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Antenna-in-Package (AiP) Integration Strategies for High-Frequency RFICs in 5G/6G Edge Devices: Design Challenges, Performance Trade-offs, and Future Opportunities

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ABSTRACT

Within the context of super-fast development of 5G and perceived use of 6G wireless networks, the rate at which small, high-frequency and power efficient Radio Frequency Integrated Circuits (RFICs) that can drive edge intelligence grows fast. An attractive candidate solution is known as the Antenna-in-Package (AiP) technology, which is the concept of integrating both RF transceiver and antenna groups in the same, miniaturized component to reduce parasitic losses and provide a better performance at millimeter-wave (mmWave) and sub-THz frequencies. This paper seeks to explore the state-of-the-art AiP-based solutions to the high-frequency RFICs in the 5G/6G edge devices. The overall approach synthesizing the tools of literature review,comparative analysis, and the electromagnetic simulation considerations is used to determine the significant design bottlenecks. The most important of these difficulties are electromagnetic interference, heat risen outflow, interconnect dispenses, and constraints in substances material. Antenna gain versus beam-steering fidelity graph and form factor versus cost graph are performed. Other technologies discussed in the review include advanced packaging concepts, which include fan-out wafer-level packaging (FOWLP), system-in-package (SiP) and 3D heterogeneous integration. The paper finds a conclusion by pointing out some new research challenges such as reconfigurable AiPs, AI-enabled co-design processes, co nformal flexible packages, and sub-THz antenna arrays to be used beyond 6G. The results herein offer a great basis of future research and implementation of next-generation wireless edge systems with scalable, high-performance AiP architectures to the industry.

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INTRODUCTION

The advent of new-fangled wireless applications like ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communications (mMTC) in 5G - and future 6G services and services like holographic telepresence, immersive XR, and intelligent edge computing - have produced an urgent need to diminish size, energy use, and frequencies of RF front-end structures. At millimeter-wave (mmWave) and sub-terahertz (sub-THz) frequencies, common PCB-based antenna implementations have a significant problem of low performance caused by parasitic effects, signal loss, and space limitation. Antenna-in-Package (AiP) technology overcomes these issues as the antennas are closely integrated with the RFICs at the same substrate or 3D stack and, thus, provides low interconnect losses, lower size and supports high performance beamforming and phased array designs.[6] Although there have been some promising prototypes and commercial demonstrations, existing studies tend to ignore some of the critical considerations including the thermal reliability at high levels of integration density, electromagnetic isolation capabilities with multiple layers, and the co-design approaches, which consider both electrical performance and mechanical performance at the mmWave band. Additionally, introduction of AiP on the edge adds a new dimension of dealing with performance, cost and manufacturability tradeoffs on a dynamic edge workload.

The question of how to combine these into a coherent design framework is only now starting to be addressed, but material and thermal issues, reconfigurability of the antenna array, and effects of package-induced signal distortion all remain understudied.[1] The purpose of this paper is to fill it by giving an in-depth description of AiP integration approaches, trade-offs, and new opportunities in edge device applications of 5G/6G.

Related Work

Lately, Antenna-in-Package (AiP) technologies are an emerging solution to the problem created by traditional PCB-based or off-chip antenna design, in particular very high frequencies in the millimeter-wave (mmWave) and sub-terahertz (sub-THz) portions of the electromagnetic spectrum. The higher integration density and communication rates in 5G and future 6G systems factor in AiP providing much improved coupling of antennas and RFICs compared to conventional interconnects based on Green-House concepts, resulting in minimized loss, greater bandwidth and small scale factor.

Lee et al.[2] discussed design considerations to be employed in 28 GHz AiP modules designed to support 5G applications in beamforming. Their work was able to show less insertion loss and higher radiation efficiency through the use of multilayered organic substrates. Nevertheless, they did not pay enough attention to thermal mitigation measures, which is an essential consideration of edge node deployment in high-density packaging circumstances.

Hien et al.[3] fabricated a FOWLP AiP system operating at 60 GHz to be used with near-term communications over short distances. The architecture recorded high miniaturization and gain, but it had reliability problems which were caused by via fatigue as well as substrate warpage that were important in the experience of long-time deployment in industrial edge applications.

Kang et al.[4] have introduced an LTCC-based AiP as an element of automotive 77 GHz radars. Although the design could provide excellent electromagnetic isolation as well as gain stability, the complexity of manufacturing and high cost of LTCC technology are not suitable to deploy to commercial edge products at scale.

Another reconfigurable AiP (28/39 GHz) capable of dynamic beam switching was demonstrated by Liu et al.[5] Effective frequency agility was enabled, but the system was susceptible to congestion in the routing of control signals, and also to greater electromagnetic interference because of inadequate isolation between RF transmission paths and control signals.

Majority of the foregoing have been aimed at ensuring optimal electrical performance among others via advanced materials and layout optimisation. Nonetheless, there is not much work that has been done on a large scale in terms of multi-domain co-design, giving attention to the thermal, electromagnetic, mechanical, and AI-aided system-level integration. Additionally, other issues like 3D heterogeneous integration, conformal AiP (flexible electronics), and sub-THz scalability are underdeveloped, at least as far as 6G (and beyond) is concerned.

This paper will contribute to these. Underlying drivers, including future-proofing, eminent EM intrusion on RFIC performance, and comparing AiP designs that support beamforming schemes, are discussed in an integrated package.

Fundamentals of AiP for mmWave RFICs

Principle of AiP Integration

To date, the architecture behind the Antenna attached on or being part of the packaging substrate that is concealing the Radio Frequency Integrated Circuit (RFIC) is known as Antenna-in-Package (AiP) technology. AiP allows physically mounting the antennas closer to the active RFIC circuitry as opposed to the traditional design where antennas are attached to printed circuit boards (PCBs) which are outside the RFIC. This will reduce the parasitic losses, interconnect distance and allow greater integration density- a critical need at millimeter-wave (mmWave) and sub-terahertz (sub-THz) frequencies, where layout dependant signal attenuation is extremely sensitive. The figure 1 shows the structural layout of Flip-Chip, FOWLP, and SiP techniques that indicates such trade-offs continue between compactness, routing complexity, and phased-array capability.

There are three main AiP integration strategies which are in prevalent use:

- Flip-chip Packaging: Here, the RFIC chip is one that is bonded face down on the package substrate with use of short and low-inductance interconnections. It is possible to make antennas on the other side of the substrate or through redistribution layers (RDLs).

- Fan-Out Wafer-Level Packaging (FOWLP): This technology gives higher flexibility in routing because the I/O pads are rearranged on an epoxy mold compound, such that antennas and passives can be co-integrated with the RFIC through a small footprint.
- System-in-Package (SiP): A design and technology that integrates multiple chips (such as RFIC, baseband, power amplifiers) and embedded or surface-mounted antennas into a unit package with multi-layer interposers or LTCC substrates, allowing complex phased-array applications.

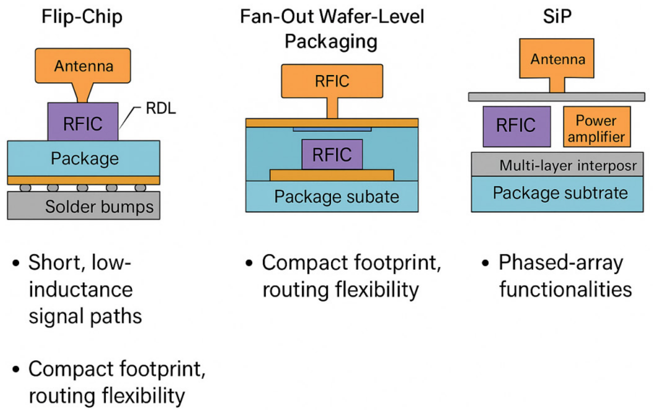

Fig. 1: Antenna-in-Package (AiP) Integration Approaches

These solutions are also maximized on signal integrity, scalability, and mechanical protection, which is essential in edge and portable systems. Also, AiP will support multi-beam, beam-steering, and massive MIMO designs that are key attributes of next-generation wireless networks.

Relevance to 5G and 6G Communication Systems

The mmWave and sub-THz portions of the spectrum intended to be used in 5G and 6G create large losses in the propagation process, large free-space path loss, and high sensitivity to component mismatches. AiP technology specifically eliminates these concerns by having short transmission lines and provides co-optimized EM-material-thermal component in the same form factor.

- 5G NR FR2 Bands: These bands comprise the frequency bands inclusive of 26 GHz (n258), 28 GHz (n257) and 39 GHz (n260), whereby AiP has already been successful in beamforming front-end modules in base stations, user equipment and CPEs (Customer Premises Equipment).[7]
- 6G Candidate Bands: The 6G systems are envisaged to span up to 300 GHz to 100 GHz, including D-band and G-band, which will need the exceptionally high accuracy in terms of packaging. It is supposed that AiP will play a pivotal role, as it enables ultra compact arrays, sub-wavelength spacing of elements and multi-functional electromagnetic layers.

In addition to insertion loss, AiP also deals with:

- Antenna Footprint: An absolute must in smartphones, IoT sensors and AR/VR headsets all have limited surface area.
- System Latency: The group delay and response time in the system can be minimized by use of shorter interconnects and embedded signal routing tracks.
- Thermal Management Synergy: Integration enables co-design of the thermal behavior and the EM behavior via embedded heat sinks or vias.

Therefore, AiP presents a reasonable way out of scaling up high-frequency RFICs, which can address the challenges of 5G and prospective 6G wireless edge systems in terms of compactness, efficiency, and reconfigurability. Figure 2 illustrates that AiP technology can be the key to the deployment of high performance RFICs in the bands used by current 5G FR2 and future 6G bands across the spectrum as well.

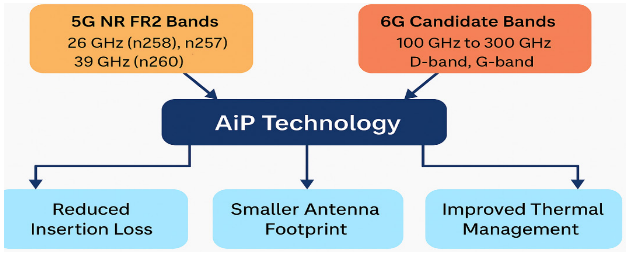

Fig. 2: Relevance of Antenna-in-Package (AiP) Technology for 5G and 6G

DESIGN CHALLENGES IN AIP IMPLEMENTATION

Antenna-in-Package (AiP) technology is an emerging solution that promises to deliver a range of benefits to compact mmWave and sub-THz systems; however, its commercial use makes it comparable to multi-domain design complexities thanks to electromagnetic (EM), thermal, material and interconnect complexities. Such issues become magnified when such systems are scaled up to dense 5G/6G edge deployment patterns.

Electromagnetic Coupling and Isolation

EM radiation pattern coupling between antennas (inter-antenna) and EM radiation pattern coupling between active RF blocks (e.g., PAs, LNAs) may negatively impact radiation patterns and precision of beamforming even in more densely occupied AiP arrays. The inter-element spacing is smaller than wavelength, which increases mutual coupling in phased-array systems. Reduction measures refer to

- substrate isolation trenches, EM shielding planes and ground planes.
- Optimization of co-simulation of full-wave EM (e.g. CST, HFSS).

Substrate Material Selection

Signal loss and thermal reliability are directly affected by the dielectric characteristics of substrate material. Common options:

- LTCC: Very good RF performance, very high cost.
- Glass interposers: RoHS, RoHS-free Low loss, High I/O density, Fragile [8].
- Organic e.g., ABF: Has low cost but can be scaled to have high dielectric losses.

Stacking of multi-layer RDL and dielectric is employed to find a compromise between manufacturing and performance.

Thermal Management

High-power RF output AiP modules in miniaturized form result in the formation of hot spots and the drift of frequencies. Thermal management is effective when it incorporates:

- thermal vias, heatsink (e.g. AlN)
- Phase-change materials (PCMs),
- Co-simulation tools incorporating the EM and thermal modeling,
- Passive cooling of edge devices due to limited space.

Interconnect Losses and I/O Density

The signal degradation is caused by mmWave interconnect parasitics (in the form of reflection, skin effect, and RC delay). Solutions include:

- TSVs in order to minimize vertical inductance,
- Fan-out and RDL based routing to improve SI/PI,
- Multimode high density silicon interposers.

RF switching is an important component to operation robustness and switching is done dynamically with I/PI co-optimization.

Charts and checklists

- Table 3 Comparison of LTCC, Glass and Organic substrate materials.

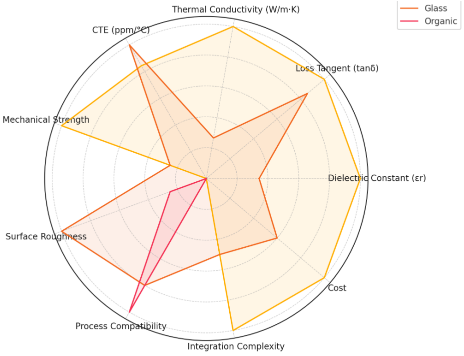

Fig. 3: Radar Chart Comparison of AiP Substrate Materials

Table 1: Comparative Properties of Packaging Substrates for AiP Implementation

Property	LTCC (Low-Temperature Co-Fired Ceramic)	Glass Substrate	Organic Substrate (e.g., ABF, BT)
Dielectric Constant (εr)	~5.8-7.8	~4.5-5.0	~3.0-4.2
Loss Tangent (tan δ)	0.0005-0.002	0.0003-0.004	0.005-0.01
Thermal Conductivity	2.5-4.5 W/m·K	~1.0-1.5 W/m·K	0.3-0.6 W/m·K
Coefficient of Thermal Expansion (CTE)	5-8 ppm/°C	3-5 ppm/°C	15-25 ppm/°C
Mechanical Strength	High (rigid, brittle)	Moderate (brittle)	Moderate (flexible)
Surface Roughness	Moderate	Very Low	Low
Process Compatibility	Limited to RF-specific processes	Excellent for fine-line RDLs	Compatible with high-volume PCB fabrication
Integration Complexity	High (multilayer co-firing, costly)	Medium (fragile, needs protection)	Low (easily stackable and routable)
Cost	High	Medium	Low
Typical Applications	Automotive radar, aerospace modules	3D integration, interposers	Smartphones, consumer IoT

- Table 1: AiP-Packaging trade-offs substrate survey.

A comparison of LTCC, glass, and organic substrates based on critical parameters such as dielectric constant, loss tangent, thermal conductivity, coefficient of thermal expansion (CTE) mechanical strength, and surface roughness as well as process compatibility, integration complexity and cost was normalized. This plot shows the trade-offs such that RF performance, heat management, manufacturability, and economic feasibility in 5G/6G AiP application will be covered.

PERFORMANCE TRADE-OFFS

Although the Antenna-in-Package (AiP) technology has enormous advantages in high-frequency RFICs on 5G /6G systems, its realization has key trade-offs that need to be weighed with respect to performance, cost, and complexity of integration.

Size vs. Integration Complexity

Instead of decreasing footprint by 25% or so, AiP offers a major footprint reduction by integrating the antenna into the package-this works wonders with small devices (smartphones, wearables, drones).[9]

Trade-off: The high integration density also demands accurate multilayering processing, narrow tolerances and sophisticated packaging to make production process costly and intricate.

RF Loss vs. Thermal Management

AiP improves RF loss and signal path, therefore, enhancing gain and an integrity of signal by removes bond wires.

Trade-off: Since the RFIC and antenna are closely situated, there will be a buildup of heat. Where there is no proper heat dissipation, hotspots can become detrimental to the reliability and frequency drift may develop as a consequence of these hotspots.

Beamforming vs. Routing Congestion

AiP allows smaller phased arrays, which are important to 5G/6G as they support beam-steering and massive MIMO to provide agility in link connections.

Trade-off: Layout congestion, crosstalk and increased design cycles result when many RF routing paths and phase-control lines are concentrated in a small area.

Cost vs. Volume Scalability

Wafer-level and fan-out packaging enable low cost and fewer assembly stages in the high-volume manufacturing processes.

Trade-off: NRE is costly to develop early e.g. mask, simulation, custom packaging, therefore not preferable to be used when an AiP is needed during prototyping or/ and at low volumes.

Though as noted in Table 2, AiP offers commendable advantages in integration and RF efficiency, AiP demands close attention to fabrication complexity, thermal behavior, and development expenses out-front of the product development stage.

Table 2: Performance Trade-Offs in AiP-Based RFIC Systems

Parameter	AiP Advantage	Trade-Off
Size & Integration	Reduced system footprint	Complex fabrication
RF Loss	Minimized interconnect losses	Increased thermal density
Beamforming Capability	Easier integration of phased arrays	High routing complexity
Cost	Lower at volume scale	High NRE for initial prototyping

RECENT ADVANCEMENTS IN AIP ARCHITECTURES

The Antenna-in-Package (AiP) technology has evolved to the phase of adaptive, intelligent and heterogeneous structures that become compatible with high requirements of 5G/6G standards. The latest developments are motivated by the requirements of enhanced spectral efficiency, dynamic reconfigurability, and smaller multi-purpose systems in the mmWave (mmWave) and sub-terahertz (sub-THz) frequencies. In the next subsections, significant milestones in the use of AiP are outlined.

Beam-Steerable AiP Arrays

Directional communication and massive MIMO in dynamic settings cannot be done with out beam-steerable AiP architectures. These components incorporate hybrid analogdigital beamforming as part of the package thus enabling control over beam direction, beam width and beam gain in real time (see Figure 4).

Key Applications:

- 77 GHz vehicle radar to navigate.
- 5G base stations 28/39 GHz mmWave.
- AR/VR/edge devices with low radio phased arrays.

The AiP substrate also includes integrated phase shifters, power dividers, and low-loss feed networks to minimize interconnect delays and make it possible to implement beam steering with compact, high-agility phase shifters. Also more accurate speed is achieved by the enhancement of machine learning based beam training and the codebook design that is adaptive.

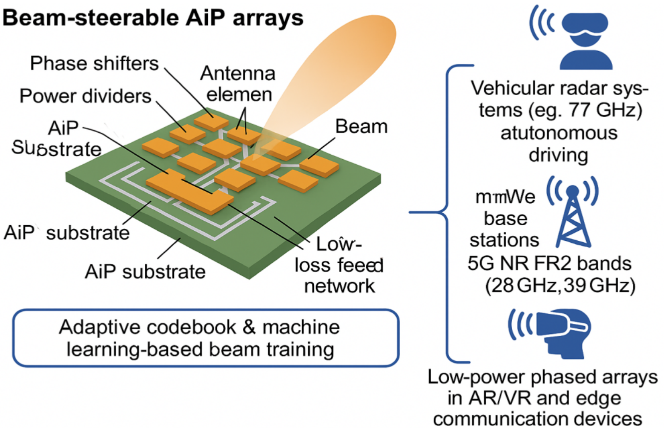

Fig. 4: Beam-Steerable Antenna-in-Package (AiP) Arrays for Directional mmWave Applications

Reconfigurable and Tunable AiP

In wireless systems nowadays, the need of multi band and adaptive antenna means that reconfigurability is a requirement. Reconfigurable AiP modules insert MEMS switches or varactors or liquid-metal tuners to tell volumes to tune on the fly:

- The resonance (agility),
- Shortening the reconfiguration delay
- Polarization (multipath resilarity).

This combination is shown in Figure 5, with these elements being embedded or co-packaged alongside the RFIC to also provide low-loss, fast-switching performance appropriate to cognitive radios, intelligent surfaces and adaptive 6G links.

Challenges include:

- Making sure of the thermal stability
- The effectiveness of resolving the tuning problem of linearity under tuning bias
- Reducing the delay of reconfiguration

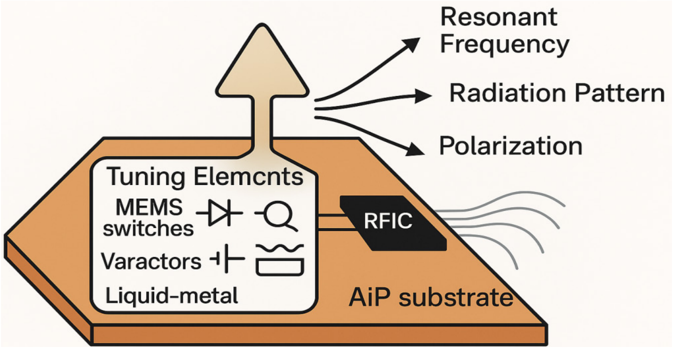

Fig. 5: Reconfigurable and Tunable Antenna-in-Package (AiP) Architecture

The tunable AiPs-based solution is a potential solution to spectrum-aware and environment-adaptable wireless front-ends in spite of the challenges in the field.

3D Heterogeneous Packaging

In order to satisfy the increasing requirements of functionality in miniature edge equipment, an integration of 3D heterogeneous AiP integration is done to vertically co-package logic die, the RF die and the memory die. This architecture facilitates AI-based beamforming where low latency and power constraints are used in the setting, as demonstrated in Figure 6.

Integration approaches:

- 2.5D silicon interposers (lateral die placement),
- Daigaku-vitaku of 3D-TSVs.

Key benefits:

- Density of interconnection to be high in order to reduce latency,
- Footprint optimization of chipletSoC.
- Avoidance of thermal/power domain through the partitioning of the substrate.

The approach supports the fusion of edge AI and RFIC to permit on-package learning and prediction of beam and mitigation of interference.

New directions of research are being unveiled; they regard chiplet synergy, wafer-on-wafer bonding, and optimization of floorplanning through AI to scale 3D AiPs to mobile, satellite, and IoT systems.

Simulation and Measurement Insights

Advance design and verification of Antenna-in-Package (AiP) systems require a co-optimized simulation-measurement process that encompass all the three

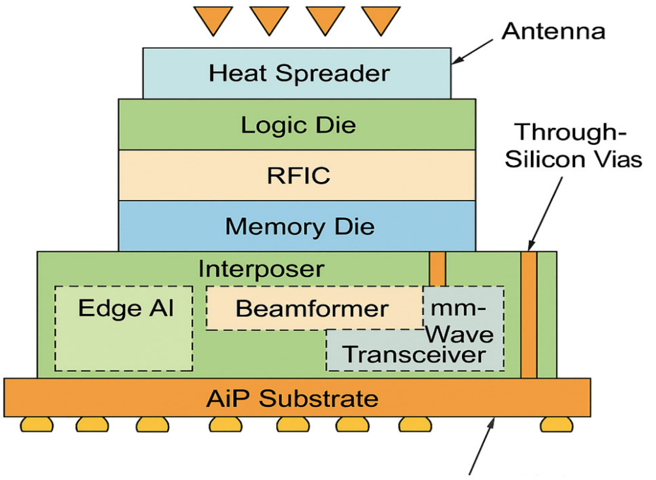

Fig. 6: 3D Heterogeneous Integration in Antenna-in-Package (AiP) Architectures

domains of electromagnetic (EM), thermal, and system levels. The finest simulation environments, like ANSYS HFSS, Keysight ADS, and CST Studio Suite, lead the way to refine characteristics of antenna, interconnect behavior as well as package parasitics.

EM and RF Performance Simulation

HFSS and CST simulators and other high-frequency structures simulators are widely applied in the analysis of 3D electromagnetic fields and optimization of the most critical performance parameters such as reflection coefficient (S11), radiation efficiency, beamwidth, gain patterns and mutual coupling between antenna elements. These tools provide support of both parametric optimization and sweep based optimization to result in accurate tuning to resonance at desired frequencies such as 28 GHz or 39 GHz but with the requirement that the return loss be kept below -10 dB. They also emulate the effect of dielectric stack-up, package metallization, and the radiation behavior and array beam performance. The layout illustrated in Figure 7 is one with the antenna and RFIC inverted (where both the antenna and RFIC are integrated vertically on a common AiP substrate) with a focus on compact packaging and a signal path minimization company network (Elhawary and Sharma, 2007).

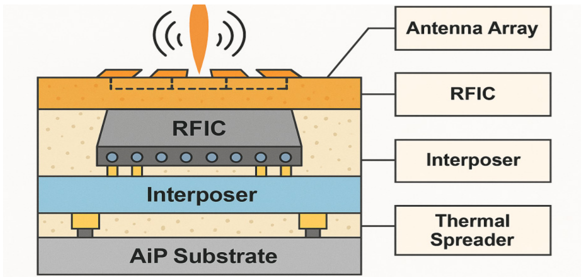

Fig. 7: Cross-Sectional Schematic of AiP Stack

Thermal and Structural Co-Simulation

Driven by the peak transmission state, the AiP modules tend to experience certain localized thermal hotgates that can degrade both RF performance and long-term reliability. The simulations of COMSOL Multiphysics can be used to simulate the Joule heating impacts of bias currents, dielectric loss effects caused by RF, and heat transfer across layers e.g. interposer, die attach, and substrate. The simulations can assist in visualizing the thermal gradients and the verification that the temperatures of components do not exceed the thermal limits of materials in order to avoid any phase shifts in impedance of antennas and functional failure of the RFIC. The simulated and measured curves of return loss and gain are in good agreement over the 26 30 GHz band as shown in Figure 8 and this results in thermal stability and model accuracy.

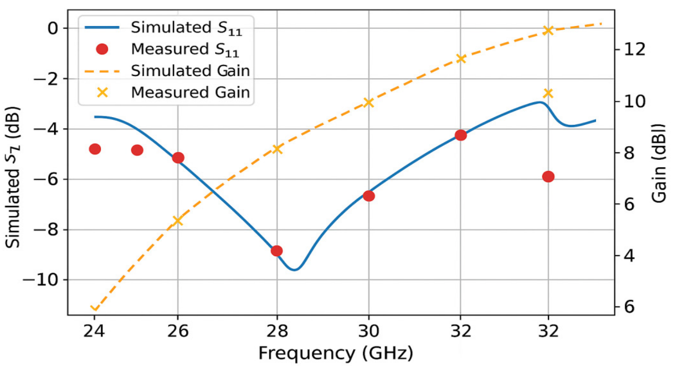

Fig.8: Simulated vs. Measured S₁₁ and Gain at 28 GHz

Simulated and measured plot of return loss (S 1 1) and peak gain of a 4 x 1 AiP phased array at 28 GHz. By running at this high echelon the accuracy and package inception loss of EM models are confirmed.

Experimental Validation: OTA and Probe-Based Measurements

Anechoic chambers are used to characterise the AiP performance through On-SILO or On-Package RF probing to directly measure S-parameters and over-the-air (OTA) testing to characterise beam patterns and gain in mmWave frequencies. The validation is usually performed based on calibrated Vector Network Analyzer (VNA) measurements, based on either SOLT or TRL calibration, as well as scan of near- and far-field radiation patterns to measure gain, EIRP, and polarization purity. These thermal hotspots (as in Figure 9) near the RF feed-line, you find very much the necessity to be thermally-aware in the layout approach of AiP implementation in order to have reliability and consistent performance under high-power operation.

OPPORTUNITIES AND FUTURE RESEARCH DIRECTIONS

AI-Driven Co-Design

Joint optimization of the EM and thermal design of AiPs is being achieved through machine learning methods like

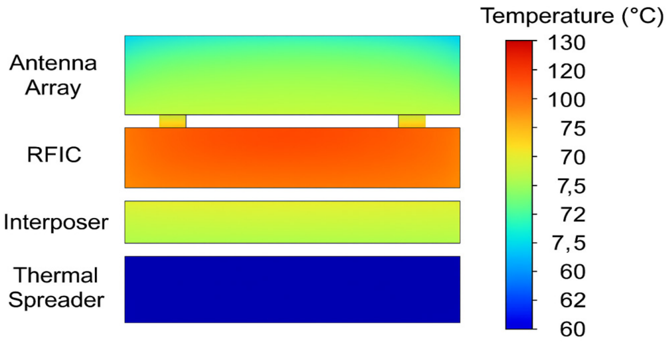

Fig. 9: Thermal Simulation Profile Under Peak Load

neural metaheuristics and surrogate modeling. These methods achieve a result of decreasing the cycle of simulation and maximize the layout usage by instructing the location of the RFICs and antenna options under thermal limits. Future studies could take advantage of the physics-informed neural networks (PINNs) to perform adaptations in real-time to the beam as well as optimization in-situ.

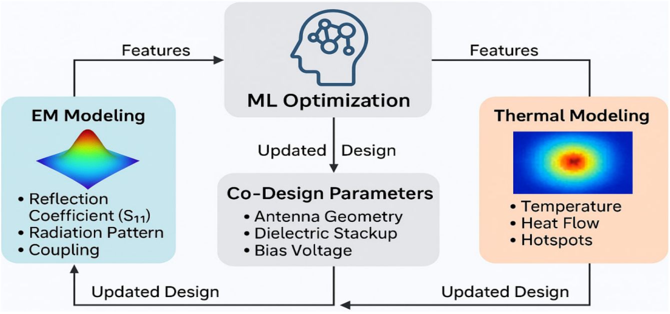

Fig. 10: AI-Based Co-Design Workflow for Thermal and EM Optimization.

Conformal and Flexible AiPs

These new applications in wearables and AR/VR are fueling the emergence of AiPs on flexible substrates such as polyimide, LCP and PDMS. The stretchable antennas and interconnects as well as embedded sensors are incorporated in these platforms. The most apparent issues will be the impedance matching under deformation and the EMI shielding in the dynamic environment.

Sub-THz AiPs for 6G

Research has now expanded AiP technology up to 140-300GHz to address high data rate wireless backhaul, chip-to-chip communications and LiDAR-on-package modules. The hybridization with InP, BiCMOS and photonic technology is also critical towards the reduction of phase noise as well as the increment of radiation efficiency. The weaknesses include the packaging parasitics and fabrication allowance.

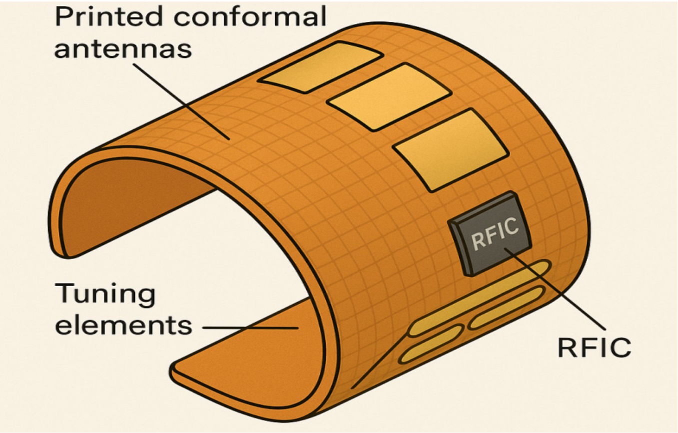

Fig. 11: Flexible AiP with Printed Conformal Antennas on a Wearable Substrate.

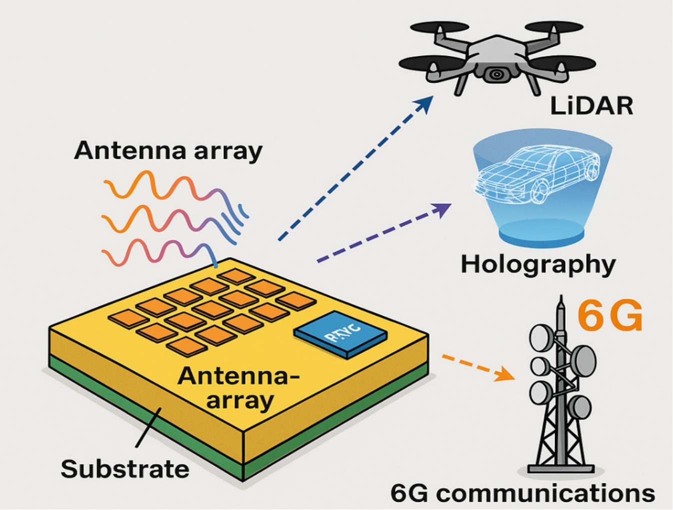

Fig. 12: Sub-THz AiP Concept for Holography, LiDAR, and 6G Communications.

Conclusion

Antenna-in-Package (AiP) technology is becoming an essential feature of high-frequency, miniaturized, and multi-functional wireless front-ends in what is becoming the 5G and future 6G era. Its own potential to multifunction antennas, RFICs, and passive elements in a miniature footprint considerably decreases connector misfortunes, improves functionality, and upholds beamforming and reprogrammable abilities in the mmWave and sub-THz bands.

Although there are promising benefits associated with AiP design, it is still plagued with electromagnetic coupling, thermal limitations and substrate magnetic material restrictions, once operating frequencies pass the 100 GHz mark. These challenges require a holistic and multi-physics co-design which can factor and alleviate such trade-offs between the EM, thermal and the mechanical worlds.

The solution to this conundrum lies in 3D heterogeneous integration and chiplet-based systems, which offer a new and scalable modular AiP platform that integrates logic, RF and AI cores into a single package. Moreover, combining machine learning-based co-design, soft substrates, and adaptable radiating structures provides new frontier and possibilities in intelligent, adaptive, and application-specific radio modules.

Future work must be focused on making the most of AiP in next-generation wireless, and edge intelligent systems:

- Innovation of the materials (e.g., low-loss, thermally conductive and flexible substrates),

- EM, thermal, and AI platform inter-system co-simulation,
- High-packaging level, interconnection (e.g. TSV, wafer-level packaging),
- Dependable fabrication techniques that are able to take mass manufacturing and environmental strength.

To conclude, the combination of the overall technology of packaging, artificial intelligence, and developing materials will be essential in the paving the way to the next iteration in scalable, reconfigurable, high-efficiency AiP systems in ultra-broadband communications.

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