

Low-Loss Suspended Crossover Interconnects using Laser Enhanced Direct Print Additive Manufacturing

Omer F. Firat, Mohamed M. Abdin, Jing Wang
Department of Electrical Engineering
University of South Florida
Tampa, Florida, USA
ofirat@mail.usf.edu

Thomas M. Weller
School of Electrical Engineering and Computer Science
Oregon State University
Corvallis, Oregon, USA

Abstract — This paper outlines a new type of versatile 3-D printed suspended coplanar waveguide (CPW) interconnects that are well suited for packaging of mm-wave systems. The design, fabrication process and characterization results are presented. 3D printing quality, namely feature size and dimensional accuracy, was improved by utilizing well-characterized laser machining techniques. The laser machining process enables the control of the dimensions of micro-dispensed conductive traces down to a few micrometers. CPW lines are printed on a fixed-fixed beam and can be extended over the bridge across devices such as a low noise amplifier MMIC chip or another interconnect layer underneath. Acrylonitrile butadiene styrene (ABS) and CB028 conductive silver paste are utilized to fabricate the CPW lines on suspended beams over an air cavity. Simulated and measured S-parameters up to 30 GHz for an interconnect are presented. The conductor width, ground width, and slot width are 160 μm , 260 μm , and 20 μm , respectively. The measured transmission line loss of the suspended CPW line is 0.26 dB/mm at 30 GHz.

Index Terms — millimeter wave, 3D printing, suspended FG-CPW, additive manufacturing, laser machining

I. INTRODUCTION

Millimeter-wave (mm-wave) wireless technology will play an important role in next-generation 5G mobile communication systems [1]. This shift to a higher frequency will result in wider channel bandwidth along with smaller components. However, current packaging and integration techniques for mm-wave devices are costly and relatively complex [2-3]. The increasing demand for higher frequencies and smaller feature size devices brings about the importance of developing and characterizing new packaging technology. Destructive parasitics, especially at high frequencies, affect the frequency response in traditional surface mount and wire bonding technology. These limitations have motivated studies on IC integration techniques to improve performance in a cost-effective manner [4].

System-on-package (SoP) is a method that enables direct integration between integrated circuit (IC) dies and

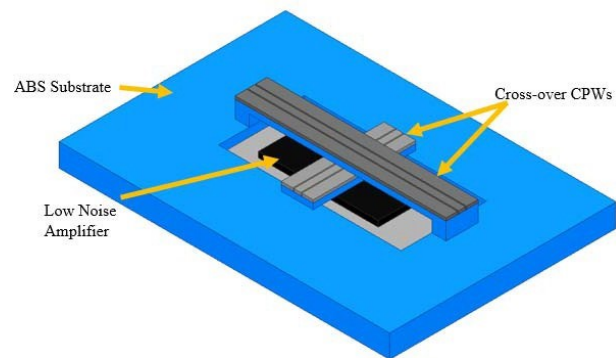


Fig. 1. A potential application of suspended interconnects - isometric view of the additively manufactured interconnects over a chip placed in a cavity.

interconnects so that frequency-dependent destructive parasitics and system size can be reduced. Therefore, this SoP technique shows promising advantages for mm-wave IC device integration and packaging.

Additionally, the use of additive manufacturing (AM) in recent years has attracted a great deal of interest. Different devices have been successfully demonstrated such as transmission lines, waveguides, antennas, and filters [5-8]. Specifically, recent advances have shown the feasibility of additive manufacturing with the realization of cost-effective multilayer packages and interconnects [9-14]. All of these devices have shown performance comparable to other commercial fabrication techniques, such as printed circuit board technology [15]. However, there is clearly still a need to investigate and characterize the innovative design of interconnects that will enable the combination of these components into an integrated packaged system.

This paper presents a new approach for the realization of suspended interconnects at microwave and mm-wave frequencies that could be used in SoP-type packaging. The method uses a combination of additive manufacturing processes and laser machining to fabricate the proposed interconnects. Specifically, 3D printed flexible and low-loss suspended CPWs are fabricated utilizing fused

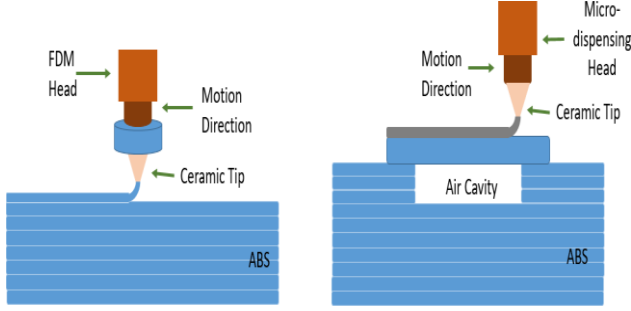


Fig. 2. Direct print additive manufacturing (DPAM) process for (a) FDM to deposit ABS substrate with the embedded cavity; (b) CB028 micro-dispensing on top of printed ABS bridge suspended across the cavity.

deposition modeling (FDM), and micro-dispensing technologies along with laser machining. These suspended interconnects could enable direct integration of multiple active or passive device chips with low coupling in SoP implementations.

As illustrated in Fig. 1, using the proposed suspended CPW scheme, multiple interconnects could be fabricated in a vertical configuration above device chips that may be embedded in a 3D printed substrate. It is also possible to make direct connections to embedded devices.

The following sections present the design, fabrication and preliminary characterization data for the suspended CPWs. The measured attenuation of the lines is approximately 0.26 dB/mm at 30 GHz. To the best of the authors' knowledge, this is the first demonstration of an mm-wave, suspended transmission line that is fabricated using an additive manufacturing approach.

II. DESIGN AND FABRICATION OF INTERCONNECTS

ABS was printed using FDM as a dielectric substrate and DuPont CB028 was selected to realize conductive traces by micro-dispensing technique using a single additive manufacturing platform (nScript 3Dn tabletop). The measured dielectric constant (ϵ_r) of ABS was found to be 2.35 with $\tan\delta$ of ~ 0.0065 at 30 GHz [16]. In the first fabrication step, a 400 μm thick ABS substrate is printed using FDM, including a $1.5 \times 10 \times 0.25 \text{ mm}^3$ cavity over which 2 mm long ABS bridges are formed by direct FDM printing and suspended across the cavity. The ABS filament is extruded at 235 $^\circ\text{C}$ while using a 125 μm inner diameter ceramic tip, and the design structure is formed over a 110 $^\circ\text{C}$ -heated metal bed. Fig. 2 (a) and (b) illustrate the fabrication process of the suspended CPW interconnects.

Multiple factors affect the formation of the bridges, namely cavity size, bridge print speed, and cooling (by using a fan for example). The process was optimized to achieve uniform and repeatable ABS bridges. The

optimum settings for a 125 μm inner diameter tip were found to be 25 mm/s bridge print speed, 1.0 mm to 1.5 mm long cavity size and a fan position placed 30 cm away from the printer bed.

The SEM image of some printed ABS bridges over the cavity using these settings is shown in Fig. 3.

With FDM, a structure is created in a layer-by-layer fashion from a rounded tip. When the material is printed onto a bed or a substrate, the tip applies a certain amount of pressure based on desired layer thickness, therefore the printed area becomes flat. However, if there is no material underneath the printed area, there is no pressure for the tip, thus the print shape retains the shape of the tip; as a result, the shape of the bridges over the cavity is cylindrical. Additionally, the suspended ABS material bends upwards during its cooling phase due to internal tension mechanisms. Due to these factors, a technique involving laser heating/machining was developed to flatten the top surface of the bridges.

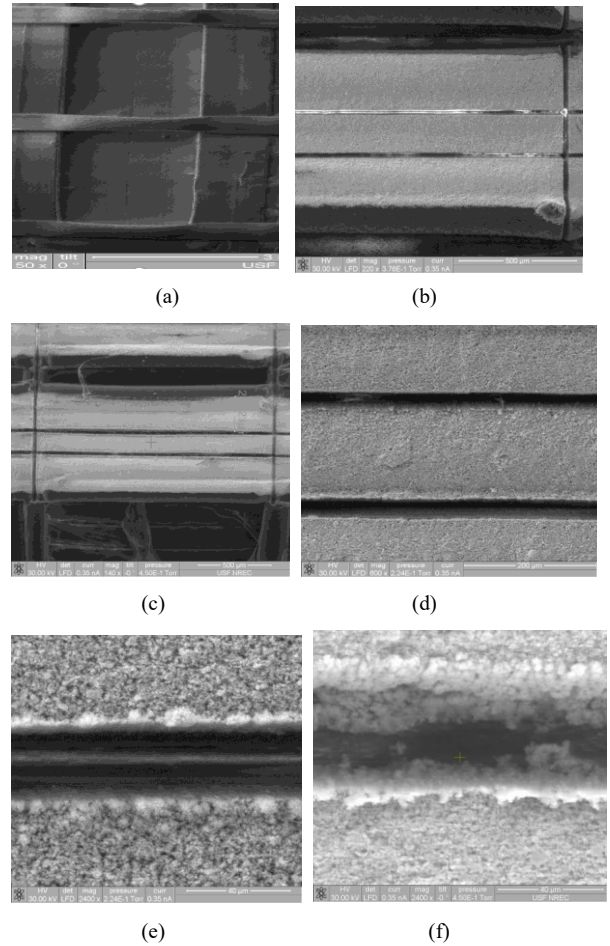


Fig. 3. SEM image of (a) top view of flat bridges, (b-c) Laser machined AM CPW cross-overs, and (c-f) 20 μm slot in silver paste.

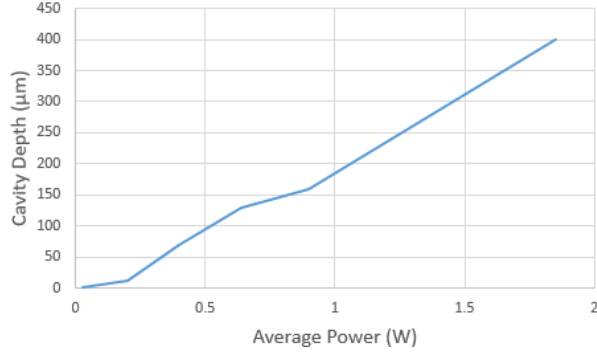


Fig. 4. ABS Laser Characterization

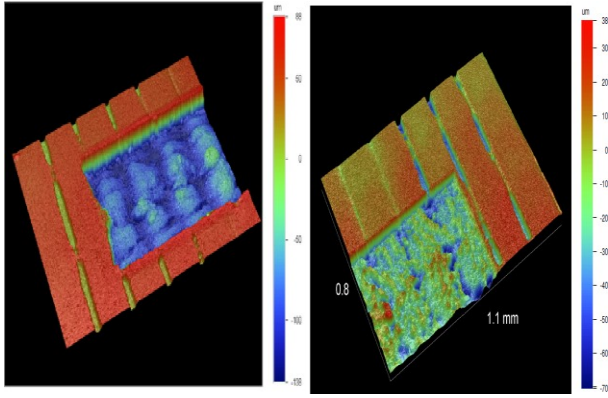


Fig. 5 a) 3D optical profiler image of the laser machined cavity on ABS with an average laser power of 0.2 W, and b) 0.4W average power level.

This technique involves programming the picosecond laser (Lumera Laser's SUPER RAPID-HE) to etch/melt the ABS bridges without causing them to bend down or detach from the surface.

In order to determine the optimum average laser power level for the melting process, one flat ABS sample was printed and then multiple cavities with dimensions of 1.5 mm x 0.5 mm² were laser machined at different average power settings using a laser machining wavelength of 355 nm. The machined cavity depths were measured with a Dektak 150 profilometer and are shown in Fig. 4. A WYKO 9100NT Optical Profiler was utilized to visualize 3D schematic images of the generated cavities with 0.2 W and 0.4 W average laser power as seen in Fig. 5 (a) and Fig. 5(b), respectively. Based on these laser characterization experiments, the optimum power level was determined to be 0.025W with 3 passes to flatten the bridges.

After finding the optimum ABS bridge print conditions, 720 μm wide bridges were printed to accommodate the center conductor, ground and slot widths of the CPW lines. The ABS bridges were then flattened using the laser process described above. After that, Dupont CB028 conductive layers were micro-dispensed onto the ABS bridges using the 125 μm inner diameter tip to form 1.5

mm long traces. The thickness of the conductor can vary between 30 μm to 90 μm because of the height difference between the flat substrate surface and the bridge height. The printed CB028 was dried in-situ on the heated bed for 1 hour at 90 °C. This process achieves a 2e6 S/m conductivity of the printed CB028 [16]. Finally, the picosecond laser was utilized with the average power level of 0.4 W and at a repetition rate of 100 kHz to machine 20 μm wide slots in the CB028 to form the 50-ohm CPW lines.

III. MEASURED RESULTS

In order to predict the CPW crossover performance, finite element method (FEM) simulations were performed using Ansys HFSS 19 for a single suspended interconnect. Simulations show that the insertion loss (IL) is < 0.4 dB for 1.5 mm long CPW line and return loss (RL) is > 20 dB from DC to 30 GHz.

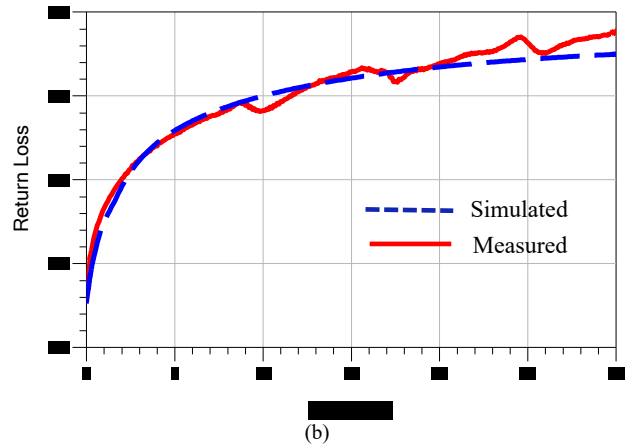
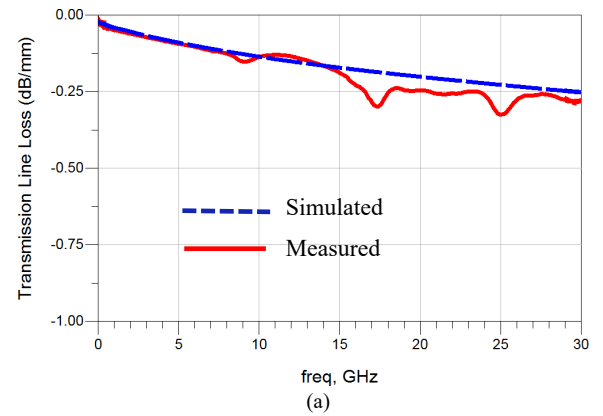


Fig. 6. Simulated and measured data for a 1.5 mm long CPW line (a) transmission line loss (dB/mm), and (b) return loss (S11) in dB.

Measurements were performed from DC to 30 GHz using a Keysight performance network analyzer (PNA) N5227A with standard 150 μm pitch ground-signal-ground (GSG) microwave probes from GGB. A multi-line Thru-Reflect-Line (mTRL) probe tip calibration was performed using a GGB CS-5 calibration substrate. Fig. 6 shows the measured and simulated S-parameters of a single fixed-fixed suspended CPW line with a length of 1.5 mm. The attenuation of the CPW line is 0.13 dB/mm at 10 GHz, 0.24 dB/mm at 20 GHz, and 0.26 dB/mm at 30 GHz. The fabrication difficulty of the conductive layers over the bridge causes a small amount of thickness variation, and that results numerically very small simulation / measurement difference.

IV. CONCLUSION

The design, fabrication, simulation, and measurement of suspended CPW cross-over interconnects for SoP microwave, and mm-wave applications have been demonstrated. Wideband performance from DC to 30 GHz was obtained exhibiting low loss. The suspended interconnects could enable a direct integration in SoP implementation with a fairly low loss. The laser enhanced direct print additive manufacturing approach utilized for this work shows the potential to become an important approach for SoP-type packaging for the next generation wireless systems such as 5G and, mm-wave transceivers.

REFERENCES

- [1] M. M. Abdin, W. Joel, D. Johnson and T. M. Weller, "A system and technology perspective on future 5G mm-wave communication systems," *2017 IEEE 18th Wireless and Microwave Technology Conference (WAMICON)*, Cocoa Beach, FL, 2017, pp. 1-6.
- [2] Y. P. Zhang and D. Liu, "Antenna-on-Chip and Antenna-in-Package Solutions to Highly Integrated Millimeter-Wave Devices for Wireless Communications," in *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 2830-2841, Oct. 2009.
- [3] A. Jentsch and W. Heinrich, "Theory and measurements of flip-chip interconnects for frequencies up to 100 GHz," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 5, pp. 871-878, May 2001.
- [4] B. K. Tehrani, et al., "Inkjet-printed 3D interconnects for millimeterwave system-on-package solutions," *2016 IEEE MTT-S International Microwave Symposium (IMS)*, San Francisco, CA, 2016, pp. 1-4.
- [5] E. A. Rojas-Nastrucci, J. T. Nussbaum, N. B. Crane and T. M. Weller, "Ka-Band Characterization of Binder Jetting for 3-D Printing of Metallic Rectangular Waveguide Circuits and Antennas," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3099-3108, Sept. 2017.
- [6] D. C. Lugo, R. A. Ramirez, J. Wang and T. M. Weller, "Multilayer Dielectric End-Fire Antenna With Enhanced Gain," in *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 12, pp. 2213-2217, Dec. 2018.
- [7] D. Hawatmeh and T. Weller, "2.4 GHz Band Pass Filter Architecture for Direct Print Additive Manufacturing," *2018 IEEE/MTT-S International Microwave Symposium - IMS*, Philadelphia, PA, 2018, pp. 67-70.
- [8] M. M. Abdin, W. J. D. Johnson, J. Wang and T. M. Weller, "W-band Finite Ground Coplanar Waveguide (FG-CPW) using Laser Enhanced Direct-Print Additive Manufacturing (LE-DPAM)," *2019 IEEE/MTT-S International Microwave Symposium - IMS*, Boston, MA, 2019, unpublished.
- [9] C. Mariotti, F. Alimenti, L. Roselli and M. M. Tentzeris, "High-Performance RF Devices and Components on Flexible Cellulose Substrate by Vertically Integrated Additive Manufacturing Technologies," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 1, pp. 62-71, Jan. 2017.
- [10] M. T. Craton, J. Sorocki, I. Piekarczyk, S. Gruszczynski, K. Wincza and J. Papapolymerou, "Realization of Fully 3D Printed W-Band Bandpass Filters Using Aerosol Jet Printing Technology," *2018 48th European Microwave Conference (EuMC)*, Madrid, 2018, pp. 1013-1016.
- [11] A. Delage *et al.*, "Aerosol jet printing of millimeter wave transmission lines on 3D ceramic substrates made by additive manufacturing," *2018 IEEE/MTT-S International Microwave Symposium - IMS*, Philadelphia, PA, 2018, pp. 1557-1560.
- [12] F. Cai, Y. Chang, K. Wang, C. Zhang, B. Wang and J. Papapolymerou, "Low-Loss 3-D Multilayer Transmission Lines and Interconnects Fabricated by Additive Manufacturing Technologies," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 10, pp. 3208-3216, Oct. 2016.
- [13] R. A. Ramirez, D. Lan, J. Wang and T. M. Weller, "MMIC packaging and on-chip low-loss lateral interconnection using additive manufacturing and laser machining," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, Honolulu, HI, 2017, pp. 38-40.
- [14] E. A. Rojas-Nastrucci, R. Ramirez, D. Hawatmeh, D. Lan, J. Wang and T. Weller, "Laser enhanced direct print additive manufacturing for mm-wave components and packaging," *2017 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, Verona, 2017, pp. 1531-1534.
- [15] T. P. Ketterl, et al., "A 2.45 GHz Phased Array Antenna Unit Cell Fabricated Using 3-D Multi-Layer Direct Digital Manufacturing," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 12, pp. 4382-4394, Dec. 2015.
- [16] E. A. Rojas-Nastrucci *et al.*, "Characterization and Modeling of K-Band Coplanar Waveguides Digitally Manufactured Using Pulsed Picosecond Laser Machining of Thick-Film Conductive Paste," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3180-3187, Sept. 2017.