Additively Manufactured Highly Integrated mm-Wave Packaging Structures

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***Abstract*— Modern 5G, Internet of Things (IoT), and wearable devices require tons of features packed into a small, portable form factor. This brings significant challenges to both the design of the packaging and the manufacturing of the device. This is where additive manufacturing (AM) can play a critical role. AM is a technology which can deposit various of materials in both 2D and 3D manner to realize complex geometries with superior resolution, accuracy, and speed. Compared to traditional subtractive manufacturing methods such as milling and chemical etching, AM techniques only use the minimum amount of materials which can reduce the cost significantly, making it the ideal candidate for future "smart city" that promises to connect billions of devices in all different types of environments.**

AM also enables novel integration of structures that are un-realizable with traditional manufacturing techniques. With AM, fully featured electronic devices can be realized in a customized 3D multi-layer stack within a single package. This paper gives a review of additively manufactured highly integrated packaging structures that operate at 5G mm-wave frequencies.

I. Introduction

With the recent development in 5G and wireless technologies, our society is undergoing what is known as the forth industrial revolution, also known as the digital revolution. The forth industrial revolution highlights the advances in manufacturing technologies with full automation, high resolution, as well as great sustainability. Within this revolution, AM is becoming an innovatory tool for massively on-demand realization of electronic designs such as wireless sensors, antennas, microfluidics, energy harvesters, etc [1]–[4].

The combination of 3D printing and inkjet printing technologies forms the "hybrid printing [5]" technique which has great potential of introducing new and novel "smart" packaging designs that are difficult to implement using traditional technologies. Fig. 1 demonstrates a fully integrated 3D stacked module enabled by the hybrid printing technique. 3D printable low-loss polymer enables the realization of conformal substrates, through-package vias, smart encapsulates, microfluidic channels, as well as dielectric lenses. Inkjet printing technology can deposit conductive materials onto the 3D surfaces directly to realize interconnects, circuits, and EMI shielding layers. By combining various AM technologies, 3D intergrated designs with more complicated structures and functionalities can be realized in mm-wave frequencies for both 5G and IoT modules.

This paper provides a review of additively manufactured highly integrated packing structures that operate at 5G mm-wave frequencies including System on Antenna (SoA) integration, flexible system-on/in-package, as well as printed "smart" mm-wave encapsulants.

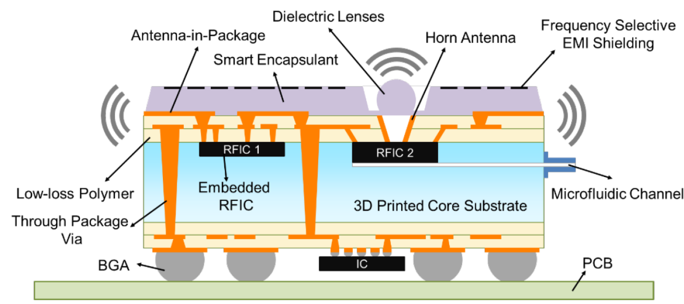


Fig. 1. Schematic of a fully integrated 3D stacked module enabled by 3D printing and inkjet printing techniques [6].

II. System on Antenna Integration

Fig. 2a shows a completed System on Antenna (SoA) design [7] that has a customized 3D printed antenna excited by integrated MMIC and inkjet printed feeding lines. The SoA design is a combination of traditional SoC/SoP and 3D printed antennas, which can provide the high intergration seen in SoC/SoP and high performance on-package antennas in a low-cost fashion. By embedding the ICs and circuits within the antenna, the entire RF system can be integrated into one single structure, eliminating the need for flanges, coax transitions, and cables so that the system size and losses can be reduced dramatically.

The proof-of-concept design of this SoA system is a radar transmitter that can be used for tracking applications. A Ku-band amplifier and a voltage controlled oscillator (VCO) are embedded into the 3D printed horn antenna to provide variable frequency control. The circuit is realized with inkjet printed conductive traces to enable trasmission of Ku-band signals. The full circuit design is shown in Fig. 2b.

The fabrication of this SoA design consists of four critical steps: 1) 3D print the antenna structure with integrated cavity housing for ICs, then metalize the structure. 2) Selectively metalize the microstrip antenna feed. 3) Install ICs, then inkjet print gapfill dielectrics, inkjet print RF and DC interconnects. 4) 3D print the heat sink structure for heat dissipation. The fabricated sample is shown in Fig. 2c and the measurement results are shown in Fig. 2d. The measurement demostrated solid received signals from the SoA with different tuning voltages. This SoA design demonstrates the versatility of AM

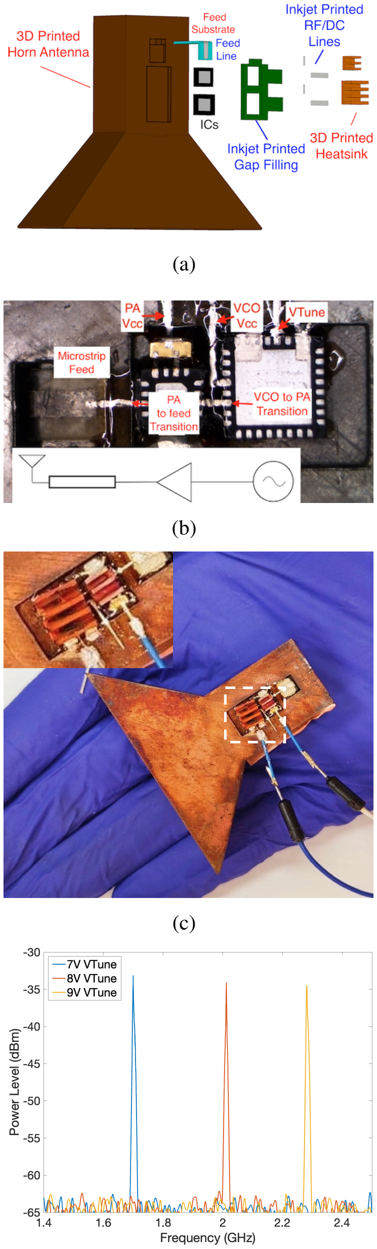


Fig. 2. (a) Exploded view of the of a SoA proof-of-concept topology, with the various components required. (b) Fully printed SoA with RF and DC inkjet printed lines and equivalent schematic. (c) The top view of the SoA module prototype with enlarged heat sink. (d) Received power level from the SoA, with different tuning voltage demonstrating system level applications [7].

that allows the designer to realize un-conventional geometry as integration layers for RF devices, that can enhance the system performance while reducing the size.

III. Flexible System-on/in-package

With the development of 3D printing technology, flexible materials such as hermo-plastic polyurethane (TPU), polypropylene (PP) for Fused Deposition Modeling (FDM) 3D printers, and Formlabs Flexible 80A, Formlabs Elastic 50A resin for Stereolithography (SLA) 3d printers are now

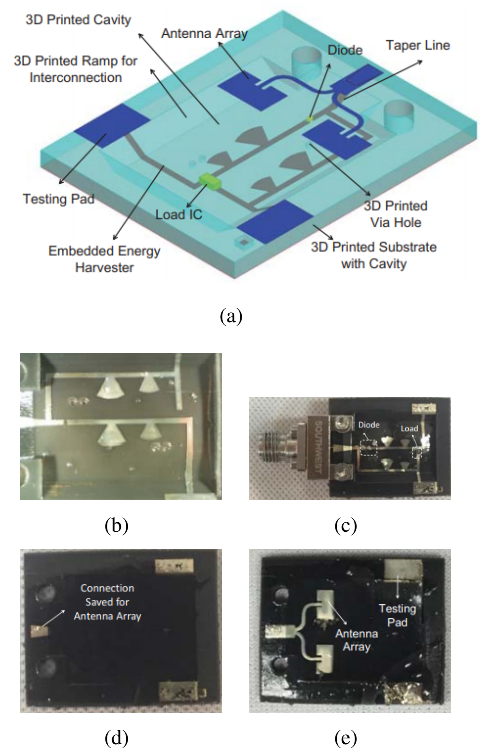
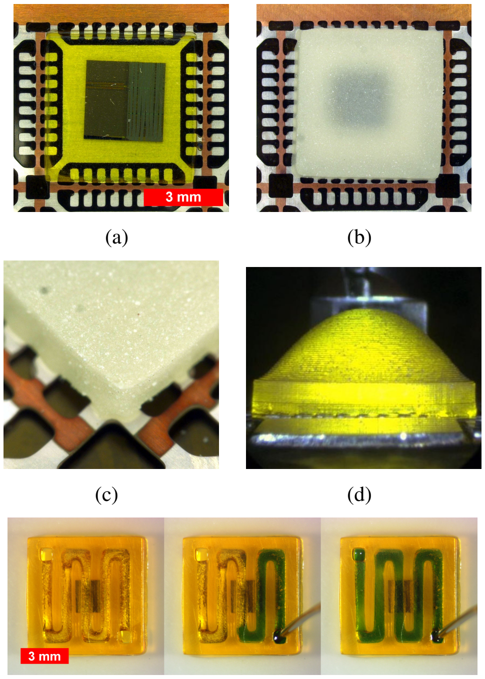


Fig. 3. (a) Flexible system that is demonstrated layer by layer beginning with (b) encapsulated inkjet printed support circuitry layout with radial stubs (c) integration of rectifying diode and load for measurement (d) encapsulation of integrated circuit and support circuitry (e) SoP antenna used at 26 GHz energy harvesting. [8]

becoming commercially available. When combined with inkjet printing technology, complex system-on/in-package design shown in Fig. 3 with embedded energy harvester, loading circuits, and antenna arrays can be realized in a flexible fashion [8]. This design utilizes non-planar interconnects across integrated circuits of various heights, with non-planar ramps enabling improved performance. The top of the structure contains inkjet printed on-package antenna that convers 5G mm-wave band from 24.4 GHz to 30.1 GHz. The embedded energy harvester eliminates the requirements for external batteries or super capacitors by collecting energy from the nearby 5G base stations. The integration of this full system in a flexible package enables compact electronic devices that can be ideal candidates for the next stage of wearables, where devices are integrated directly into the human body.

IV. Additively Manufactured "Smart" Encapsulants

Conventional IC die encapsulations utilize expoxy molding process that offers limited freedom for system in package integration. Mmwave packaging also requires compact structures with air cavities over the devices to minimize dielectric loading. These processes usually come with high cost and challenges in integration. Recent development on 3D printing technologies has shown the potential in solving packaging problems in a low-profile manner. 3D printer can directly build encapsulations onto front-end circuits with

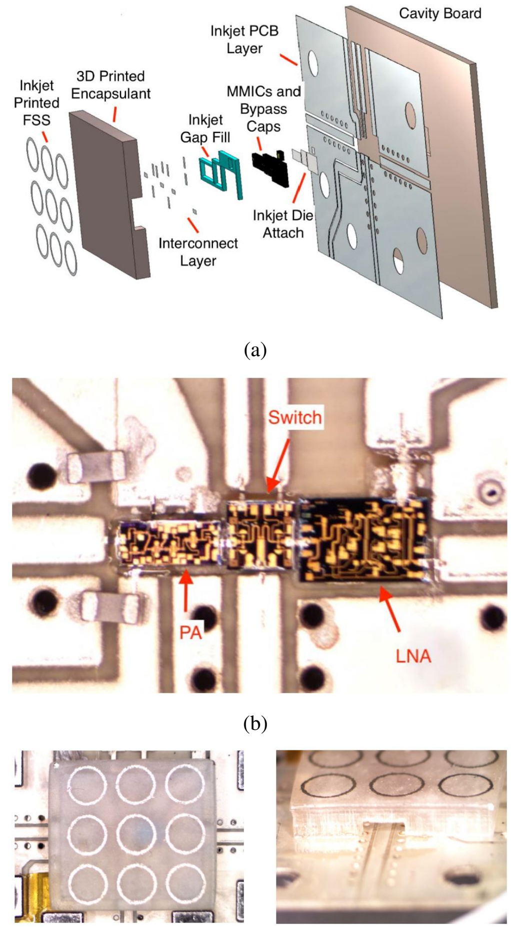


(a) (b) (c) (d) (e)

Fig. 4. 3D-printed die encapsulants on a metallic QFN leadframe: Vorex encapsulation (a) top view; (b) perspective view and (c) Porcelite encapsulant perspective view. Vorex encapsulant with (d) dielectric lens and (e) microfluidic network. [10]

customized shapes, spacing and dimensions. SLA printing as a widely accepted and low cost 3D printing technology, provides high resolution and low surface roughness, which also makes SLA printed materials excellent substrates for inkjet printing conductive traces [9].

Fig. 4 shows SLA printed encapsulants using Vorex and Porcelite materials over a 280mm thick silicon die package, that was attached to a metallic QFN by inkjet printed polymers [10]. The Vorex encapsulants including dielectric lens and microfluidic networks are demonstrated in Fig. 4 (d) and (e). A fully additively manufactured MCM module with a "smart" frequency selective surface (FSS) enabled encapsulation is shown in Fig. 5. The FSS encapsulation is only 0.2mm thick and is 1mm higher than the packaged device. It completely covers the circuits and leaves openings for external connections. The FSS pattern consists of 9 circular rings that were inkjet printed with silver nano particle ink to achieve EMI shielding. The measurement results of the integrated MCM with FSS encapsulation show that more than 18dB isolation is added at 24GHz compared to the case of no encapsulation, while the S21 remains the same for both cases. In addition, in this MCM design, inkjet-printed gap-filled interconnects were used, which easily connects the MMICs inside the 3D printed encapsulation to out-of-cavity circuits. Compared with traditional wire-bonding, the inkjet printed interconnects feature a more compact structure with lower parasitic loss and shorter loop length. These interconnects were inkjet printed with multiple layers of SU8 to fill the gaps and build bridges for inkjet printed silver traces. These highly-integrated novel packaging structures prove the on-demand reconfigurable nature of AM techniques for diverse packaging applications.



(a) (b) (c) (d)

Fig. 5. (a) Exploded view of the complete encapsulated RF front-end MCM with an additively manufactured multilayer structure. (b) Non-encapsulated mm-wave front-end MCM fabricated using inkjet printing (c) 24-GHz FSS inkjet printed on top of the 3-D printed encapsulation. (d) Perspective image showing the cavity and the FSS-enabled "smart" encapsulation of the front-end MCM [11].

V. Conclusion

In this paper, various types of additively manufactured highly integrated packaging structures for 5G mm-wave frequencies are discussed. The capabilities of AM in System on Antenna (SoA) integration, flexible system-on/in-package, as well as printed "smart" mm-wave encapsulates demonstrate novel integration process with high performance and low cost, providing future solutions for 5G and B5G devices. The wide range of potential applications of AM in mm-wave packaging also sets the foundation for wearable biomonitoring, autonomous car implementations and reconfigurable intelligent surfaces up to sub-THz frequencies.

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