From the Guest Editors' Desk

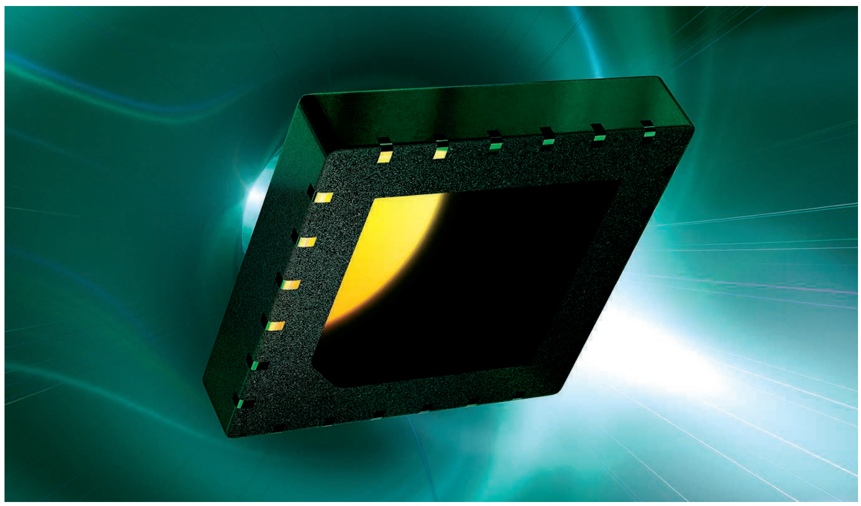
Microwave/Millimeter-Wave Packaging for 5G and Beyond: Materials, Technologies, and Techniques

■ **Kamal K. Samanta and Kemal Aygün**

It is our pleasure to write this column and introduce the *IEEE Microwave Magazine* reader to this focus issue "Microwave/Millimeter-Wave Packaging for 5G and Beyond." This focus issue was inspired by past presidents of the IEEE Microwave Theory and Technology Society (MTT-S) as a means to promote the visibility of other IEEE Societies within MTT-S activities. The issue is sponsored by the MTT-S Technical Committee (TC)-16, Microwave and Millimeter-Wave Packaging, Interconnect and Integration. Advanced microwave and millimeter-wave (mm-wave) packaging is a multidisciplinary research area where transdisciplinary innovation is key to enabling the challenging applications of 5G and mm-wave. As a result, in parallel with the MTT-S, several other societies within IEEE are working to address these challenging issues.

Kamal K. Samanta (kksamanta@ieee.org) is with the IEEE Microwave Theory and Technology Society Technical Committee-16 and AMWT Ltd., London, N3 3AT, U.K. Kemal Aygün (kemal.aygun@intel.com) is with the Electrical Packaging Society and Intel Corporation, Chandler, Arizona, 85226, USA.

Digital Object Identifier 10.1109/MMM.2022.3173478
Date of current version: 8 July 2022



©SHUTTERSTOCK.COM/JOHN CUMMINGS

The IEEE Electronic Packaging Society (EP-S), as the name suggests, is one of the frontrunners in this area. Therefore, for showcasing a wider perspective and advancement in this area, the MTT-S TC-16 has taken the initiative and invited the EP-S to jointly guest edit this focus issue for the *IEEE Microwave Magazine*. This issue reviews a wide range of exciting new advances and outlines challenges and future research directions in the area of microwave and mm-wave packaging materials and technologies for 5G/beyond applications, with contributions and perspectives of experts from both the EP-S and MTT-S.

We are living in a time when the value and impact of technology on humanity are more important than ever. From mobile to satellite and military communications and ubiquitous computing to pervasive connectivity, new capabilities have been changing how we interact with devices everywhere in our lives and impacting how we experience the world. Consequently, the demand for electronic systems and components and the complexity of their design to meet the ever-increasing performance demands have been rising in an unprecedented fashion. From wearable and handheld devices to autonomous vehicles to data centers and supercomputers, the growing amount of integration and the demand for more efficient access to ever-increasing data are pushing the state-of-art capabilities to their limits. Areas where novel capabilities are needed more than ever are in microwave packaging materials, technologies, and techniques for 5G and mm-wave applications.

Historically, the role of semiconductor (SC) packaging has been to

1) provide connectivity and the space transformation between the SC die(s) and the motherboard
2) maintain the fidelity of high-speed signals (signal integrity), supply adequate power (power delivery), and minimize electromagnetic interference
3) help with heat dissipation from the die(s) and provide mechanical stability and performance reliability and repeatability.

Within the last decade, a new set of technologies called *advanced packaging* has emerged. In addition to the previously listed historical functions, the goal of these advanced packaging technologies has been to seamlessly connect multiple dies and, at the module and system level, provide the best possible performance and lowest power consumption. Multilayer/3D multichip module (MCM) and systems on package/systems in package (SoP/SiP) incorporating subtractive and additive printing technologies provide an excellent means for realizing highly integrated mm-wave systems.

For optimizing compactness, performance, and cost, MCM/SoP integrates dissimilar/heterogeneous SC devices—silicon (Si) and compound SC—and high-Q passive components (including filters and antennas) on a single multilayer substrate. At the same time, short interconnections result in higher performance and much denser circuits compared to conventional printed circuit board technologies. Figure 1 shows a 3D view of a highly compact 60-GHz MCM/SoP architecture, integrating monolithic microwave integrated circuits (MMICs) with a substrate-integrated waveguide (SIW) filter and antenna and other high-Q passives on a single multilayer substrate [1]. A very good summary of the challenges and the potential solutions in this new area of heterogeneous integration is provided in [2] and [3]. It should not be a surprise that the emergence of heterogeneous integration was both necessitated and accompanied by the emergence of a wide range of package-integrated electronics applications. These applications, which include 5G and mm-wave, require more advanced capabilities than those provided by traditional technologies.

Three Basic Challenges

Broadly speaking, there are three types of challenges associated with the package-integrated 5G and mm-wave applications.

Technologies

As is common with some other heterogeneous integration applications, some of the emerging 5G and mm-wave package applications require a widely varying set of design rules, together with potentially unique requirements on specific geometries and constructions. In addition, standard packaging materials and standard die materials may not always be sufficient to reach the targeted performance levels. This, as a result, has required the development and integration of novel materials for RF applications such as antennas in package (AiPs), high-power amplifiers (HPAs), RF transmission lines, and integrated high-Q RF passive components. One example in this area is the use of glass interposers, in addition to Si interposers, due to the electrical advantages of certain glass materials. An overview of different materials for package-integrated RF applications is reviewed in [4] and [5]. Another consequence of the introduction of novel materials and complex dimensions/shapes to packaging has been to investigate and assess alternate manufacturing methods compared to traditional package and die manufacturing processes, such as additive manufacturing (AM).

Modeling Capabilities

Package-integrated 5G and mm-wave applications have also introduced challenges in the area of electrical modeling, which is an integrated and key part of

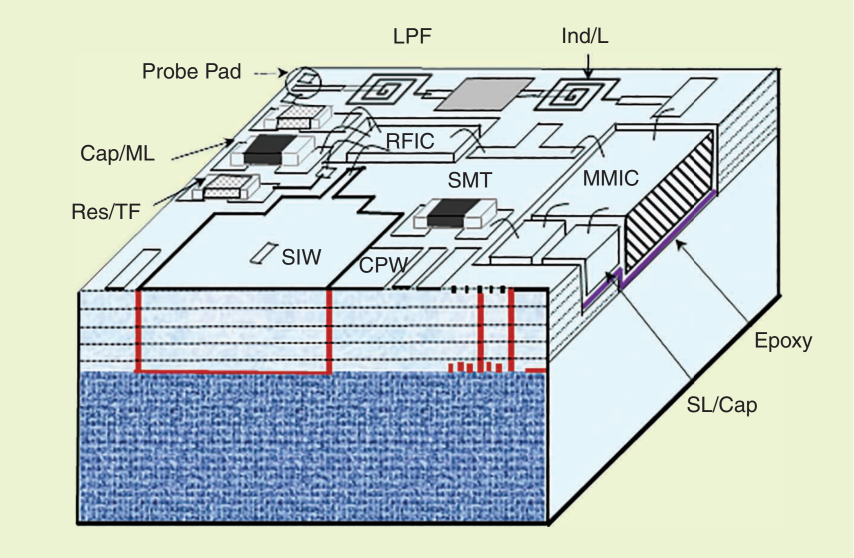


Figure 1. *A 3D view of an MCM/SoP technology [1]. SIW: substrate-integrated waveguide; CPW: coplanar waveguide; RFIC: RF integrated circuit; MMIC: monolithic microwave integrated circuit; LPF: low pass filter; Ind/L: inductor; Cap/ML: multilayer capacitor; Res/TF: thick-film resistor; SMT: surface mount technology; SL/Cap: single layer capacitor.*

the overall electrical design process. These challenges have stemmed from two areas. First, by definition, 5G and mm-wave applications include spectra that have significantly higher frequencies than those employed by historical packaging applications. Even though there are some emerging data center applications employing signaling speeds greater than 100 gigabits/s and whose upper bound frequency of interest may be similar to 5G and mm-wave, the differences in the applications themselves still often require dedicated modeling capabilities for RF applications. This will include the cosimulation of complex multilayer dielectric with heterogeneous SCs (Si and III-V SC) for RF as well as thermal performance. Second, the aforementioned technological aspects of 5G and mm-wave package-integrated applications in terms of dimensions, shapes, materials, and manufacturing techniques have also paved the need for new modeling capabilities for these applications.

Finally, as one would expect, there has been an increased interest in expanding the application space of recently developed machine learning and artificial intelligence optimization and design methods in this area, even though one can argue that this has been more of an opportunity than a challenge. One area that the EP-S is helping is to attract more researchers in industry and academia to concentrate on the challenging problems in packaging via a set of published packaging benchmark problems that are available publicly [6]. The MTT-S is working with the EP-S on the IEEE Heterogeneous Integration Roadmap technical working group on 5G RF-analog/mixed signal, producing the International Technology Roadmap for Semiconductors Roadmap (15/25 years strategic forecast of technology) [7].

Measurement Capabilities

The measurements of packages used for 5G and mm-wave applications also come with their own set of challenges. Similar to modeling, there are multiple reasons for this. First, higher-frequency content for 5G and mm-wave applications requires high-frequency characterization and validation methods for packages, package subcomponents, and various packaging materials. Compared to historical packaging electrical functions of signal integrity and power delivery, where more of the spectral content is at lower frequencies, 5G and mm-wave applications require band-limited measurement data at a higher frequency range. This typically also comes with stringent accuracy requirements where the performance sensitivity to the precision of the measurement data at these frequencies can be high.

Furthermore, the differences in the types of applications for 5G and mm-wave, which may require components such as AiPs, HPAs, filters, and high-precision, low-loss RF transmission lines and interconnects, require a different type of measurement than those historically needed by signal integrity and power delivery. While impedance and S-parameter measurements may suffice for most of these, components such as AiPs, for example, usually require radiation pattern measurements in an anechoic chamber, and PAs require an analyzer for a wideband error vector magnitude and adjacent channel power ratio measurement, which can be quite challenging due to the nature of the dimensions and the geometries involved or with higher-order modulation requirements and frequency range. For the characterization of 5G and mm-wave materials, including those used for package-integrated applications, a recent collaborative effort in the industry is reported in [8]. This effort has aimed both to develop a standardized material measurement methodology for 5G/mm-wave frequencies and also to establish an mm-wave permittivity reference material set.

The previous three described areas were intended to highlight the high-level classification of challenges and the opportunities in the area of microwave packaging materials, technologies, and techniques for 5G and mm-wave applications. As providing a comprehensive list of all the associated challenges and potential solution paths will constitute a much larger effort, the examples provided here should be interpreted as some representative examples in this area.

A Preview of This Focus Issue

There is an increasing interest and demand for wideband and high-speed communication and high-resolution applications. This focus issue on "Microwave/mm-Wave Packaging for 5G and Beyond" brings together experts from the EP-S and MTT-S. The issue showcases technical features that present exciting new developments and improvements along with challenges and future directions in some key areas of microwave and mm-wave packaging technologies: advanced materials; transmission lines and interconnects; integration techniques; and components and systems that use subtractive as well as AM technologies, aimed toward making the next-generation mm-wave applications feasible.

In a package, the close proximity of components requires optimized design achieving signal integrity and reduced interconnection and packaging parasitics with low loss at the IC, board, and module levels. At extremely high operating frequencies, conventionally used copper (Cu) interconnects face challenges due to their higher skin effect, dispersion, coupling noise, and electromigration. This focus issue will highlight the advanced material, technologies, and processes that have been recently developed for overcoming the issues of packaging interconnects. These include carbon nanotube, graphene nanoribbon, hybrid interconnects (Cu-graphene, aluminum-graphene), and plasmonic and metaconductors that consist of nonmagnetic/magnetic materials.

The issue will also detail the latest advances in subtractive and AM technologies with application spaces. AM is a digital technology, where information about the structure is stored and fabricated digitally, and it can recreate structures that are sometimes difficult to implement using traditional technologies. The evolutions with comparative advantages of various AM technologies are detailed:

additive/2.5D printing technologies (such as aerosol jet printing and inkjet printing) and also 3D printing, such as fused deposition modeling, selective laser sintering, and stereolithography.

In this focus issue, the editorial section provides an overview of packaging challenges and introduces four cover features. The first feature article, by Kamal K. Samanta, is titled "Cost-Effective Technologies for Next-Generation System on Package." This article reviews various advanced multilayer subtractive manufacturing processes and integration and packaging technologies with the latest advances and a relative performance, maturity, and cost analysis for mm-wave applications. The interconnects, layer transitions, planar transmission lines, and fence posts, as well as trench-via-based dielectric-filled and hollow/empty SIWs, are analyzed for various lateral dimensions and ground widths, optimizing miniaturization and performance up to 200 GHz. The new split-ground coplanar waveguide (CPW) has shown promise for highly dense packaging. Finally, comprehensive and comparative performances of planar and SIW lines from a circuit/system design perspective are analyzed for enabling optimum selection for size and performance.

The second article is "High-Speed Interconnects," by Vijay Rao Kumbhare et al. This article provides a detailed overview of the evolution of interconnection materials and technologies with milestones that have been attained over the past four decades. These advances include graphene nanoribbon and carbon nanotube with limitations as well as Cu-graphene-based hybrid technologies. Also discussed in the article are the design and fabrication challenges with the current state of the art and the techniques, such as graphene-based through-silicon vias, ThruChip Interfaces, spintronics, and plasmonic and optical-based interconnects, for replacing Cu for high-frequency applications.

The third contribution, "Highly Energy-Efficient Metaconductor-Based Integrated RF Passives," by Renuka Bowrothu et al., reviews and compares metaconductor technologies that consist of alternate nanolayers of nonferromagnetic and ferromagnetic metals, such as copper/nickel (Cu/Ni), copper/nickel-iron (Cu/NiFe), and copper/cobalt (Cu/Co), and their progress and applications. Theoretical and experimental verification of metaconductors on different passive components and their thermal stability are discussed. Finally, highlights of the challenges with possible alternative materials and future research directions toward implementing metaconductor-based interconnects as an alternative material to Cu for 5G are presented.

The final technical feature, "Additively Manufactured "Smart" RF/mm-Wave Packaging Structures," by Xuanke He et al., discusses the benefits of AM technologies and their applications to packaging, with a comparison between AM technologies in terms of printability, integration capability, mechanical/physical reliability, and cost. Also, the article presents a novel packaging solution by combining two of the most commonly used AM technologies, inkjet printing and 3D printing. This includes the system on antenna; antenna structures housing RF electronics; flexible package integrating antennas with ICs for energy harvesting; encapsulants; enabling integrated "smart" packaging features; and all-additive packaging to replace traditional wire/ribbon bond interconnects.

Closing Comments

Microwave and mm-wave packaging for 5G and beyond applications is a transdisciplinary subject of intense research and development worldwide. This focused issue incorporates the contributions of experts from the EP-S and MTT-S on the latest exciting innovations in materials and fabrication process, thermal management, and circuit/system integration and packaging techniques, which are keys to the realization of next-generation, 5G and beyond, and mm-wave systems.

We hope that, within the limited available space, the technical features in this issue of *IEEE Microwave Magazine* will inspire researchers around the world to continue to push the boundaries for scientific achievements in the exciting area of microwave and mm-wave packaging materials and technologies for 5G and mm-wave applications. Moreover, we hope you will enjoy reading the issue!

Finally, we would like to heartily thank the editor-in-chief, Robert Caverly, and his team for administrating the review, revision, and decision-making processes with extreme efficiency. The first guest editor, Kamal Samanta, would like to thank Kemal Aygün and the authors from the EP-S for their excellent support and contributions to successfully implementing the first intersociety-edited, focused issue on microwave/mm-wave packaging. We also would like to thank the other authors and reviewers for their great help.

References

[1] K. K. Samanta, D. Stephens, and I. D. Robertson, "Design and performance of a 60 GHz multi-chip-module receiver employing substrate integrated waveguides," *IET Microw. Antennas Propag.*, vol. 1, no. 5, pp. 961–967, Nov. 2007, doi: 10.1049/iet-map:20060301.

[2] "Heterogeneous integration roadmap 2021 edition." Presented at IEEE Electron. Packag. Soc. 2021. [Online]. Available: https://eps.ieee.org/technology/heterogeneous-integration-roadmap/2021-edition.html

[3] K. K. Samanta, "Pushing the envelope for heterogeneity: Multilayer and 3-D heterogeneous integrations for next generation millimeter- and submillimeter-wave circuits and systems," *IEEE Microw. Mag.*, vol. 18, no. 2, pp. 28–43, 2017, doi: 10.1109/MMM.2016.2635858.

[4] K. K. Samanta, "Ceramics for the future: Advanced millimeter-wave multilayer multichip module integration and packaging," *IEEE Microw. Mag.*, vol. 19, no. 1, pp. 22–35, Jan./Feb. 2018, doi: 10.1109/MMM.2017.2759598.

[5] M. ur Rehman, S. Ravichandran, A. O. Watanabe, S. Erdogan, and M. Swaminathan, "Characterization of ABF/glass/ABF substrates for mmWave applications," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 11, no. 3, pp. 384–394, Mar. 2021, doi: 10.1109/TCPMT.2021.3061485.

[6] F. Guo *et al.*, "The IEEE EPS packaging benchmark suite," in *Proc. 2021 IEEE 30th Conf. Electr. Perform. Electron. Packag. Syst. (EPEPS)*, pp. 1–4, doi: 10.1109/EPEPS51341.2021.9609142.

[7] K. K. Samanta and T. Lee, "Heterogeneous integration roadmap: 5G communications," presented at the Workshop on Heterogeneous Integration Roadmap IEEE Electron. Syst.- Integr. Technol. Conf. (ESTC), Norway, Sep. 2020.

[8] "Section: 5G electronics," International Electronics Manufacturing Initiative, Morrisville, NC, USA, 2021. [Online]. Available: https://www.inemi.org/article_section.asp?edition=3&section=9