Additively Manufactured mm-Wave Multichip Modules With Fully Printed “Smart” Encapsulation Structures

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Abstract—This article presents the first time that an mm-wave (mm-wave) multichip module (MCM) with on-demand “smart” encapsulation has been fabricated utilizing additive manufacturing technologies. RF and dc interconnects were fabricated using inkjet printing, while the encapsulation was realized using 3-D printing. Inkjet-printed interconnects feature superior RF performance, better mechanical reliability, and on-demand, low-cost fabrication process. Numerous test vehicles were initially produced to evaluate these additive manufacturing technologies and compare them with traditional ribbon bonding, exhibiting a superior [821] performance throughout the whole operation range up to 40 GHz with a peak of 3.3 dB better gain for a Ka-band low noise amplifier (LNA). A fully functioning front-end MCM was fabricated using the same inkjet-printed interconnect technology, which features smart encapsulation technology fabricated using the 3-D printing and integrated on-demand “smart” encapsulation for electromagnetic interference (EMI) mitigation. The proof-of-concept MCM demonstrates exceptional performance taking advantage of a low-cost, on-demand additive manufacturing method that requires minimal tooling and process steps, which can drastically accelerate the time to market for future 5G and Internet-of-Things applications. The methodologies presented in this article could potentially enable rapid production of high-performance, high-frequency customizable circuit packaging structures with on-demand “smart” features, such as self-diagnostics, EMI/EMC filtering, and integrated sensors.

Index Terms—Additive manufacturing, frequency-selective surface (FSSs), inkjet printing, interconnects, millimeter wave (mm-wave), monolithic microwave integrated circuit (MMIC), multichip module (MCM), RF packaging, ribbon bonding, 3-D printing.

I. INTRODUCTION

As more and more wireless and mobile devices get added into the wireless spectrum, lower frequency bands are becoming increasingly cluttered and devices are constantly competing for enough bandwidth. Currently, there has been a push to move toward higher bandwidth, higher frequency communication channels for 5G and radar applications, featuring dramatically higher data rates that take advantage of the cluttered frequency bands around 24 GHz or higher. As the devices move up in frequency and consequently move down in wavelength, components become smaller and can be more readily integrated into systems. However, shorter wavelength/higher frequency means larger path losses, requiring many small cells or repeaters for optimal communication channels. Adding multiple cells adds cost and slows down the implementation of 5G, issues effectively addressed by additive manufacturing methods, such as inkjet and 3-D printing. Additive manufacturing can dramatically speed up the implementation of 5G networks. Not only do they reduce manufacturing cost by simplifying the traditional multistep fabrication methodologies of photomasking, lithography, etching, and so on but also allowing print-on-demand capabilities and enabling the realization of a multitude of customized parts that can be assembled quickly and cheaply, reducing the development of a concept to final product from weeks to just hours [1]. The use of inkjet printing and 3-D printing to make RF components, such as passives, waveguides, transmission lines, and antennas, has been previously demonstrated and continues to grow in maturity [2]–[5], but its uses in packaging are still under investigation. However, some have heralded that additive manufacturing in electronics integration can help push “beyond Moore’s” [6].

Packaging is a major component in 5G systems and is an excellent candidate for additive manufacturing. Typically, interconnects between the chips at millimeter-wave (mm-wave) frequencies utilize thermosonic ribbon or wirebonds to bridge ICs together as well as to allow communication to the host packaging substrate or printed circuit board (PCB). However, these methods can introduce a long loop length, large parasitic inductance at high frequencies, and greater discontinuities [7]. It can also lead to unintended radiation losses due to the high-arching bond wires [8]. Inkjet-printed interconnects feature a more rugged, planar and conformal structure, which offers an improved RF performance even in challenging configurations. Using higher performance inkjet-printed interconnects allows designers to create more efficient systems, integrating multiple chips into compact miniaturized
multilayer RF modules. Packaging mm-wave devices also typically requires encapsulation using an air cavity encapsulant to minimize dielectric loading on the chip, which is an expensive process. This can be replaced with 3-D printed encapsulation, where the air cavity is easily printed onto the modules. Additionally, multiple functionality, such as frequency-selective surfaces (FSSs), can be integrated on top for additional functionality, such as electromagnetic interference (EMI) protection. These fully printed multichip modules (MCMs) demonstrate the high level of integration and cheap manufacturing cost that is capable of using additive manufacturing.

This article begins with a demonstration of inkjet-printed interconnects where two 50-Ω microstrip transmission lines are connected using printed transmission lines to evaluate the losses compared to a regular transmission line. Additionally, Ka-band low noise amplifiers (LNAs) are interconnected using the inkjet printing technology, while another two samples are interconnected using ribbon bonds to evaluate the interconnect performance on active monolithic microwave integrated circuits (MMICs). All test vehicles are fabricated on the exact same substrate material to keep assembly characteristics consistent. The work is then extended to a real-world RF front-end module application integrating LNA, power amplifier (PA), and switch MMICs, which is fully encapsulated using 3-D printing and features an integrated FSS for EMI mitigation. The summary of the fully printed gap-filled interconnects discussed in this article is shown in a schematic form in Fig. 1, and the complete additively manufactured RF front-end MCM module is shown in Fig. 2 in the 3-D form.

II. FABRICATION METHODOLOGY

In this article, all chips were mounted in a surface-mounting fashion, meaning that the bond pads for the chip are facing upward. The alternative to this is flip-chip technology. However, flip-chip assembly yields a lower throughput from a manufacturing standpoint in addition to requiring very flat surfaces, underfilling layers, and accurate pick-and-place. Additionally, many mm-wave ICs require backside grounding that is not possible with flip chip [9]. Other works regarding packaging of mm-wave/high-frequency devices have utilized aerosol jet printing for mm-wave packaging such as [10]–[12] but only on simple passive structures. Compared to inkjet printing, aerosol jet printing offers an increased resolution but at a higher operating cost while utilizing only a few printing nozzles, compared to the thousands available on a commercial inkjet printhead, making it less suitable for large-scale production settings. Similar works, such as [13], demonstrate the inkjet-printed ramp interconnects with active devices and [14] discuss a cavity-embedded chip on a 3-D printed substrate. However, the ramped structure in [13] lacks a good grounding of the chip and mechanical stability of cavity embedding and [14] features wirebonded interconnects, for which this article that will demonstrate is an inferior interconnect technique. References [15] and [16] demonstrated a D-band MCMs’ technology that is fabricated partially using 3-D printing, but the process is not entirely additive since it uses multistep masking lithography to build the 3-D structure, polymerizing and liftoff processes, and additionally does not fully demonstrate the multichip aspect of the MCM since there is only one active chip. Other works have also demonstrated 3-D printed chip encapsulations, such as [17] and [18], but the chip that was encapsulated was a dummy and lacked quantifiable results. This article presents for the first time to the authors’ knowledge that such an MCM system in the mm-wave regime with this level of integration has been characterized, fabricated, and encapsulated entirely using additive manufacturing.
When MMICs are placed within a cavity, there is a gap between the chip and the outside metal connections, which is typically bridged with bond wires or ribbons, as shown in Fig. 1(b). Bond wires are nonplanar and typically feature an arcing shape, which effectively increases the length of the wire. Increasing the wire length would, in turn, increase the mismatch due to a larger inductance and a larger discontinuity between the chip pads and the transmission lines. To reduce the length-induced wire inductance, inkjet-printed interconnects are proposed as an alternative; a novel inkjet printing approach presented in this article addresses the need for an accurate filling of the gap between the MMIC and the substrate with a dielectric in a smooth fashion despite its very steep transitions.

The materials required for the printed interconnect prototypes were inkjet printed using a Dimatix-2800 series inkjet printer. An SU8 photoresist ink was inkjet printed as the dielectric material, and the metallization was accomplished using Suntronic EMD5730 silver nanoparticle (SNP) ink from Sun Chemical. SU8 has a dielectric constant of 2.85 and a loss tangent of 0.04 at above 20 GHz [19] and is formulated according to [20] to have a viscosity of 13 cP, making it suitable for inkjet printing. The Suntronic EMD5730 has a volume resistivity of 5–30 $\mu\Omega \cdot$cm according to the manufacturer’s datasheet. The LNA used for the characterization of the interconnects is the Analog Devices ALH369 Ka-band amplifier that was hardbaked at 155 °C for 30 min. Finally, three layers, which correspond to around 5-$\mu$m metal thickness, of SNP ink, at 20-$\mu$m drop spacing, were printed as interconnects for pad-to-pad or pad-to-board connections. The SNP ink was sintered at 150 °C for 30 min. The proof-of-concept front-end MCM is interconnected in an identical fashion, except with the board-level circuitry also additively printed. The encapsulant is 3-D printed using FormLabs Form 2 High Temperature material and was adhered around the chip on the board using inkjet-printed SU8 epoxy. The additional FSS features printed on the top of the encapsulant were inkjet printed using the identical SNP printing techniques described previously.

III. Measurements

Three different test vehicles were fabricated in this article to evaluate this novel packaging technique. Initially, a completely passive transmission line structure was fabricated with a 400-$\mu$m-wide, 100-$\mu$m-deep gap separating the two transmission lines. Another continuous (no gap) transmission line was also fabricated on the same substrate with the same dimensions as a benchmarking reference for the printed interconnects to compare the losses between the two. Second, the active ALH369 LNA was connected using the same inkjet-printed technique, with 2 fabricated to evaluate the consistency. Using the same evaluation board, two ribbon-bonded LNA samples were fabricated and used as a test benchmark against the inkjet-printed samples. Finally, an entire MCM utilizing three distinct MMICs was fabricated and encapsulated.

A. Transmission Line

As an initial technology demonstrator, interfacing two passive structures was seen as the most logical first step. Two 50-$\Omega$ transmission lines on the MEG6 substrate were fabricated with a separation gap distance of 400 $\mu$m. This distance was chosen for a few reasons. First, it considers milling accuracy, and second, it gives spacing for the ribbon bonder to make a good bond due to the size of the ultrasonic head. A 100-$\mu$m-deep gap was then milled into the substrate, creating a cavity. An equivalent circuit for the proposed inkjet-printed interconnect is shown in Fig. 4 based on models found in the literature. The gap-filling process is shown in Fig. 5,
and it is visually clear that the inkjet-printed dielectric SU8 material completely filled the cavity creating a smooth transition between the two transmission lines. Following UV cure and postbaking, a small interconnect that was 75 μm in width was printed to bridge the two transmission lines. Southwest Microwave end-launch connectors were attached to the two ends of the transmission lines in order to facilitate VNA measurements. Measurements that were taken of the return loss and insertion loss of the printed interconnect were plotted in comparison to a continuous thru transmission. The data in Fig. 6 show an approximate 0.5-dB nominal degradation from a regular transmission line $S_{21}$, with an exception at 35 GHz, where the printed interconnect experiences a slight resonance with the insertion loss dipping $-2.5$ dB. This is experimentally found to be due to the increased inductance, which causes a resonance in the printed interconnect versus a regular transmission line. This resonance can be reduced by printing a thicker trace, but the trace thickness is limited by the chip pad dimensions discussed later in this article.

### B. Active Devices

To evaluate the performance of the inkjet-printed interconnect technology in real-world applications, active devices underwent the same inkjet-printed gap-filling interconnect fabrication process. Traditionally, MMIC devices require ribbon bonding for the RF interconnects, so it is necessary to offer a comparison between the traditional and the new technique.
In an effort to better understand the effects of the proposed interconnects on amplifier gain, the \( |S_{21}| \) measurements of the two printed and two bonded interconnect devices are averaged accordingly and subtracted from one another to identify the difference in gain. Fig. 9 shows the average gain versus frequency of the LNA with printed and bonded transitions (left axis). The average \( |S_{21}| \) measurements for bonded transitions are subtracted from the average \( |S_{21}| \) of the printed transitions, yielding a plot of \( |S_{21}| \) difference presented in Fig. 9 (right axis). From the measurements, it is clear that due to the decreased interconnect length and inductance, better matching was achieved, leading to a better insertion loss/gain performance. The average increase in the gain is at least 1 dB and with a peak of 3.3-dB improvement over the whole frequency range of 20–40 GHz. The improvement is especially noticeable in 30 GHz and above where the decreased inductance in the inkjet-printed interconnect translates to a weaker resonance.

### C. Front-End MCM

The front-end MCM consisting of three active MMICs along with a smart encapsulation is the final proof-of-concept demonstrator of this article. With the characterization of the inkjet-printed interconnects complete, fully functioning systems can utilize the inkjet printing technology for interconnects. The ALH369 LNA was used as the receiver IC, the TGA4036 was used as the transmitter IC, and TGS4302 was used as the switching module between the TX/RX and the
shared output port, allowing for time-domain duplexing in the same module. All the packaging is done in a fully additive fashion. Instead of the copper circuit board interface, the entire circuit board conductor layer was inkjet printed on Rogers 4003C instead of MEG 6 due to the better adhesion SNP on the Rogers substrate. This enhances the speed of production and reduces the tooling required as a major portion of the fabrication process is done on a single inkjet printer. The system is shown in Fig. 10. The module’s S-parameter performance is plotted in Fig. 11, demonstrating the performance of both TX and RX chains and the isolation between the TX and RX paths. From Fig. 11, both the LNA and PA turn on and provided gain, which is nominally around 3.5–4 dB below the bare die measurements. This considers the losses of the switch MMIC and additional chip-to-chip (PA to switch and switch to LNA) interconnects and the transmission line losses and Southwest connectors, which is in line with the expected losses from this system.

Additionally, the devices were encapsulated for environmental shielding purposes with a cavity to reduce dielectric loading on the front-end MCM. The nature of the additive manufacturing method allows for a straightforward incorporation of “smart” features on the encapsulation structure. A circular ring FSS was designed at around 24 GHz in order to block out interference in this band of interest. The encapsulation has an air cavity that is 1 mm in height with the thickness of the encapsulant being 0.2 mm, making the total encapsulant height 1.2 mm. The FSS is then printed on top of this 1.2-mm encapsulation structure. Simulation of the FSS was conducted using the Floquet port simulation method in CST Microwave Studio and following design guidelines outlined in [26] and [27], and the circular unit cells were kept at around one wavelength at 24 GHz. Due to the size constraints, only a $3 \times 3$ FSS was utilized. From the S-parameter data previously shown, the front-end MCM can cover the 5G mm-wave frequency bands, and thus, it is imperative that the module’s sensitivity is not degraded by the adjacent bands or other mm-wave frequency sources during operation when using a particular frequency.

In order to evaluate RX EMI susceptibility, simulations and measurements were set up to evaluate a potential interferer’s effect on the module, as shown in Fig. 12. In the simulation, the on-package $3 \times 3$ FSS was placed between a CST model of the horn antenna, placed 40 cm away from the module, and a waveguide port. The target frequencies for the FSS to block are a 2-GHz bandwidth around 24 GHz, which covers a good portion of the 24-GHz 5G band and other point-to-point communication standards. Due to the 3-D electromagnetic (EM) model of the chip that was not readily available, a waveguide port was used instead for evaluation purposes to simulate the interference received by the IC. A rough estimate of the interference signal attenuation using the free space path loss equation at 40 cm in addition to the gain of the LNA at 24 GHz (23 dB) results in a combined interference signal attenuation of only around 11 dB, which is approximately what is shown in the simulations in Fig. 13. The simulation results demonstrate a clear filter response at around 24 GHz due to the $3 \times 3$ FSS capping compared to the baseline, with no FSS capping in between the two waveports. The fabricated 3-D printed encapsulant on top of the MCM is shown in Fig. 14.
performance of the MCM. This enhances the capabilities of the module providing features that enhance EMI shielding and helps to reduce desense, degradation of sensitivity, and lays the groundwork for more advanced “smart” features to be incorporated into the packaging, such as sensors or antennas.

IV. CONCLUSION

In this article, the fundamental additive manufacturing technology of inkjet-printed interconnects is characterized for passive devices and active MMICs, exhibiting minimal losses across the majority of the 5G mm-wave frequency bands. This article also demonstrates for the first time a low-cost additive manufacturing approach for fully printed packaging of mm-wave MCM systems, which incorporates “smart” encapsulation in the form of a frequency-selective EMI shield. Additional research is focusing on further integration of MMICs and other components. This includes incorporating additional front-end elements, such as mixers and oscillator ICs and printing on-package antennas, to create fully integrated front-end MCM devices for 5G and Internet-of-Things (IoT) applications. Additionally, this technique of inkjet-printed interconnects increases the reliability of devices because it removes free-standing bond wires and provides a mechanical stress buffer for the cavity-embedded MMICs. However, additional quantitative work needs to be done to evaluate the reliability of this technique for use in high-reliability aerospace or military applications. With low-cost and highly scalable additive manufacturing, wireless circuits and electronics can be rapidly prototyped and deployed into different environments. This article 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.

ACKNOWLEDGMENT

The authors would like to thank D. Fanning and G. Romas of Lockheed Martin for their help in the inkjet printing interconnect characterization efforts.

REFERENCES


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