Design of Millimeter-Wave Antenna-in-Package (AiP) for 5G NR

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Abstract: For 5G new radio (NR), there are two frequency bands: Frequency Range 1 (FR-1) (low frequency) and Frequency Range 2 (FR-2) (millimeter-wave frequency). Millimeter-wave has been officially utilized in mobile applications. The wide bandwidth is the key for the millimeter-wave band. However, higher loss has become the major challenge for the wide use of this frequency range. Antenna array and beamforming technologies have been introduced to resolve the path loss and coverage problems. The key design considerations of the beamforming antenna array are low loss, compact system and small size. Antenna-in-package (AiP) has become the most attractive technology for millimeter-wave front-end system. For the design of AiP, many parameters such as RF transition, material and heat need to be considered and designed properly. The Over-the-Air (OTA) testing technology is also very critical for AiP mass production. In this paper, the detail of AiP design and new OTA testing technology are discussed and demonstrated.

Keywords: 5G; antenna-in-package (AiP); beamforming; FR-2; millimeter-wave; new radio (NR); phased-array; low temperature cofired ceramic (LTCC)

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1 Introduction

Antenna-in-package (AiP) is a technology that integrates antennas along with the transceiver and power dies into a system-in-package module. It has been widely used in the millimeter-wave antenna array such as 60 GHz gesture sensors, 77 GHz automobile radars, 94 GHz phased array, or even frequencies as high as 122 GHz for imaging sensors and 300 GHz for wireless links. 5G millimeter-wave spectrum can promise sufficient bandwidth to provide the next-generation user experience and industrial applications by using millimeter-wave as the carrier frequencies.

The idea of AiP technology can be traced back to the 90s when antenna designers had dedicated their time to minimizing the size of the antenna. In the meantime, another idea was to integrate the antenna with the front-end system to achieve a more compact system. At an early development stage, AiP was developed together with Bluetooth technology. Later on, AiP was widely implemented into millimeter-wave radar systems. IBM, Intel, Samsung, Google, etc., have realized the AiP modules at 60 GHz, 77 GHz, and 94 GHz. Recently, 5G mobile communications and terahertz technology are becoming more and more important. Qualcomm has announced the world's first 28 GHz AiP module for cellphone[1]. Except for radar applications, 60 GHz is used for wireless communications of the

IEEE 802.15.3c standard. Besides the AiP technology, antenna-on-chip (AoC) has also been studied for 60 GHz, where the antenna is fabricated with other circuits on a wafer. AoC technology is more suitable for terahertz applications. However, the efficiency of AoC is only 11.5%. Instead, AiP has shown high efficiency of more than 90% when low temperature co-fired ceramic (LTCC)[2] is used for manufacturing.

The requirements of AiP are multifunction, high-capacity and small size. The multilayer integration and package technology have demonstrated its capability of low profile, low cost and potentially high-volume production. A proper multilayer design can help to improve the bandwidth and impedance match and lower the coupling effect between lines. For millimeter-wave systems, the fabrication process and capability affect the performance significantly. High density interconnects printed circuit board (HDI PCB) and LTCC are conventional multilayer technologies. The microstrip line is the most common technology for signal transmission between the layers. However, the flexibility of the microstrip line is limited by its two-dimensional structure. An innovative multilayer substrate integrated waveguide (SIW) is presented to give designers more freedom when designing AiP modules. SIW is an emerging type of rectangular dielectric-filled waveguide which is fabricated by arrays of metallic vias to realize the bilateral edge or sidewalls. The three-dimensional structure supports very high flexibility when designing an AiP module [3].

In this paper, the design considerations and architectures will be discussed along with the capabilities and the products of TMY Technology Inc. (TMYTEK). TMYTEK is a millimeter-wave company that specializes in 5G solutions such as AiP front-end modules, beamforming technologies and testing systems.

2 Design Considerations and Architectures

To fulfill the increasing demands in the millimeter-wave front-end module (FEM), AiP turns into the most promising and suitable technology to achieve the phased arrays cost-effectively. At the same time, the material and process choices involving tradeoffs among engineering constraints are also considered, including heat management, control design, RF performance, calibrations, and more (**Fig. 1**). The solution to multiple dimensional engineering problems is not linear and needs a lot of experience and creativity to realize the products. In addition to design, mass production is also a significant challenge, especially in Over-the-Air (OTA) testing.

2.1 System Architectures

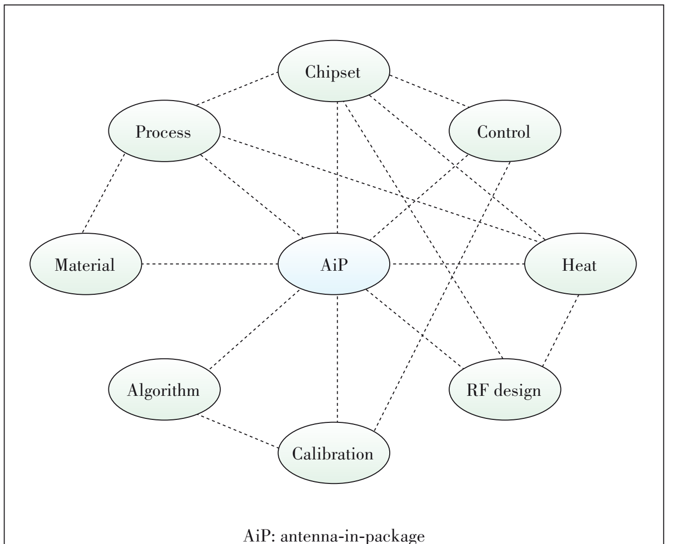
Fig. 2 shows three different architectures for the 5G phased array. In the antenna and beamformer architecture, the block shows an RF FEM with an analog beamformer which includes antenna array, duplexer and beamformer. Nowadays, a couple of beamformer chip makers have announced beamformer chips optimized for 5G millimeter-wave bands. The second architecture integrates intemediate frequency (IF)-radio frequency (RF) conversion into the module as indicated in the rectangular block labeled with up and down conversion. Given that frequency converters dramatically affect the quality of communication, embedding it into the system increases system performance and reduces the complication of integration. Integrating mixers and filters in the package is not a trivial job, and local oscillator (LO) signal distribution is another concern, especially in large, tiled array. The third architecture is based on open radio access network's (ORAN's) split option 7.2 to integrate the low physical (Low PHY) layer into the module to offload the front-haul network on the radio access network (RAN). In this architecture, digital components are included, which raise the challenges to a new level.

2.2 Design Considerations

The design considerations of AiP are the multi-dimensional engineering problems due to its complexity and high density. This section is divided into four sub-sections: beamforming integrated circuit (IC) and up/down converter chips, fabrication technologies and materials, design of antenna and transition, and design of feeding networks and filters.

2.2.1 Beamforming IC and Up/Down Converter Chips

A modern beamformer chip integrates power amplifiers (PAs), low noise amplifiers (LNAs), phase shifters (PSs), variable attenuators and T/R switches. Complementary metal oxide semiconductor (CMOS), CMOS silicon on insulator (SOI), and bipolar CMOS (BiCMOS) technologies are preferred due to the benefit of digital circuit integration and low cost, even if the output power is not as good as the III-V compound processes such as GaAs and GaN. The main specifications that need to be considered are transmitter gain and power, receiver gain



▲**Figure 1. System context diagram of AiP design parameters.**

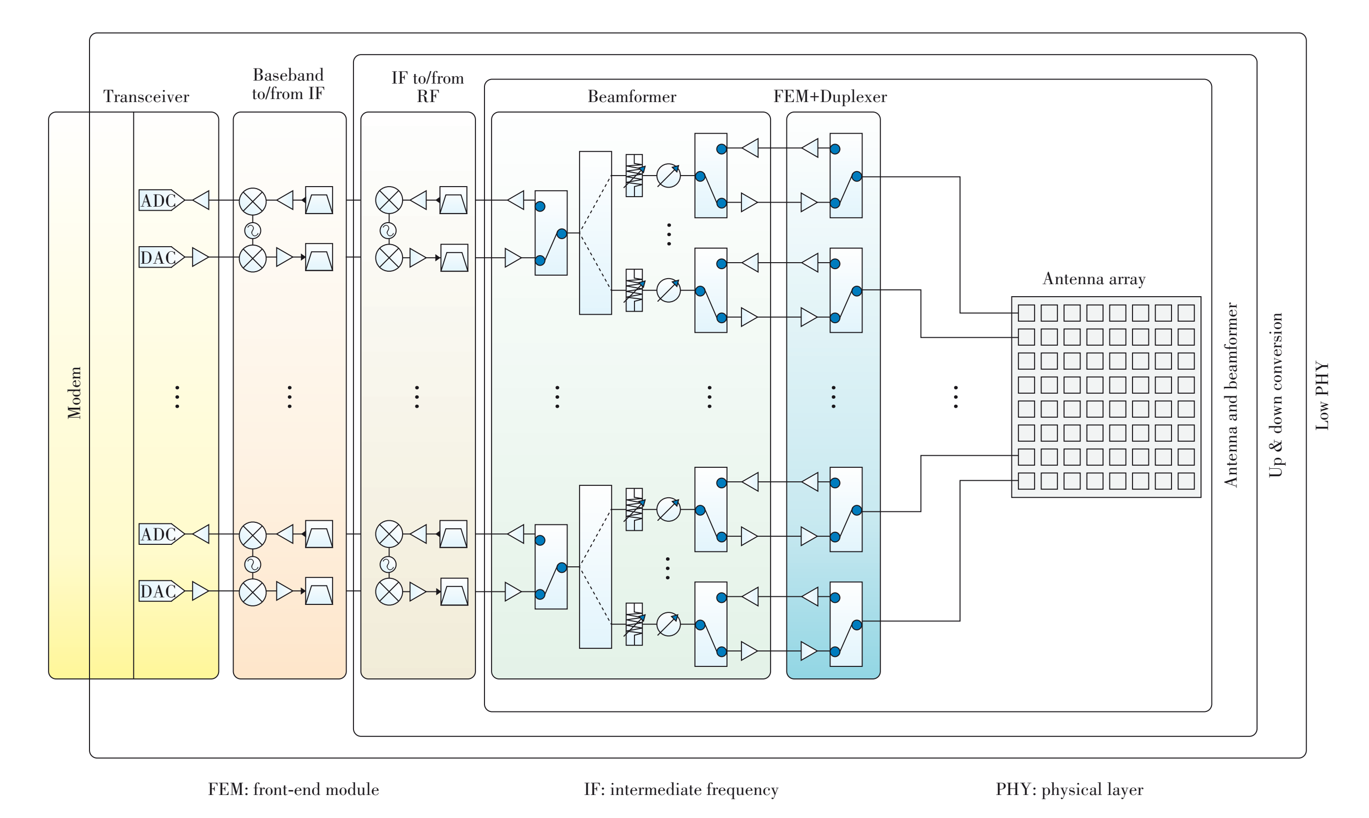
and noise, phase resolution and RMS error, attenuation range and resolution, memory size, beamforming control speed, power consumption, and cost. In a 5G millimeter-wave phased array, the output power is not the only concern. Due to the feature of Orthogonal Frequency Division Multiplexing (OFDM) in 5G, the power amplifier (PA) back-off operation is necessary. It is considered along with antenna array gain to form a system with targeted equivalent isotropically radiated power (EIRP) and reasonable power efficiency (**Table 1**). The design considerations of up/down converters are conversion gain, noise, linearity, LO pumping power, and isolations.

2.2.2 Fabrication Technologies and Materials

Fabrication technologies and materials are critical for the performance, cost, and size of the AiP module. There are three major technologies for AiP manufacturing: HDI PCB, LTCC and fan-out wafer-level packaging (FOWLP)[4]. **Table 2** shows the capability comparison of the three technologies. For the material selection, dielectric constant (Dk) and loss tangent (Df) are the main considerations. Thermal conductivity, Dk and Df change with temperature. Thickness ranges of core board and prepreg are also important in AiP design. **Fig. 3** shows the performances of Dk and Df with different materials.

2.2.3 Design of Antenna and Transition

In low frequency (FR-1), the antenna radiation pattern is typically designed as omnidirectional antenna. In millimeter-wave frequency (FR-2), antenna array has become the essential solution to compensating for the higher path loss at this frequency range. The consideration of the antenna array is dif-



▲Figure 2. Three different system architectures of antenna-in-package (AiP) design.

▼Table 1. Beamforming design considerations and TMYTEK's capability

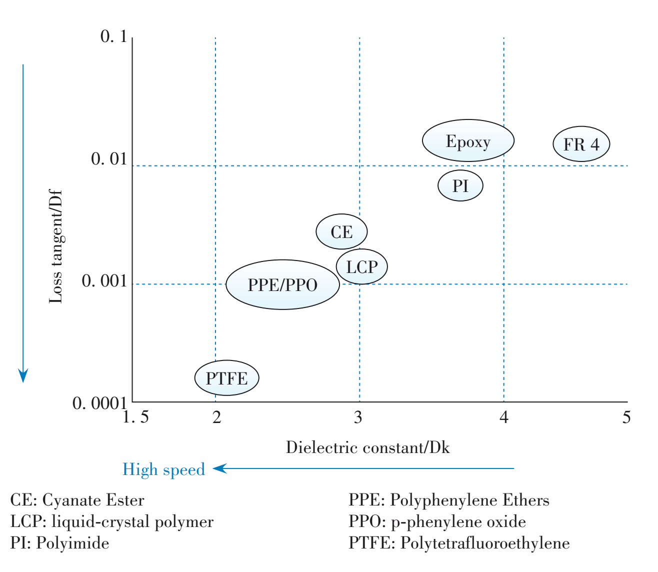
Index	Consideration	TMYTEK's Capability
Tx Power	Output power of each element	18 dBm for 28 GHz 15 dBm for 39 GHz
Frequency	Meeting operator's frequency bands	n257, n258, n260, n261 Ranges from 24 to 41 GHz
Rx NF	Better system sensitivity provided by lower noise floor	4.5 dBm in 28 GHz 6.5 dBm for 39 GHz.
Phase	Phase difference is the basic of beamforming; step size and error are the key considerations.	6-bit phase shifter ±3° RMS phase error

NF: noise figure RMS: root-mean square

▼ **Table 2. Capability comparison of three main antenna-in-package (AiP) fabrication technologies**

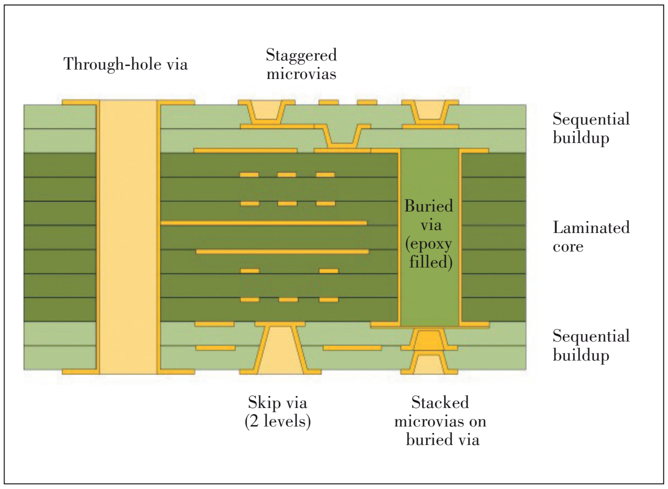
Parameter	HDI PCB	LTCC	FOWLP
Maximum layer	16	60	2 - 6
Minimum layer thickness/μm	35	25	5
Minimum board thickness/μm	300	500	400
Dielectric constant	3 - 6	4 - 8	2.6 - 3.6
Loss tangent	0.002 - 0.02	0.002 - 0.005	0.004 - 0.01
Metal	Cu	Au, Ag, Cu	Cu
Line/space/μm	45/45	40/40	5/5
Via diameter/μm	75	50	25
Inner cavity build	x	v	v

FOWLP: fan-out wafer-level packaging
HDI PCB: high density interconnects printed circuit board
LTCC: low temperature cofired ceramic



▲ **Figure 3. Dielectric constant and loss tangent of different materials.**

ferent compared with the design of single antenna, especially including the beamforming technology. Beam pattern, beam steering range, sidelobe suppression, beam pattern symmetry between two polarizations, antenna gain, isolation between array elements, antenna bandwidth, antenna efficiency, and return loss are all the critical design parameters. Normally, the traditional planar antenna has a design of two layers, which is hard to have a good performance for the above parameters simultaneously. The multilayer antenna technology has more design flexibility to achieve better performance. However, the design also becomes more complicated. The design of multilayer introduces the vertical structures such as the via wall into the antenna to improve the isolation or the director to improve the directivity. Nevertheless, the transition design between layers is the most critical part of this multilayer antenna design. A good transition design means having a better impedance match. The manufacturing process and capability affect the flexibility of transition and limit the final performance. **Fig. 4**



▲ **Figure 4. High density interconnects (HDI) type III structure[5].**

shows the HDI type III stack and via types. It has two levels of microvias, buried vias and regular through-hole vias. The microvias are used effectively in improving signal and power integrity.

2.2.4 Design of Feeding Networks and Filters

Building a feeding network is critical to the antenna array as the components cannot be placed off-board. Size and complexity are important for measuring feeding network performance. The commercial off-the-shelf (COTS) beamforming ICs has 4, 8, or 16 channels. For 5G gNB, 4 × 4 or 8 × 8 antenna array is used as a standard unit cell, which might operate as single or dual polarization. Since the feeding network connects the beamforming ICs and antenna elements, it has to incorporate matching circuits to achieve wideband operation. Good isolation between dual-polarization ports has to be assured to achieve a low cross-polarization coefficient[6]. The multilayer design which is described in the last section is also considered for achieving a better impedance match of transition.

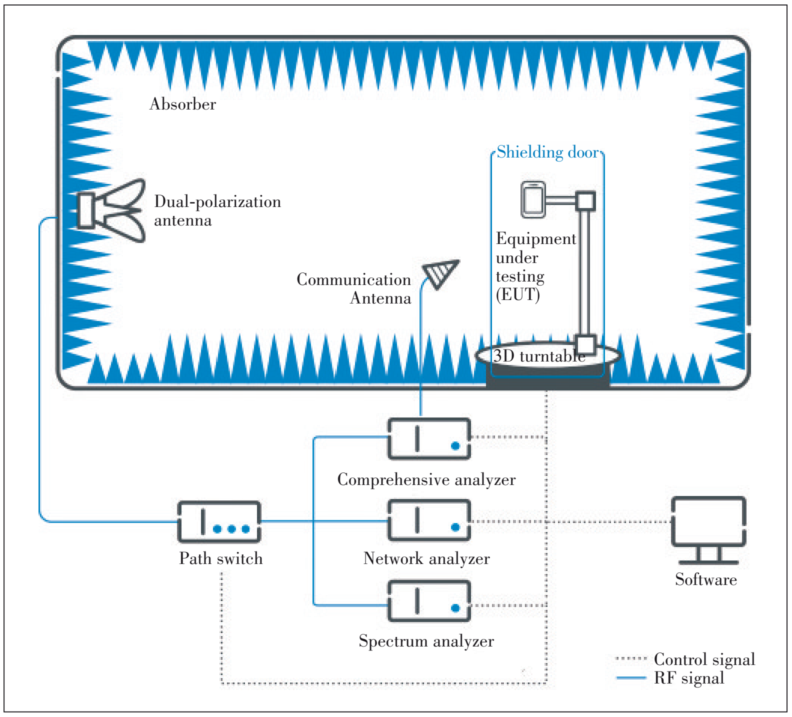
The filter design is limited to the board area available for passive components. The larger the room for filters, the better the rejection performance can be achieved. At the same time, thermal stability and repeatability are also challenging for designers to reduce the tuning effort to achieve an SMT- capable device. As an example of the microstrip structure, the tolerance of substrate thickness, etching size and even dielectric constant should be considered and calculated carefully to achieve the best performance at the millimeter-wave range.

2.3 OTA Measurement for AiP Module

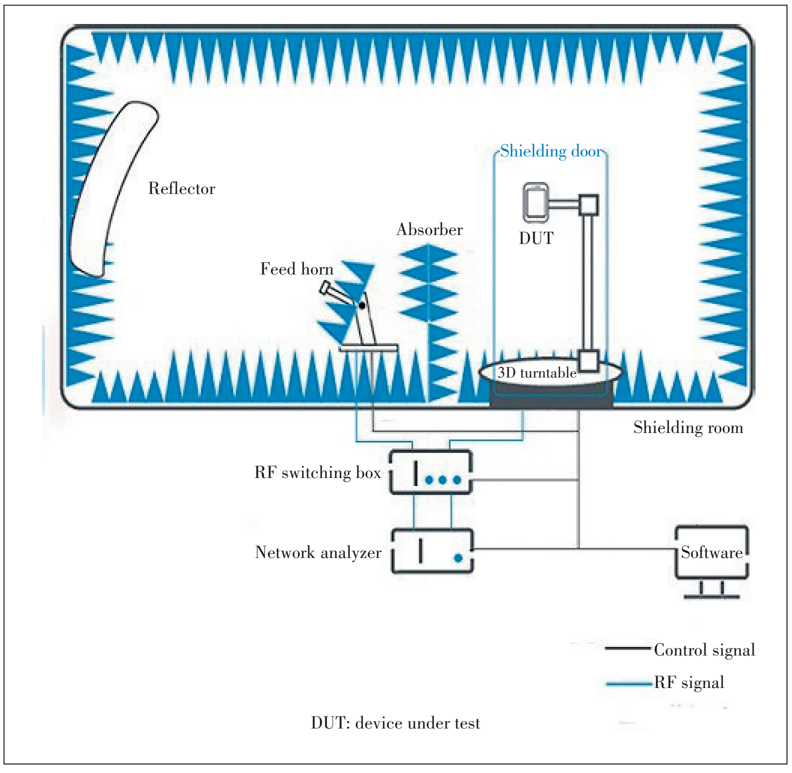
Conductive testing is no longer an option for the millimeter-wave module implemented by AiP technology. There are no connectors or testing points available for the purpose. The only way to characterize the module is through the OTA method.

Traditionally, a bulky chamber along with one or more mechanical positioners needs to ensure the device under test's (DUT's) radiation pattern can be measured correctly and precisely, as shown in **Fig. 5**[7]. More recently, a compact antenna test range (CATR) technology has reduced the size of the chamber but still retains the same concept of mechanical parts and testing items based on radiation patterns shown in **Fig. 6**[8]. The approach used for decades has become an industry standard for research and design. However, in the coming 5G era, the number of devices to be tested on the product line will overwhelm this old technology. A traditional chamber or CATR is a good tool for research and design purposes, but it is too slow and bulky for production lines. For example, the latest technology in the industry can get a pattern in about a few minutes, which is impressive if we compare it to our predecessors with a half-hour or longer testing cycles. However, achieving the level of seconds is still not guaranteed. Furthermore, the nature of mechanical positioners makes automation integration in product lines not a straightforward task.

A new method for OTA measurement of production lines is built for 5G millimeter-wave beamforming antenna arrays by TMYTEK[9]. It adopts different approaches to meet the production demands of millimeter-wave AiP modules. The mechanical positioner is removed to speed up the OTA testing time. TMYTEK's BBox™ technology is used to measure the RF performance of a millimeter-wave module or device, including error vector magnitude (EVM), EIRP, frequency error, adjacent channel leakage ratio (ACLR), etc. [10-11]. The system architecture is shown in **Fig. 7**. The main idea is to measure AiP with another beamforming array (BBox™). This topology requires the calibration process to eliminate the phase and amplitude errors due to the angular misalignment between the two antenna patterns. The results are measured by a signal analyzer with a signal generator and integrate the up/down converters (UD Box) to down-convert the millimeter-wave signal to lower frequency. The measuring time is dramatically decreased since the scanning is done by electronic control.



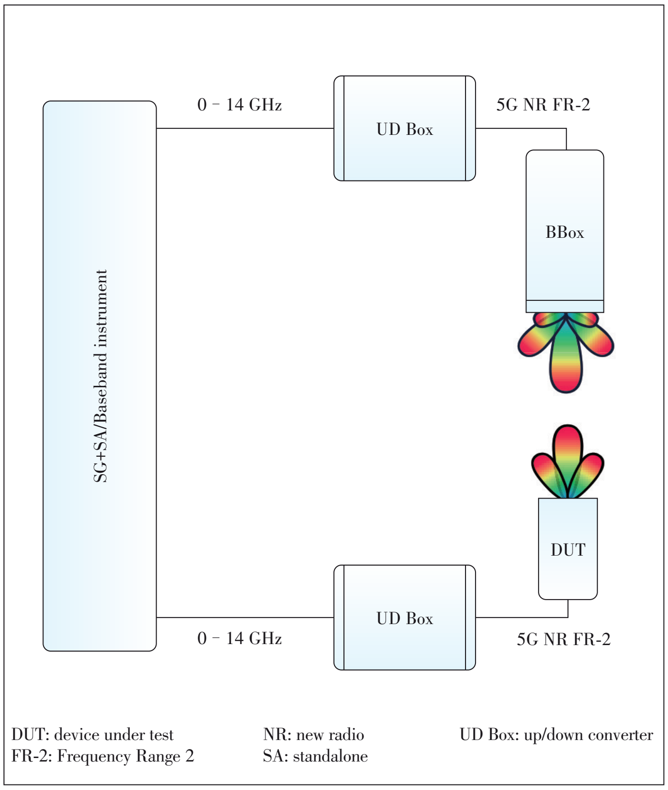
▲**Figure 5. Traditional Over-the-Air (OTA) chamber system.**



▲**Figure 6. Compact antenna test range (CATR) chamber system.**

3 Design Example

TMYTEK cooperated with NTK Technologies, Inc.[12], a Japanese LTCC technology company. A 4 × 4 LTCC unit AiP module for the 5G FR2 n261 band (27.5 – 28.35 GHz) has been designed by TMYTEK and manufactured by NTK. A larger 8×8 array is also demonstrated by tiling up to four-unit modules on one single motherboard. For the design of 5G NR millimeter wave beamforming antenna array, the size of the antenna array could be very different, i.e. 4 × 4, 8 × 8, 16 × 16, even larger, for different applications. Therefore, the modularization meth-

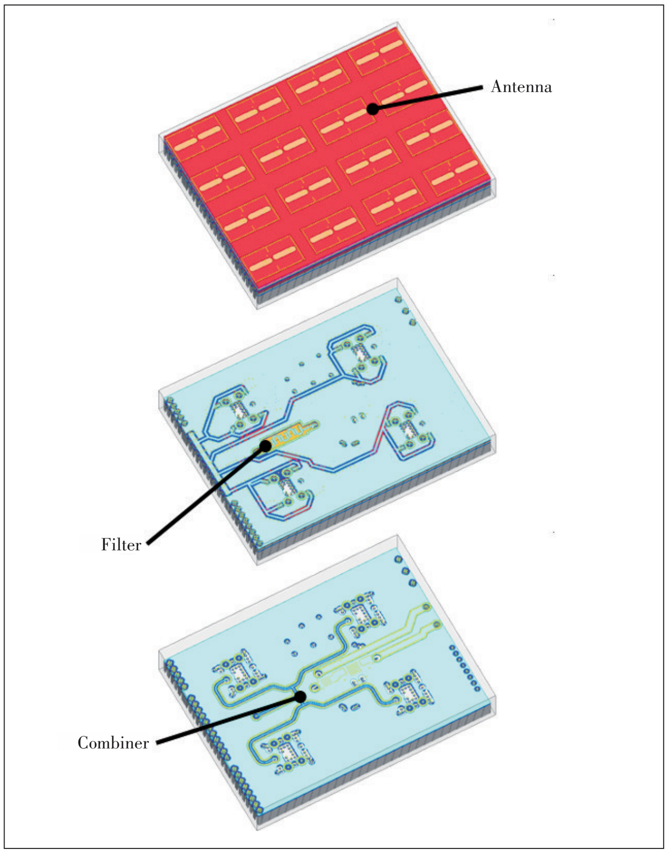


▲**Figure 7. New over-the-air (OTA) system.**

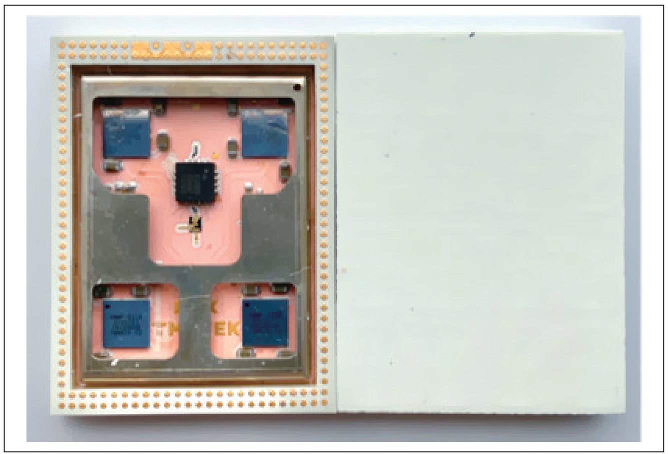
od provides a better way to configure a phased array system for adapting different dimensions of antenna arrays.

A 4 × 4 LTCC antenna-in-package front-end module (AiP FEM) is presented in this paper, along with the 28 GHz 8 × 8 phased array system which is fully integrated with four 4×4 AiP FEMs, an up/down converter and a phase-locked oscillator. The AiP FEM is fabricated with a 26-layer LTCC process by NTK. It is integrated with four 4-channel beamformer chipsets, power combiner, filter, mixer, frequency doubler and sixteen substrate integrated waveguide (SIW) antennas. **Fig. 8** shows three layers of the 26-layer LTCC AiP FEM. The input and output ports are the transmitting/receiving IF signals, LO source, digital control signals and DC power supply. The phase and amplitude of each antenna channel can be controlled independently for beam steering and beam shaping capabilities. The serial peripheral interface (SPI) control interface is used for fast control of beamforming characteristics, and the highest SPI clock rate has reached 50 MHz. The dimension of AiP FEM is 29.3 × 22.1 × 4.1 mm^3 (**Fig. 9**). The cavity shown on the backside is designed for easy mounting of devices to form a different size of the phased array using these modularized AiP FEMs.

The 8 × 8 phased array system was integrated using four AiP FEMs mounted on the motherboard. For obtaining better phase noise, the local oscillator source was not embedded in the AiP FEMs; instead, they are integrated into the motherboard. **Fig. 10** shows the integrated system photo. There are two fans placed beside the AiP FEMs, which are not shown on the photo, to have better heat dissipation.



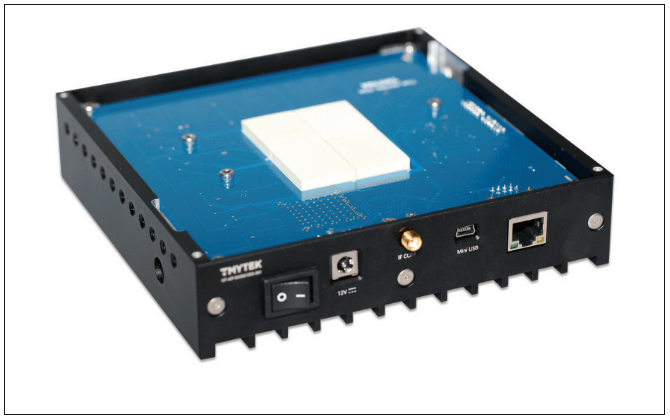
▲**Figure 8. Three layers of the 26-layer low temperature cofired ceramic (LTCC) antenna-in-package front-end module: antenna, filter and combiner.**



▲ **Figure 9. Top and bottom view of the 26-layer low temperature cofired ceramic (LTCC) 4 × 4 antenna-in-package front-end module for 28 GHz band.**

4 Conclusions

The design of millimeter-wave antenna-in-package is discussed and an example from TMYTEK is presented in this paper. The millimeter-wave technology has become more and



▲ **Figure 10. 8 × 8 phased array system integrated with four antenna-in-package front-end modules.**

more important for communications and radar applications. Thus, the considerations for AiP mass production are very critical for having better system performance and lower cost. This paper has discussed the manufacturing technologies and materials. Moreover, the importance of the OTA measurement solution is highlighted. TMYTEK has developed the best OTA solution for AiP mass production to accelerate the development of 5G millimeter-wave industries.

Acknowledgment

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References

[1] ZHANG Y P. A review of the development of antenna-in-package technology [J]. ZTE technology journal, 2017, 23(6): 41–49. DOI: 10.3969/ j.issn.1009-6868.2017.06.010

[2] ZHANG Y P, LIU D X. Antenna-on-chip and antenna-in-package solutions to highly integrated millimeter-wave devices for wireless communications [J]. IEEE transactions on antennas and propagation, 2009, 57(10): 2830–2841. DOI: 10.1109/tap.2009.2029295

[3] DJERAFI T, WU K. Multilayer integration and packaging on substrate integrated waveguide for next generation wireless applications [C]//46th European Microwave Conference (EuMC), London, UK: IEEE, 2016: 858–861. DOI: 10.1109/eumc.2016.7824479

[4] ZHANG Y P. Recent advances in antenna-in-package technology [J]. ZTE technology journal, 2018, 24(5): 47–53. DOI: 10.19729/j.cnki.1009-6868.2018.05.010

[5] HUSBY H. High density interconnect [EB/OL]. [2020-05-01]. https://www.datarespons.com/high-density-interconnect

[6] JAWORSKI G, KROZER V. A design of feeding network for a dual-linear polarization, stacked, probe-fed microstrip patch antenna array [C]//15th International Conference on Microwaves, Radar and Wireless Communications, Warsaw, Poland: IEEE, 2004: 473–476. DOI: 10.1109/mikon.2004.1357069

[7] ATENLAB. OTA [EB/OL]. [2020-05-01]. https://www.atenlab.com.tw/article-OTA.html

[8] ATENLAB. CATR [EB/OL]. [2020-05-01]. https://www.atenlab.com.tw/article-CATR.html

[9] CHANG S.W. New method of OTA measurement for 5G mmWave beamforming antenna array [C]//Asia-Pacific Microwave Conference. Singapore, Singapore, 2019

[10] TMYTEK. Bbox [EB/OL]. [2020-05-01]. https://www.tmytek.com/product/bbox

[11] TSUTOMU Tokuke. 5G test challenges [EB/OL]. [2020-05-01]. https://www.tele.soumu.go.jp/resource/j/equ/mra/pdf/30/e/11.pdf

[12] NTK. TMYTEK cooperated with NTK Technologies [EB/OL]. [2020-04-20]. http://www.ntktech.com

Biographies

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LIN Chueh-Jen is a serial entrepreneur who has founded three companies since 2007. He is the VP and co-founder of TMYTEK, a start-up company that focuses on 5G mmWave solutions. He leads the software technology and marketing teams and helped the company successfully raise pre-A and A funds. Before TMYTEK, he founded Scarlet Tech, a successful IoT company still running today. He ever worked for the smartphone maker HTC and cooperated with Microsoft and Qualcomm closely in software and wireless communications. He built the world's largest infrared telescope (WIRCam) for CFHT in Hawaii in the first job. He received the master's degree in electronics engineering on Quantum dots IR detectors from Chiao-Tung University, Taiwan, China.

TSAI Wen-Tsai received the B.S. degree in electrical engineering from Kaohsiung Marine University, Taiwan, China in 2002, and the M.S. degree in electrical engineering from Feng Chia University, Taiwan, China in 2004. He has five years of experience in the antenna-related design, including the wireless local-area network (WLAN) antenna, global position system (GPS) antenna, mmWave circuit, 5G small cell, 5G AiP module, mobile antenna and antenna diversity. Moreover, he set up the far-field antenna pattern measurement systems (in anechoic chamber) and control program and has nine-to-ten years of experience in the design of Ku and Ka bands circuits, as well as the design, fabrication and measurement of low-noise amplifiers, mixers, filters, phase-lock loop (PLL) and dielectric resonant oscillator (DRO) circuits, integrated the horn antennas. He also has rich experience in HSpice simulation of active circuits.

HUNG Tzu-Chieh received the B.S. degree in electrical engineering from Feng Chia University, Taiwan, China in 2006, and the M.S. degree in electrical engineering from Central University, Taiwan, China in 2008. During college, he participated in ASIAA student program and joined the Yuan-Tseh Lee Array (YTLA, formerly AMiBA) project. He started his professional career at Lite-On technology Inc. in 2009, where he was an antenna designer. From 2013–2015, he was an RF engineer with Ubiqconn technology Inc. In March 2015, he joined TMYTEK Inc. as a RF/mmWave system designer and has become an R&D manager in February 2020. His research interests include mmWave circuit design and system integration.

HUANG Po-Chia has rich experience in embedded system software development and digital signal processing and now focuses on software system and architecture design with TMYTEK. Before TMYTEK, he joined Scarlet Tech at the end of 2014 for building up IoT solutions in safety industry. His expertise is in MCU programming and a variety of protocol stacks for wireless technologies, such as BLE and LoRa. In 2011, he worked at HTC and took responsibility of mobile graphic framework and relevant BSP for a customized mobile OS on Qualcomm Snapdragon 600. He received the master's degree in electrical and control engineering on DSP and embedded system development from Chia-Tung University, Taiwan, China.