pads together with their non-ideal transmission line routing (see also Fig. 1) as well as the additional glob-top on the PCB transmission line.

In order to not directly place the chip on a metal plate, a cut-out in a large metal area on the top side of the PCB was introduced (see Fig. 4). The bottom side was completely metalized. The width of the resulting cavity has the same width as the chip (1.5 mm). Its length was chosen such that the edge of the plate on the chip (see [3]) coincides with the edge of the cavity when the antenna is centered over the cavity. Note that, due to the thickness of 0.5 mm, only the fundamental parallel plate mode, i.e., the transverse electromagnetic (TEM) mode, can propagate between the plates. The
energy excited in this mode, however, is considered to be small due to the field distribution associated with a dipole. The resulting input impedance of the AoC (without bond-wires, etc.) is depicted in Fig. 5.

3. MEASUREMENTS AND DISCUSSIONS

The measurement package from the preceding section was manufactured and assembled with the chips described in [3]. For this, the chips had to be sawn in order to be able to attach bond-wires to the pad structure that is connected to the AoC (saw line #4 in Fig. 1). The realized setup is shown in Fig. 6. The PCB material is RO3003 [6]. Also depicted on the left in the figure is the landed GSSG infinity probe (pitch: 200 µm) to connect the AoC to the network analyzer (VNA) [7].

The input impedance measurement was carried out on a probe station. First, a short-open-load (SOL) one-port calibration was carried out using the calibration substrate of the probe manufacturer. Then the embedded AoC in the measurement package was measured. For comparison, the simulation result of the AoC when centered over the cavity (Fig. 5) and the simulation data of the two-port consisting of the bond-wires and on-PCB transmission line were combined using MATLAB. Both, measurement and simulation results, are depicted in Fig. 7. Due to the reflections from the probe station, which is not optimized for antenna measurements, time-gating was applied to the measured signal in order to obtain the result of the AoC without reflections from the environment.

The comparisons of the normalized radiation patterns in the E- and H-plane are depicted in Fig. 8. They have been obtained with the setup.
described in [8]. As described in [8], also for this measurement time-gating had to be used to obtain the reflection-free signal from the antenna.

When comparing the measured with the simulated input impedance in Fig. 7, one observes an apparent frequency offset between the corresponding curves. Additionally, the absolute values are higher for the measurement than for the simulation result. This is seen to be the result of the simplified simulation setup compared to the realized one (cp. Fig. 2 and Fig. 6). The glob-top shape was chosen to be an ideal cuboid covering an arbitrary length of the on-PCB transmission line. In the physical setup the glob-top shows a complete different shape and the covered length of the on-PCB line is not exactly known. Additionally, the bond-wire structure in the simulation setup is idealized. Though the bond-wire structure in the realized setup closely matches the one in the simulation model, as observed during manufacturing, it is not an exact match. When comparing the measured radiation patterns with the simulated patterns in Fig. 8, one observes a quite good match. The discrepancy in E- and H-plane can be partly explained by a slight misalignment of the AoC on the measurement chuck. Furthermore, the influence of the probe on the measurement could not be fully eliminated. This can be best observed in the H-plane plot at the bottom of Fig. 8. For angles smaller than about -25° the probe blocks the line-of-sight (LOS) between AoC and the reference antenna. Additionally, the ripples for angles larger than -25° indicate a remaining interference pattern of the LOS signal from the AoC and the reflected signals from the probe’s body as already described in [3].

4. CONCLUSION AND RECOMMENDATIONS

This paper presents a low-cost package for mm-wave AoC measurements. It shows that wire-bonding still is a feasible interconnect option at mm-wave frequencies. It allows extending the feed line of an on-chip antenna to a standard PCB. This allows probing in a sufficient distance away from the AoC, which reduces the influence of the probe.

Especially for the radiation pattern measurement, however, time-gating cannot be fully avoided. Therefore, it is recommended to look for alternatives. Since mm-wave AoCs are very small and exhibit in general low radiation efficiencies, we see measurement methods that are used for electrically small antennas, e.g., the radar-cross-section (RCS) method [9], as a good option.

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6. REFERENCES


