Test interface solution for mmWave and AiP applications

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Since the launch of 5G new radio (NR) communication technology, many countries such as South Korea, China, and Japan have dedicated their initial 5G roll-out to the 3GPP-defined FR1 bands (4.1GHz to 7.1GHz). Other countries/regions, like the United States and the European Union, are focusing on the FR2 bands of mmWave frequencies (24.25GHz to 52.6GHz) [1]. The major reasons for choosing FR2 bands are the availability of spectrum and wider bandwidth operating at mmWave bands. The next-generation wireless networks are required to be faster, ultra-reliable and reactive. According to the 3GPP standard, 5G FR2 signals also have a wider synchronization signal block (SSB) – 28.8MHz and 57.6MHz, respectively – because these have subcarrier spacing up to 240kHz, compared to only 30kHz and 60kHz for FR1. FR2 signals also have more SSB beams. All 5G NR base stations transmit SSB beams through the transmission of a sector antenna, but FR2 radios use up to 64 beams, whereas FR1 radios are limited to a maximum of 8 beams. With 64 beams, the radio can transmit narrower beams with high power, which improves the efficiency of the radio and helps avoid interference because of high signal to noise ratio. However, more beams require decoding multiple bits from the physical broadcast channel (PBCH) in order to read out all 64 beam indexes in the correct location. Having more beams also requires a greater number of antenna elements in the antenna array, which enable better superposition of waves using beam-forming technology. This makes it difficult to do connected testing and verification of the radios, forcing the test engineer to do testing over-the-air (OTA). High-frequency signals have shorter wavelengths, which will cause higher propagation losses through both air and most physical objects. This means 5G FR2 service will require more radio density and strategic placement at the package and system levels. It will also make signals more vulnerable to interference, and requires test equipment with lower noise floors and faster sweep speeds in the mmWave bands.

Prior to discussing the test solution for antenna-in-package (AiP) and mmWave technology, it is helpful to consider why we need AiP in high-frequency design, instead of conventional external radio frequency (RF) circuit design. The answer is because the higher frequency results in a shorter wavelength with the roll-out of 5G FR2. On the other hand, the RF circuit design at mmWave frequencies considers the smaller form factor with more integration in the package technology, especially with respect to signal loss and cost tradeoffs. AiP is one option for achieving the goal of integration with shorter interconnections between the antenna and the RF chip (see **Figure 1**). Considering mmWave applications, signal loss becomes more critical at high frequencies and system design challenges increase rapidly in complexity. With AiP technology, the antenna is no longer a separate component within the wireless device, but is integrated into a system in package (SiP) with RF switches, filters, and amplifiers. A variety of AiP methodologies provide the required form factor and function for these applications and can include more than one antenna or an antenna array, such as flip-chip ball grid array (FCBGA)-based AiP, fan-out AiP, and AiP modules. The use of mmWave frequencies in AiP applications presents an extreme challenge for engineers in charge of characterization and validation of integrated designs who need to look for accurate OTA and coupling test solutions. The challenge is that engineers need to measure and validate package antenna performance by checking hundreds or thousands of data points in the test setup.

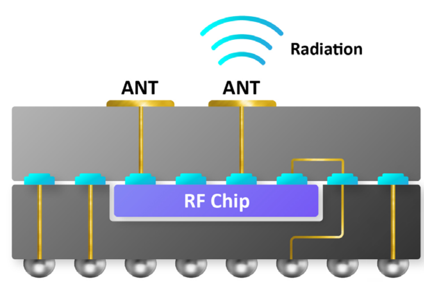

Figure 1: AiP cross section.

Test interface solutions

Under the complex package construction and electrical properties needed to handle the higher frequencies at 5G FR2, the data challenge noted above is especially true in mmWave applications. In such applications, the signals are especially vulnerable to interference given the higher amounts of path loss in transmission of conduction and radiation. This makes measurement accuracy and repeatability even more critical. Wavelengths in the mmWave range are extremely sensitive to cable and connector errors, so learning how to make multiple measurements per connection can help remove uncertainty from those measurements. In this article, we have shared valuable information on designing test interface solutions to help understand mmWave test solutions. Design considerations include mechanical design along with dielectric material selection, and socket solutions to fit the multiple test requirements, such as near/far-field defined in OTA, gain, error vector magnitude (EVM), etc. [2-5]. Therefore, the test interface in mmWave is a "multiphysics" problem, which is a term used to describe systems with mutual coupling interactions among physical fields.

To test the mmWave AiP package, the design with a manual lid that has a wide opening area and low dielectric loss material (see **Figure 2**) is one of the effective testing solutions used in the beginning stage of

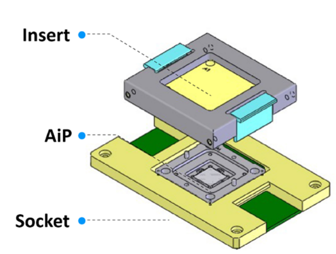

Figure 2: Manual lid socket design.

Properties				
Insert Material	ESD	PI	Peek	Low Loss Material
Mechanical				
Density (g/cm³)	1.30 ~ 1.2	1.41 ~ 1.48	1.31 ~ 1.65	0.052 ~ 0.11
Compressive Strength (MPa)	155 ~ 180	185 ~ 640	117 ~ 138	0.8 ~ 3.6
Tensile Strength (MPa)	96 ~ 140	110 ~ 163	86 ~ 110	1.6 ~ 3.7
Elastic Modulus (MPa)	6480 ~ 10480	3923 ~ 4000	3447 ~ 5500	75 ~ 180
Electrical				
Dielectric Constant (Dk)	5.3 ~ 7.9	3.3 ~ 3.7	3.3 ~ 4.1	1.04 ~ 1.1
Loss Tangent (Df)	0.16 ~ 0.22	0.001 ~ 0.004	0.003 ~ 0.005	0.0002 ~ 0.015

Table 1: Material properties of the insert design.

device characterization. The purpose of lid design (both the wide opening and the low dielectric loss material) is to ensure the least amount of radiation loss when radiation propagates through the lid material. In the semiconductor test field, advanced engineering plastic materials are designed for the socket housing to position the spring probe and as an insert to press the device into the socket test position. The plastic materials in **Table 1** need to be considered in order to fulfill the test considerations, such as mechanical strength, electrical loss, thermal stability, chemical consistency, and anti-statistic properties. However, dielectric constant and loss tangent are more important than the other parameters and are very sensitive with respect to how they affect the measurement results in mmWave AiP testing. By combining the horn antenna, sophisticated instruments and printed circuit board (PCB) layout, a simple OTA test setup for mmWave AiP can be made (**Figure 3**). In this setup, radiation and conducting measurements can be performed at different conditions. The purpose of these measurements is to check the influence of different inputs so that data correlation will help determine solutions for high-volume production. The open top lid design with the engineering plastic material and low-loss insert material are compared (**Figure 4**) to show the radiation propagation interference in spatial radiation distribution and gain measurement. The mechanical strength of the low-loss material is much worse than that of the engineering

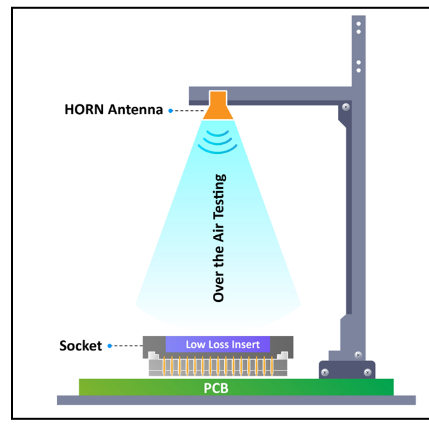

Figure 3: Antenna OTA testing schematic.

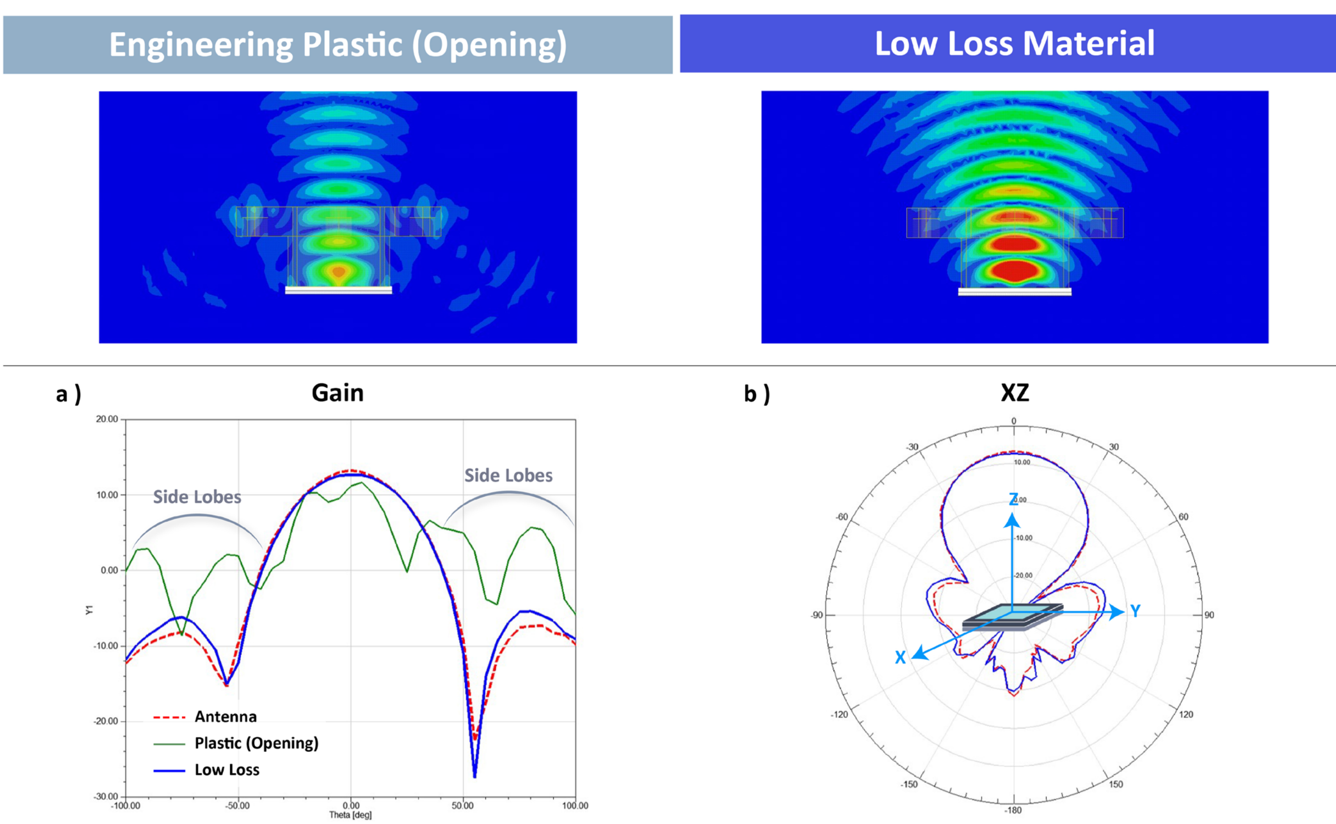

Figure 4: The influence of different materials on antenna radiation: a) effects on antenna gain; and b) effects on XZ radiation.

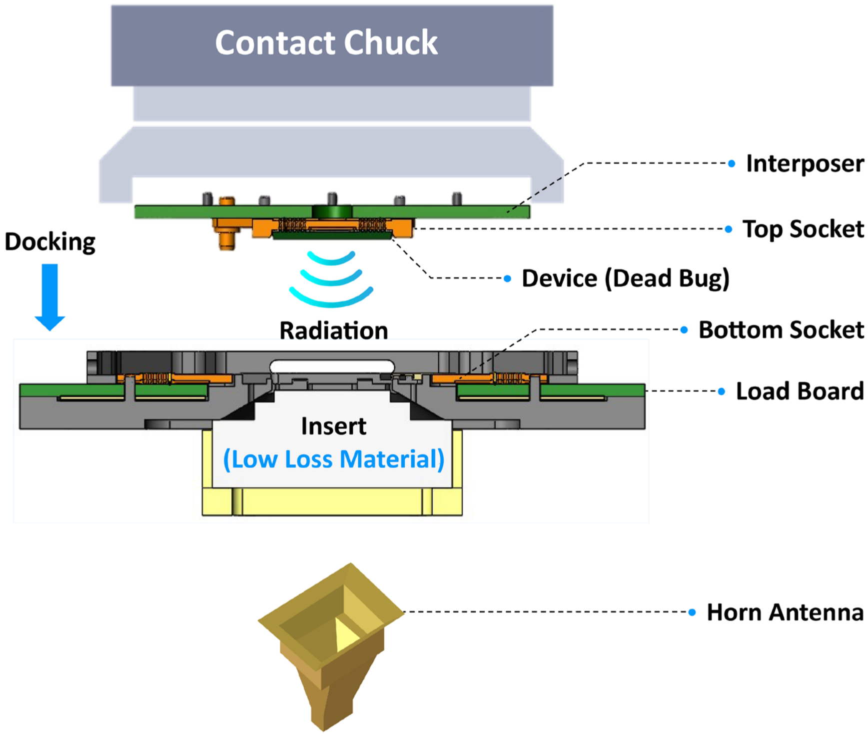

Figure 5: Production solution for AiP testing.

plastic material because of the porosity structure of the foam, which is a tradeoff for long-term operational reliability and high-frequency measurement accuracy. To better ensure a comprehensive design consideration, it is suggested that the design and material selection be simulated by using electromagnetic (EM) field characterization software and that there be a review of the frequency-dependent radiation distribution generated from the top side antenna array of the AiP package.

Regarding a production solution design: "dead bug" testing of the AiP package is one of the solutions for adapting the device's package format to the pick and place handlers. However, the bottom side of the package design needs to be considered as part of the keep out area for the nozzle (see Figure 5). The pros of conducting "dead bug" testing are that it will easily establish the OTA test environment rather than a test using a "live" device because the radiation is propagated down the entire side of the test setup. Therefore, the transmitted signal will not interfere with the mechanical pick and place parts of the handler. In general, all those parts are made of metal and will block or reflect the radiation. The cons of "dead bug" testing are that there is a longer trace loss through the top socket and interposer, and through the loopback to the bottom socket and load board. A customer's major concern with this kind of testing is how to control the loss or frequency shift within the expectation for these particular measurement environments. Therefore, 3D model co-simulation including the package, socket, and PCB will be preferred instead of cascading the individual component's S parameter both in signal integrity (SI) and power integrity (PI). As an example, Figure 6 shows that impedance behavior will be significantly violated by different simulation setups, and the insertion and return loss will become uncontrollable if impedance is not matched. As previously mentioned, the difficulties and the different kinds of mmWave testing include the use of a smaller signal wavelength that will induce more realistic setup issues on the measurement results, such as pad size, via size and location, as well as manufacturing tolerance. The fine-tuning process in the simulation model compared with the actual manufacturing parts in the measurement system will be crucial to success of the process.

The housing and contact elements of the test socket are the most critical components in semiconductor testing. These components seriously influence the SI among electrical test interfaces. As previously noted, in the conduction and radiation setup, a mmWave test solution needs to seriously consider the fragile signal transmission path. In Figure 7, the experimental results of return losses up to 100GHz using various socket solutions were verified by using an impedance optimizing spring probe in 5G FR2 and automotive radar, and in a so-called RF socket, Brownie coaxial socket [6], and the recently launched contact pin solution, eHORN. How should one design a suitable mmWave test socket? The answer is highly dependent on the customer's requirements for the socket. Requirements include the package type and the preference for mass production hardware

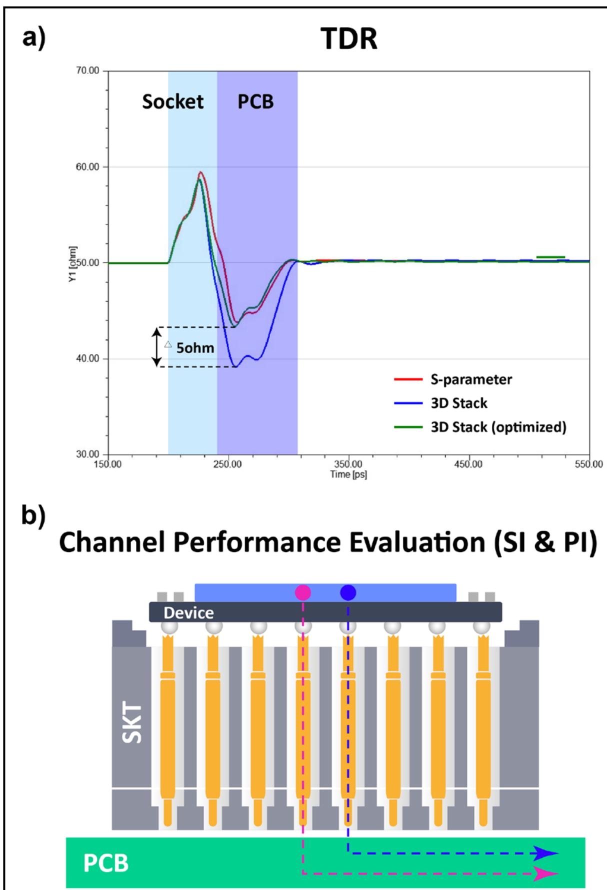

Figure 6: a) Channel simulation results between a 3D stack and an S-parameter cascade; b) Channel performance evaluation (SI and PI).

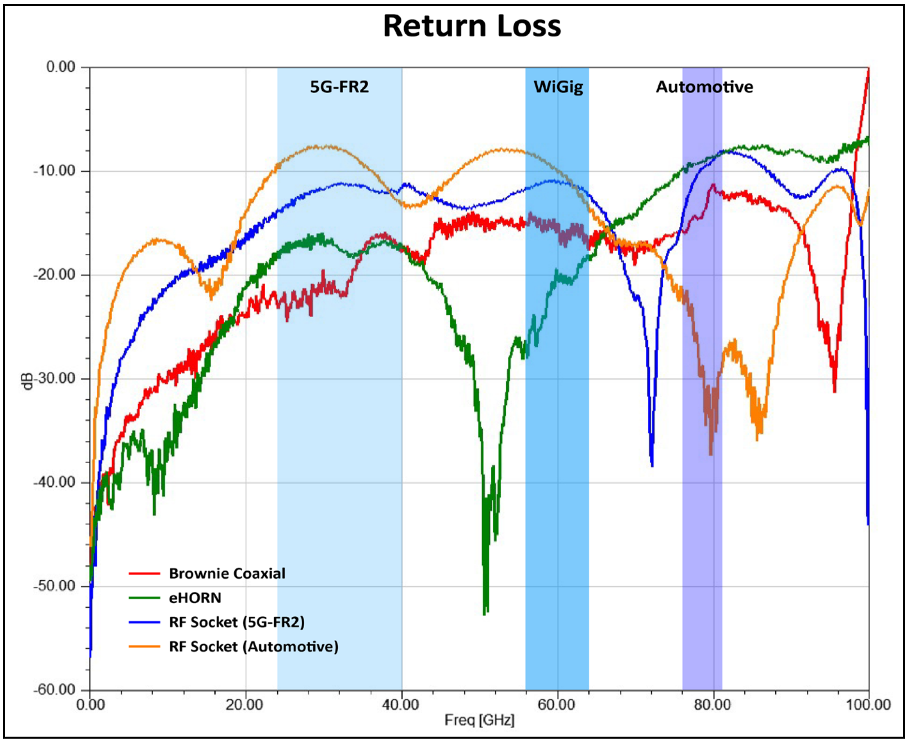

Figure 7: Measurement results for various mmWave socket solutions.

Socket Solution	RF Socket (5G-FR2)	RF Socket (Automotive)	eHORN	Brownie Coaxial
Contact Element	Spring Probe	Spring Probe	Contact pin	Spring Probe
Housing Material	Engineering Plastic	Engineering Plastic	Engineering Plastic	Metal
Pin Length (mm)	2.8	2.2	1.32	2.5
Travel (mm)	0.4	0.35	0.125	0.4
Avg. DC Resistance (mΩ)	< 60	< 60	< 20	< 85

Table 2: Socket solution comparison.

selection. Regarding the RF socket: the electrical performance can be adjusted based on the specific pin map that is used to achieve the target by changing design parameters, and for which the housing material is engineering plastic. In general, an extremely short probe (less than 2mm) is a preferred option for testing at high frequencies, but not necessary. Not only impedance matching in design, but also impedance matching with the test interface is a more realistic procedure. A Brownie coaxial socket is made by using a metal housing and can adjust the individual probe's impedance to optimize for the best performance. To deal with the quad flat no-leads (QFN) package, the newly developed contact element, eHORN, can support up to 80GHz and has the smallest scratch length (~0.08mm) on the device pad to satisfy the smaller package outline along with a shrinking pad size. The comparison table of socket solutions is listed in detail in **Table 2**.

Summary

The test interface solution for mmWave and AiP applications is a very hot topic because of the high-volume devices coming to market. What we have provided is a total test interface solution to analyze the radiation and conduction measurements including engineering and mass production solutions. By carefully checking the design factors for mmWave test requirements, mechanical considerations with proper material selection and socket solution need to be verified by 3D simulation before being released to manufacturing. The cascading S-parameter of each component is not suitable for high-speed and high-frequency applications. 3D simulation is a more straight forward way to analyze the properties from the component to the system level. At frequencies above 6GHz, channel simulation including package, socket, and PCB will be a recommended method to design the test solution, which creates a barrier for semiconductor test market entry.

References

1. 5G PPP Architecture Working Group, "View on 5G Architecture," July (2016).
2. J. S. Hurtarte, "RF test strategies and solutions for 5G millimeter wave devices," TestConx, 2020.
3. J. Moreira, "Testing AiP modules in high-volume production for 5G applications," *Chip Scale Review*, May/June 2020.
4. J. Moreira, "Testing AiP modules in high-volume production for 5G applications," *Chip Scale Review*, Nov/Dec 2020.
5. A. Kikuchi, N.Shiota, Y. Kato, H. Mineo, J. Moreira, H. Takasu, "Socket design and handler integration for high-volume over the air testing of 5G applications," TestConx, 2021.
6. C. Sun, R. Chen, H. Chen, "More than you think: the beauty of coaxial sockets," *Chip Scale Review*, July/Aug 2018.

Biographies

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