SCIENCE CHINA
Information Sciences

• LETTER •

November 2026, Vol. 69, Iss. 11, 219307:1–219307:2
https://doi.org/10.1007/s11432-025-5061-8

A THz omnidirectional AiP system based on hybrid wafer-level packaged process for chip-to-chip wireless interconnect applications

Yafei WU[1,2*†], Gang ZHUANG[1,2†], Sirui LIU[1,2], Shuli LIU[3], Yuhang YIN[3], Peigen ZHOU[4], Jixin CHEN[4] & Yujian CHENG[1,2*]

[1]*School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*
[2]*Tianfu Wireless Intelligence Research Institute, Chengdu 611730, China*
[3]*The 58th Research Institute of China Electronics Technology Group Corporation, Wuxi 214035, China*
[4]*State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China*

Received 2 November 2025/Revised 5 March 2026/Accepted 24 July 2026/Published online 23 September 2026

Citation Wu Y F, Zhuang G, Liu S R, et al. A THz omnidirectional AiP system based on hybrid wafer-level packaged process for chip-to-chip wireless interconnect applications. Sci China Inf Sci, 2026, 69(11): 219307, https://doi.org/10.1007/s11432-025-5061-8

With the continued development of system-on-wafer (SoW) architectures, high-density integration of multiple chips within a compact footprint has become a promising approach to improving computing throughput. In such systems, however, chip-to-chip (C2C) interconnects increasingly emerge as a critical bottleneck in terms of bandwidth, latency, and scalability. Conventional wired interconnects suffer from severe bandwidth-density and delay limitations under large-scale integration, while optical interconnects introduce considerable energy overhead and system complexity due to electro-optic conversion. Moreover, both approaches rely on fixed physical routing, inherently limiting reconfigurability. Wireless interconnects enabled by integrated antennas exploit free-space electromagnetic propagation to establish broadband and reconfigurable links, offering a compelling alternative to conventional interconnect paradigms [1]. To simultaneously support compact antenna integration and ultra-wideband transmission, operation at higher frequencies is required. Millimeter-wave bands are constrained by limited spectral resources and antenna size, whereas the terahertz (THz) band provides abundant spectrum and naturally supports chip-scale antenna integration, making it a strong candidate for C2C wireless interconnects. In addition, SoW architectures often demand one-to-many communication, imposing stringent requirements on omnidirectional radiation performance. These factors collectively motivate the development of THz microsystems capable of omnidirectional wireless interconnects.

Antenna—chip integration is typically realized through antenna-on-chip (AoC) or antenna-in-package (AiP) approaches [2]. Although AoC offers high fabrication precision, its radiation efficiency is severely limited by the high dielectric loss of silicon substrates and constrained antenna profiles. AiP architectures decouple antennas from active circuitry through advanced packaging technologies, providing improved radiation performance and design flexibility [3]. However, most existing AiP implementations rely on a single process, such as fan-out wafer-level packaging (FOWLP) or glass-based platforms. FOWLP suffers from high dielectric loss and limited substrate thickness at THz frequencies, while glass-based processes offer low loss and controllable thickness but lack high-density I/O redistribution and multilayer integration capability [4]. Consequently, single-process wafer-level solutions struggle to simultaneously achieve high radiation efficiency, compact circuit integration, and stable omnidirectional performance.

To address these challenges, this work proposes a hybrid wafer-level THz AiP architecture for C2C wireless interconnects, as illustrated in Figure 1(a). The proposed system integrates a through-glass-via (TGV)—based omnidirectional antenna, an FOWLP-packaged THz chip, and a copper pillar micro-bump (CPMB)—based air-filled quasi-coaxial transition (AFQCT). By synergistically combining complementary wafer-level technologies, the proposed architecture overcomes the inherent limitations of single-process approaches.

Characterization. Due to the frequency dispersion of dielectric materials in the THz regime, accurate electromagnetic design relies on reliable broadband material characterization. In this work, an SIW multimode resonator is employed to enable broadband and high-precision extraction of dielectric parameters, as detailed in Appendix A.

Antenna design. Benefiting from the RF-friendly and low-loss nature of the glass substrate, the TGV-based antenna achieves radiation efficiency of up to 90% at 220 GHz. A parasitic ring is introduced to regulate the equivalent capacitance and inductance of the radiator, enabling impedance matching and bandwidth tuning. Furthermore, optimized circumferential parasitic directors reshape the surface current distribution, enhancing peak azimuthal gain while suppressing gain variation, as shown in Figure 1(b). Consequently, the azimuthal gain ripple is reduced from 2.79 to 2.15 dB (23%), delivering significantly improved radiation stability and link-margin uniformity for omnidirectional C2C communication. Design details are provided in Appendix B.

* Corresponding author (email: wuyafei@uestc.edu.cn, chengyujian@uestc.edu.cn)
† These authors contributed equally to this work.

© Science China Press 2026

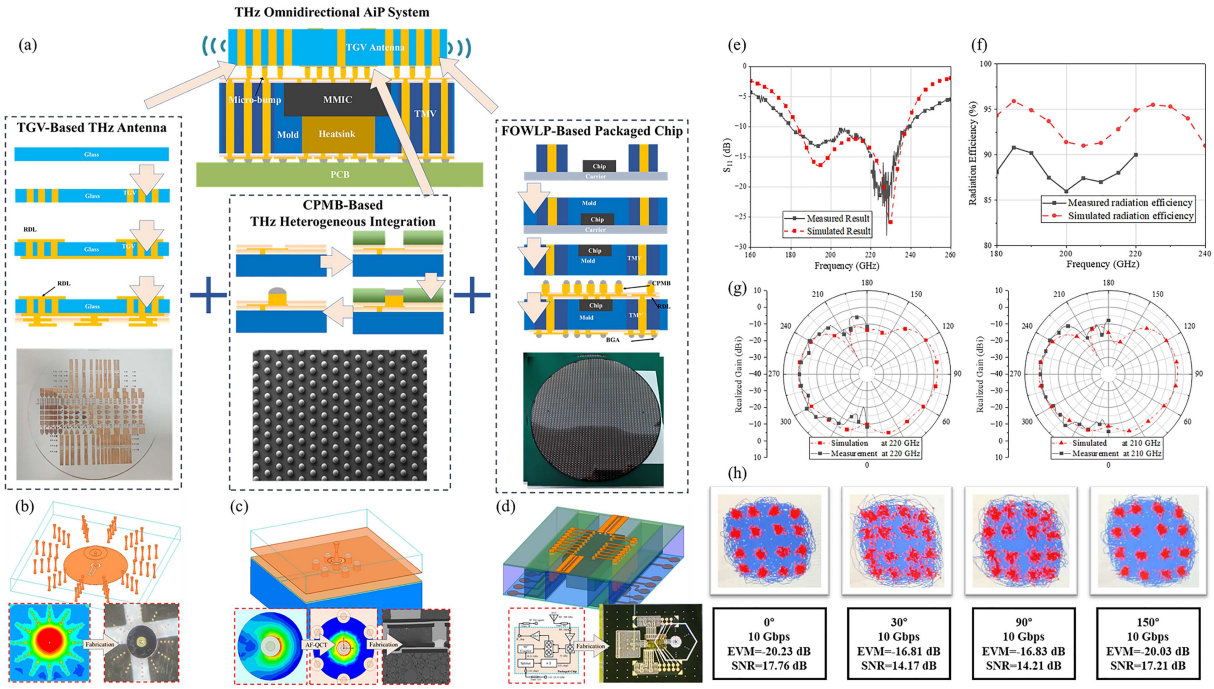

Figure 1 (Color online) (a) The concept for realization of AiP system and fabrication processes based on hybrid wafer-level package; (b) proposed TGV-based omnidirectional antenna with directors and a parasitic ring; (c) proposed CPMB-based AFQCT; (d) proposed FOWLP-based THz packaged chip; (e) measured S-parameter of antenna; (f) measured radiation efficiency of antenna; (g) measured radiation pattern of antenna; (h) measured results of omnidirectional communication rate.

AFQCT design. To realize low-loss THz vertical interconnection, a CPMB-based AFQCT is introduced, as shown in Figure 1(c). The quasi-coaxial configuration with surrounding ground shielding effectively confines electromagnetic fields, suppressing parasitic radiation and discontinuity-induced loss commonly observed in conventional micro-bump interconnects, enabling nearly 2 dB lower transmission loss. Detailed design and simulations are provided in Appendix C.

Packaged chip design. In Figure 1(d), the THz chip is packaged using a FOWLP process to achieve high integration density and flexible signal fan-out (see Appendix D). By leveraging AFQCT interconnection to integrate the FOWLP-based chip with the TGV-based antenna, a three-dimensional heterogeneous integration architecture is realized, enabling a highly integrated omnidirectional AiP system with high radiation efficiency. The packaged chip provides a P_{sat} of 8.5 dBm and a noise figure (NF) of 9 dB [5]. Based on the measured antenna gain, the characterized transmission loss, and the reported chip performance, the effective isotropic radiated power (EIRP) of the AiP is estimated to be approximately 8.8 dBm, while the corresponding system NF is about 11.3 dB. See Appendix D for details.

Measurement. Measurement details are provided in Appendix E. The measured bandwidth spans 180–240 GHz, as shown in Figure 1(e). The radiation efficiency can be extracted from the ratio between the measured gain and the simulated directivity, where the absolute gain is measured and the directivity is obtained from full-wave simulation. The radiation efficiency of the antenna was measured over the 180–220 GHz frequency range, remaining above 85% across the band and reaching 90% at 220 GHz, as shown in Figure 1(f). A peak gain of 3.2 dBi is achieved at 220 GHz, as shown in Figure 1(g). Owing to accurate material characterization, measured results closely match simulations. By integrating the packaged chip and AFQCT, a complete THz AiP system is demonstrated, and azimuthal-plane communication measurements confirm a stable data rate of 10 Gbps with an error vector magnitude (EVM) of −20.23 dB, as shown in Figure 1(h), validating robust omnidirectional communication capability.

Conclusion. In summary, this work presents a hybrid wafer-level THz AiP system that integrates a TGV-based glass omnidirectional antenna, FOWLP chip packaging, and CPMB-based quasi-coaxial interconnects. By jointly optimizing antenna radiation, packaging density, and THz interconnect loss, the proposed architecture provides an effective solution for scalable and reconfigurable C2C wireless interconnects in future SoW systems.

Acknowledgements This work was supported in part by National Key Research and Development Plan of China (Grant No. 2024YFB2807400), Sustained Support Program for Open Research Projects (Grant No. 29wz250001A), Open Research Fund of the State Key Laboratory of Millimeter Waves (Grant No. KN202501-02), Open Fund of the Sichuan Provincial Engineering Research Center for High-Density Integration of Broadband Microwave Circuits (Grant No. BMERC004-2024-01), and National Natural Science Foundation of China (Grant No.62101109).

Supporting information Appendixes A–E. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhang Y P, Chen Z M, Sun M. Propagation mechanisms of radio waves over intra-chip channels with integrated antennas: frequency-domain measurements and time-domain analysis. IEEE Trans Antennas Propag, 2007, 55: 2900–2906
2 Lee S Y, Lee D, Zhang Y P, et al. History and latest progress in antenna packaging technology: part 2: emerging materials and solutions. IEEE Antennas Propag Mag, 2025, 67: 21–33
3 Gu X X, Liu D X, Sadhu B. Packaging and antenna integration for silicon-based millimeter-wave phased arrays: 5G and beyond. IEEE J Microw, 2021, 1: 123–134
4 Wu Y F, Zhuang G, Liu S L, et al. FOWLP-based THz quasi-omnidirectional antenna-in-package for chip-to-chip wireless interconnect in AIoT. IEEE Internet Things J, 2026, 13: 4964–4974
5 Li Z K, Chen J X, Li H B, et al. A 220-GHz sliding-IF quadrature transmitter and receiver chipset for high data rate communication in 0.13-μm SiGe BiCMOS. IEEE J Solid-State Circuits, 2023, 58: 1913–1927