State-of-the-Art Packaging, Interconnects and AiP Modules for Millimeter-Wave 5G+ Applications

Introduction

The introduction of mmWave 5G introduces new challenges to interconnects and packaging. The higher frequencies means that interconnects between chips and board need to be low loss and high bandwidth. The additive manufacturing method enables a high level of integration between antenna and electronics and serves as the primary design tool to create low-cost and highly customizable wireless system designs which can enable rapid deployment of large-scale 5G communication and IoT systems. The versatility of additive manufacturing for packaging allows for customizable packaging structures and modules and allows designers to enable high performance with minimal tooling required. Additionally additive manufactured interconnects can enable novel structures which operate much better at higher frequencies than traditional methods. The nature of additive manufacturing allows electronics to be manufactured with very little waste and allows quick iteration allowing a drastic reduction in time-to-market. This article will discuss several packaging structures for mm-Wave capable modules utilizing additive manufacturing for use in communication, energy harvesting and reconfigurable surfaces.

Additively Manufactured mmWave Modules

Using higher-performance inkjet-printed interconnects allows designers to create more efficient systems, integrating multiple chips into compact miniaturized multilayer RF modules. The mmWave ICs are interconnected utilizing a fully additive approach. In the first process a ramped interconnect technology is developed to realize printed RF and DC interconnects for active MMIC dies. The processes and demonstrations presented in this work highlight the effectiveness of utilizing additive inkjet printing technology for the fabrication of highly application-specific wireless mm-wave MCM systems in a low-cost and efficient fashion [1]. Another approach is utilizing gap-filling interconnects [2]. A dielectric material is first printed to serve as a gap fill in a cavity circuit board, and then inkjet printed silver nanoparticle ink is deposited on top of the gap fill to connect the pads of the ICs together. Utilizing this approach enables shorter interconnects which allows for lower loss and higher bandwidth interconnects, Fig. 1. This approach can also be utilized to connect together various ICs to form modules as demonstrated by the front-end module demonstrated in Fig. 2 which features a LNA, PA and switch to enable Ka-band 5G TDD communication.

This work utilizing additive manufactured packaging, paves the way for future work regarding highly customizable, heterogeneously integrated high performance mm-wave systems that are cheap to manufacture, quick to implement to production, and require simple and minimal tooling.

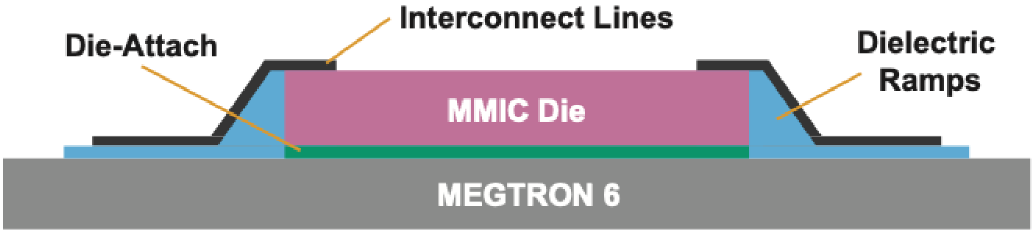


Figure 1. An inkjet-printed IC interconnect utilizing ramped interconnects structures on a MEG6 substrate which enables operation at Ka-Band frequencies [1].

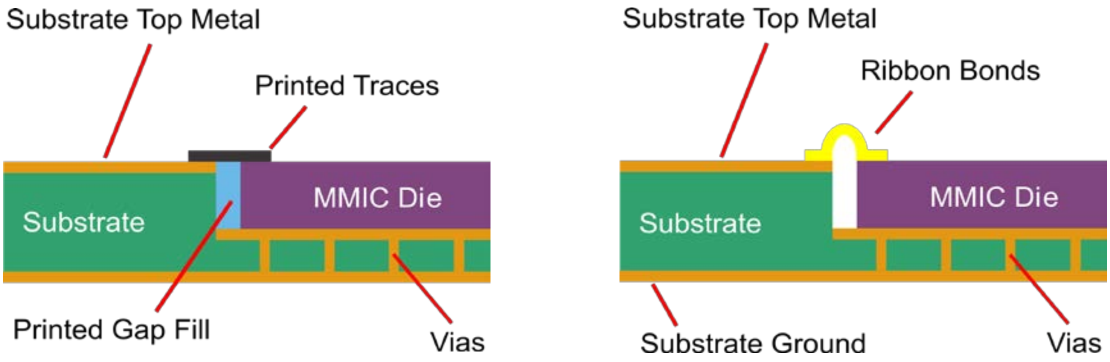


Figure 2. A interconnected IC utilizing inkjet printed traces vs ribbon bonds. Notice the longer length needed for the ribbon bonds, which introduce losses and parasitic inductances.

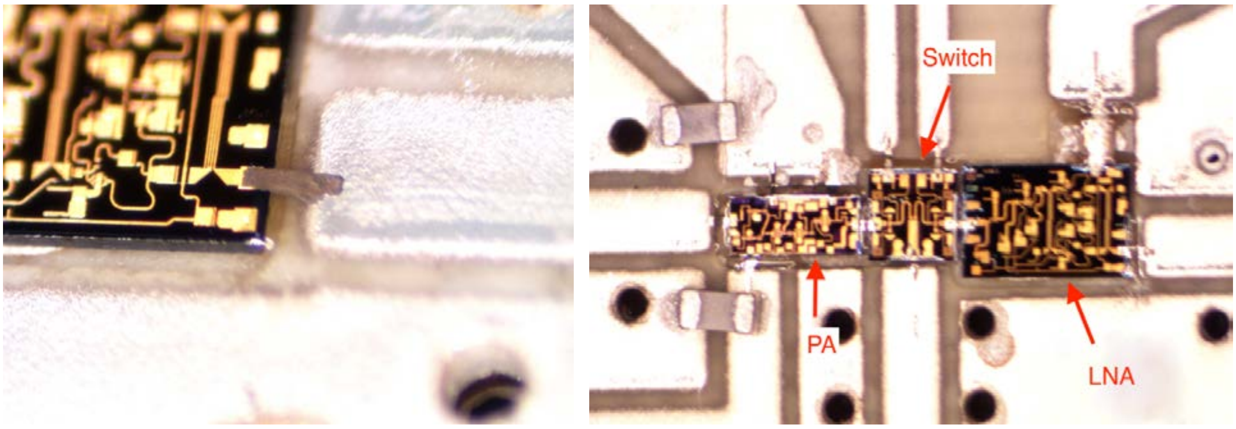
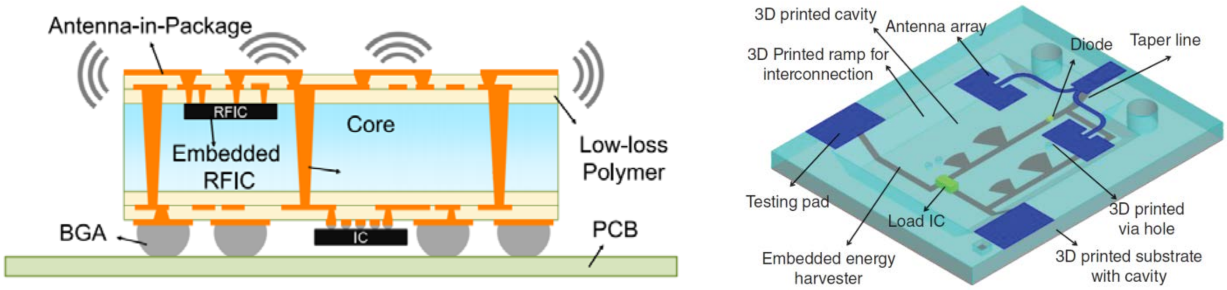


Figure 3. A close up of the inkjet printed interconnect with an ultra-smooth transition from the chip pad to a 50 ohm microstrip line. The ICs can also be connected together utilizing multiple mmWave chips to form a front-end module.

Packaging for Energy Harvesting

In applications such as mm-wave energy harvesting, the choice of the rectifying element is crucial and puts bounds on the efficiency, sensitivity and performance of the harvester. Schottky diodes with low series resistance and low junction capacitance are desired for efficient rectification at mm-wave frequencies. An example of these diodes is the W-band ZBD diode from Virginia diodes in die form. Its integration has been made possible through the inkjet-printing-based technique of die



a. b.

Figure 4: (a) General schematic of an AiP module [6] (b) The fully-embedded mm-wave energy harvester with 3D printed AiP structure [7]

attach, dielectric ramp and interconnect lines presented in [3]. With the high transmitted EIRP of 75dBm allowable by the FCC at 5G/mm-wave frequencies, and the low-cost, simple and low-loss integration of high-sensitivity diodes in harvesters using additively manufactured techniques, several µW of power can be harvested at ranges exceeding 100m [4, 5]. This technology enables the powering of fully packaged mm-wave modules, with antennas dubbed antenna in package (AiP), capable of real-time sensing and communication at long-ranges using available 5G signals. The advances in mm-wave backscattering communications described in the next paragraph, demonstrating ultra-low power operations, bridges the gap between efficient communications and wireless power transfer, yielding zero-power, sustainable and scalable solutions. The schematic shown in Fig. 4(a) shows a general schematic of a AiP module and Fig. 4(b) demonstrates the full integration and packaging of a mm-wave rectifier, demonstrating an important piece—the power supply—in the realization of a smart fully-embedded zero-power mm-wave IoT sensor [6].

With the widespread adoption of 5G/mm-wave systems which promise high-data rate communication and data-driven system infrastructures for smart city and smart home IoT applications, 5G backscattering modules provide a highly scalable, ultra-low-cost, ultra-low-power, and compact systems solution. Gigabit, high-order modulation, wireless communication was demonstrated with a single pseudomorphic high-electron-mobility transistor integrated with a 5x1 antenna array utilizing low-cost inkjet-printing-based techniques on a flexible substrate [8]. Thus, enabling ubiquitous, low-latency communication for wearable biomonitoring applications. Additionally, by taking advantage of the large bandwidth at these 5G/mm-wave frequencies, precise localization for ID and tracking systems is another natural application. The 2D micro-localization system consisting of a ultra-low-cost, ultra-compact Antenna-on-Package Frequency Modulated Continuous Wave radar module and an ultra-low-cost millimeter-wave ID displayed 2 cm ranging accuracy and 1.79° angle-of-arrival accuracy [9]. Thus, allowing for a scalable and ultra-low-cost system short range robotics, human computer interface, and smart home applications.

The exponential growth of smartphones, self-driving cars, internet of things (IoT), smart cities, etc., are pushing network providers and authorities to allocate more frequency bands to fulfil the continuously increasing data traffic. Therefore, microwave devices for next generation communication systems are required to have adaptive frequency response over a wider frequency range based on the environment, region, and type of service. To realize reconfigurable microwave devices in a sustainable and affordable manner, we developed a hybrid printing fabrication process combining 3D printing with inkjet printing technology. We demonstrated two hybrid printed origami-inspired frequency selective surfaces (FSSs) in single- and multi-layer configuration [9, 10]. The prototypes have shown in Fig. 5 achieves over 13% of frequency tunability range and excellent angle of incident (AoI) rejection.

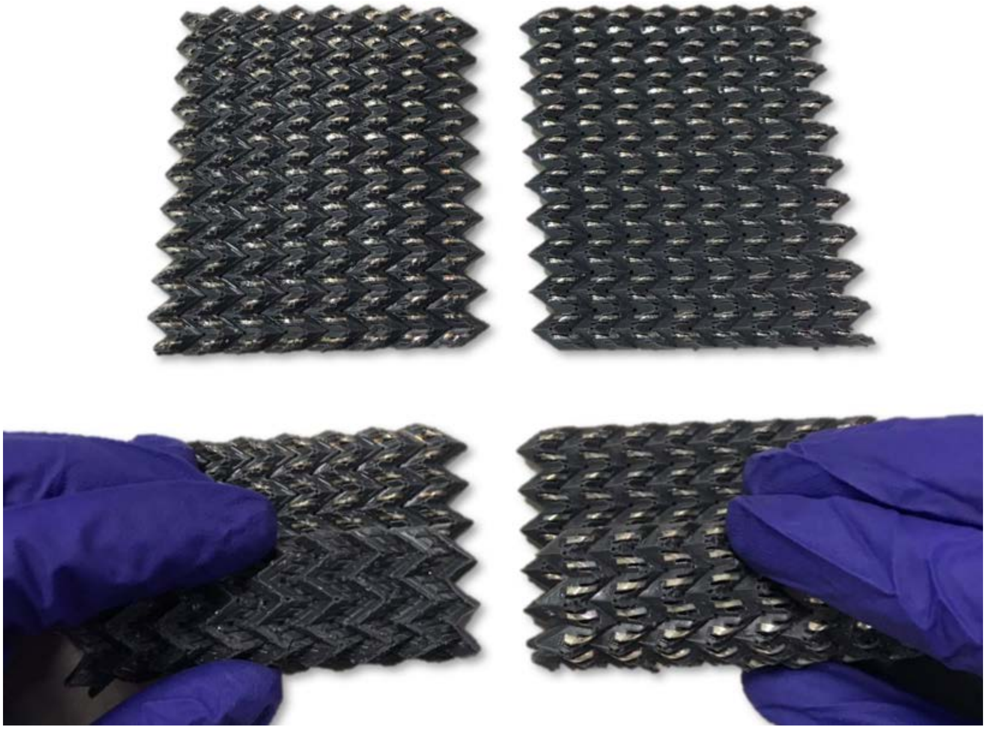


Figure 5. Hybrid printed origami-inspired FSS: single-layer configuration(left), multi-layer configuration(right).

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