Additively Manufactured Packaged 75-110 GHz Communication System

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***Abstract*— This report summarizes the main outcomes of the proposed work presented to the 2018 IEEE MTT-S Graduate Fellowship. The project demonstrates an additively manufactured (AM) 75-110 GHz (W-band) transceiver for broadband communications. Goals for the overall system include developing a quasi-planar, highly-integrated, compact communication system with the use of laser-enhanced direct-print additive manufacturing (LE-DPAM) that is feasible and inexpensive for high-volume production. LE-DPAM incorporates laser machining using a pico-second pulsed laser with a 355 nm wavelength along with fused deposition modelling and micro-dispensing in a single digital manufacturing platform. AM fabricated transmission lines, novel interconnects and packaging are demonstrated, the performance of which are either comparable or exceed that of conventional packaging.**

***Index Terms*— Additive Manufacturing, millimeter wave, W-band, 110 GHz, integrated circuits, transceiver, 3D printing, transmission lines, packaging, CPW.**

I. Introduction

MOBILE data traffic is expected to grow at an annual rate of approximately 50% for the next several years, equivalent to a 5x increase in just four years [1]. The increase is due to more throughput per device and a constantly increasing number of devices, spanning new emerging applications that require extremely low-latency. These factors are driving intense interest in fifth generation (5G) wireless technology development, while performance requirements and an already-crowded spectrum below 6 GHz fuel efforts into developing systems that operate in the millimeter-wave (mm-wave) frequency bands. Current 5G technologies are expensive due to complexities in design and manufacturability. Advancements in packaging and semiconductor technology, along with the development of innovative system architectures will be key enablers as 5G emerges and thus remain important areas for current research efforts.

This research focuses on developing the RF electronics, system-level design, interconnect and packaging technology, particularly using additive manufacturing (AM) to enable emerging 5G technologies. Additive manufacturing technologies such as aerosol jet printing (AJP), inkjet printing, and micro dispensing [2-6] are viable for the fabrication of multilayer packages and interconnects with low manufacturing costs. With continued improvements, the size and performance of additive manufactured interconnects are now comparable to those of multilayer printed circuit boards (PCB). Specifically, laser enhanced direct-print additive manufacturing (LE-DPAM) is demonstrated as a viable technology for manufacturing interconnects and packaging that operate up to 110 GHz.

As with other AM approaches, LE-DPAM combines low production costs with fast turn-around time. The pico-second pulsed laser used in LE-DPAM achieves high accuracy for features as small as 5 µm while improving the performance of transmission lines and interconnects. This approach helps to overcome some of the main challenges for AM fabrication such as low conductivity metals, low resolution in the printing features, and maintaining tight tolerances for the circuit dimensions.

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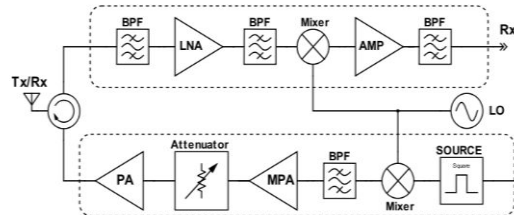

Fig. 1. Simplified transceiver setup.

With a single LE-DPAM platform capable of a 0.5 µm alignment resolution, fused deposition modeling of ABS and micro-dispensing of silver paste (DuPont CB028) were combined with pico-second pulsed laser machining at a wavelength of 355 nm for the digital manufacturing of the proposed mm-wave packaged communication system. Project outcomes are discussed that include novel AM interconnect and packaging techniques for the 75-110 GHz transceiver.

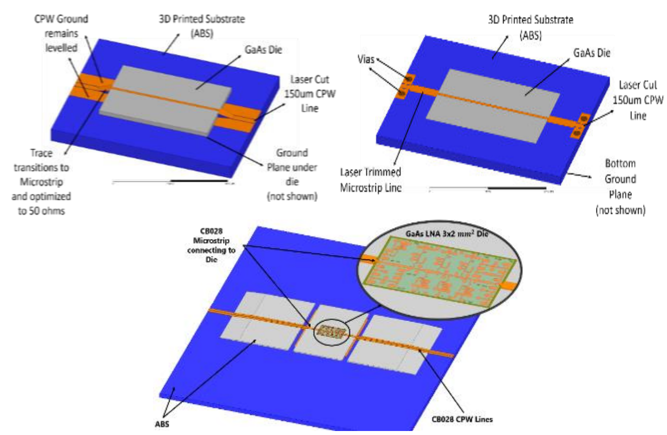

Fig. 2. Illustration of LE-DPAM IC packaging concepts.

II. Motive

Advances in mm-wave packaging have brought greater levels of integration, reduced size and weight as well as performance improvements. Historically, implementations of mm-wave packages were based on split-block, milled metal housings [1]. The need to reduce weight and cost drove the demand for system-in-a-package (SiP) concepts which led to multiple promising techniques for integration such as chip-on-board (COB) or direct-chip-attach (DCA), multi-chip module laminate/deposited/ceramic (MCM-L/C/D) packages, land-grid array (LGA) with integrated antennas, etc. These packaging technologies are non-planar, multi-layered, complex processes that require multiple tools and expensive processing techniques and development. These challenges present opportunities

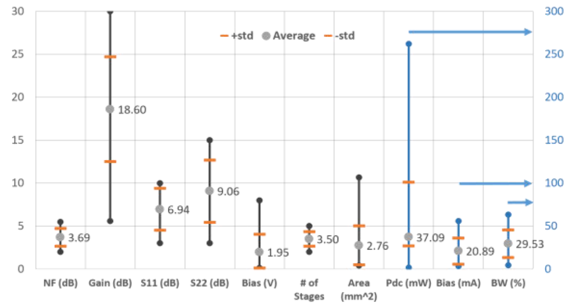

Fig. 3. Avg/Max/Min for W-band LNA parameters in literature.

for AM-based packaging solutions which can offer high performing, low-parasitic, tight integration that is both cost-effective and compact for mm-wave frequency ranges.

III. PROJECT OUTCOMES

A comprehensive literature search was completed on different W-band packaging techniques and W-band MMIC performance for low noise amplifiers (LNA), power amplifiers (PA), switches, and mixers. A summary of W-band LNA performance based on compound semiconductors since 1992-2015 is shown in Fig. 3 [1]. Additionally, the top system-level analysis, such as link budget and atmospheric propagation effects, were studied extensively to determine the RF front-end specifications for a functional communication system. The component level requirements, as well as EIRP, G/T, polarization, side-lobe level and antenna steering angle capability were determined. Additively manufactured dielectrics and conductors were characterized up to 110 GHz. A W-band 3-stage LNA using OMMIC's D007IH foundry process (Fig. 4) was designed and sent out for fabrication, AM-packaged and measured.

To enable the interconnect and packaging of the W-band transceiver, a 0-110 GHz transmission line was demonstrated (Fig. 5) [5]. Additionally, a CPW-microstrip-CPW transition using via and via-less configurations (Fig. 2) with attenuations as low as ~0.3 dB/mm at 110 GHz was demonstrated and shown to be on par with what is possible using high quality, copper-clad microwave laminates. The custom-designed W-band LNA was embedded in a laser-machined cavity to allow the top of the MMIC die to be at the same level as the substrate and was measured up to 110 GHz. This enabled a virtually zero-length interconnect from the substrate to the MMIC. The W-band transmission line and zero-length interconnect was achieved due to careful mm-wave design approaches to avoid the excitation of higher modes. Thus, special attention was given to the surrounding package, CPW feature size, via length and its placement, the selection of finite-ground CPW transmission lines, and thin microstrip substrates.

The 355 nm wavelength pico-second laser-machining process produces high-aspect ratio sidewalls resulting in fine features and smooth vertical walls. The post-deposition laser trimming not only achieves features as small as 5 µm, it also improves the conductivity 100x due to the sintering of the conductive silver paste during laser

TABLE I – SUMMARY OF LNA'S SIMULATED W-BAND PERFORMANCE

Specification	70-110 GHz LNA
NF (dB)	2.86-3.66
Gain (dB)	15.6-19.4
S_{11} *(dB)*	-10
S_{22} *(dB)*	-16
S_{12} *(dB) (Isolation)*	-40
K (in-band stability factor)	Minimum = 9.863
Total Drain Current (mA)	29
O/P P_{1dB} *(dBm)*	-10
# of Stages	3
Die Size	3 mm x 2 mm

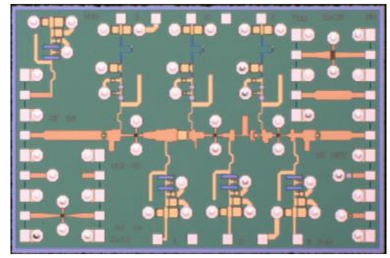

Fig. 4. Fabricated 70-110 GHz LNA with test features.

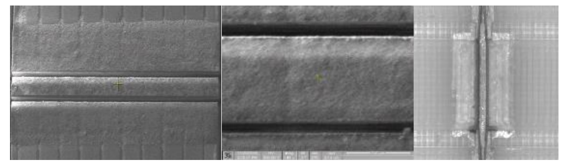

Fig. 5. SEM and optical images of TL and CPW-microstrip-CPW transition.

etching the slots of the transmission lines (Fig. 5). Laser-machined vias with high-aspect ratio sidewalls were fabricated with diameters as small as 100 µm and filled with micro-dispensed CB028 silver paste. Microstrip substrates as thin as 100 µm were also additively manufactured. These advanced packaging techniques demonstrated excellent W-band measured performances on par with traditional manufacturing. Simulations indicate that the same package can operate up to ~170 GHz before higher order modes are excited.

The work achieved will be extended and tested for a complete transceiver system with an integrated AM antenna to demonstrate a full W-band communication system.

IV. CAREER PLANS, PUBLICATIONS, FELLOWSHIP IMPACT AND IMS IMPRESSIONS

I intend to first gain more practical industry experience in the exciting field of millimeter and THz field. Ultimately, I plan to pursue a career in academia to pursue my passion in teaching and research.

During the award period, a paper was published for IMS 2019 and WAMICON 2019 while a peer-reviewed paper is being prepared to present the latest research results [5-6].

The MTT-S fellowship has significantly boosted my confidence in proposal and grant writing, as well as help me outline the overall research goals and timeline. It has significantly provided financial support for my doctoral study and granted me the opportunity to attend IMS 2018 in Philadelphia, Pennsylvania and be exposed to the latest research and meet leading scientists and researchers.

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