Direct Digital Manufacturing of mm-Wave Vertical Interconnects

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***Abstract*—Additive manufacturing (AM) is increasingly being shown as a viable technology for the fabrication of complex 3D structures. For microwave components, the combination of laser processing and AM techniques has been reported to enhance the performance and frequency limits of the devices. In this paper, a process to fabricate a 200 µm x 200 µm x 200 µm vertical interconnect that combines fused deposition modeling (FDM), micro-dispensing, and picosecond laser machining is studied. A test structure that includes two vertical transitions is designed, fabricated, and tested, as a performance benchmark. The 4 mm long structure shows a low dissipative loss (2.5 dB at 45 GHz) and excellent frequency response up to mm-wave frequencies. The described structure will help to enable the fabrication of high-performance structural RF electronics.**

***Index Terms*—3D-printing, Additive manufacturing, CPW, interconnect, mm-wave, structural electronics, via.**

I. Introduction

Additive manufacturing (AM) provides a design freedom regarding materials and 3D geometries, that is not possible to achieve by traditional subtractive fabrication [1]. Advantages of performance, size, weight, and cost have been reported in application areas that range from biomedical engineering to aerospace [1]. In the field of electronics, it has been shown that 3D printing enables the fabrication of structural circuits [2]. Furthermore, successful fabrication of multilayer RF systems has also been reported [3]. However, limitations on the resolution, surface roughness, and the microwave material properties such as electrical conductivity and dielectric losses are still being addressed by the community.

Vertical interconnects are a fundamental element for AM RF structural electronics. Technologies such as aerosol jet printing (AJP) [4], inkjet[5], micro-dispensing and fuse deposition modeling [3], have been used in the past for the fabrication of vertical interconnects. Other publications have reported the combination of AM with laser processing to achieve lower losses, and increased frequency range [6], as well as multilayer interconnects [7].

In this paper, a technique that combines fused deposition modeling (FDM), micro-dispensing, and picosecond laser machining, introduced in [8], is used to fabricated a mm-Wave multilayer coplanar waveguide (CPW) test structure (Fig. 1). This structure is comprised of a total of 4 mm of coplanar waveguide and two vertical transitions. Measured data show an overall dissipative loss of 2.5 dB at 45 GHz, and the overall performance agrees with simulations. A low-loss via of 200 µm x 200 µm x 200 µm is demonstrated.

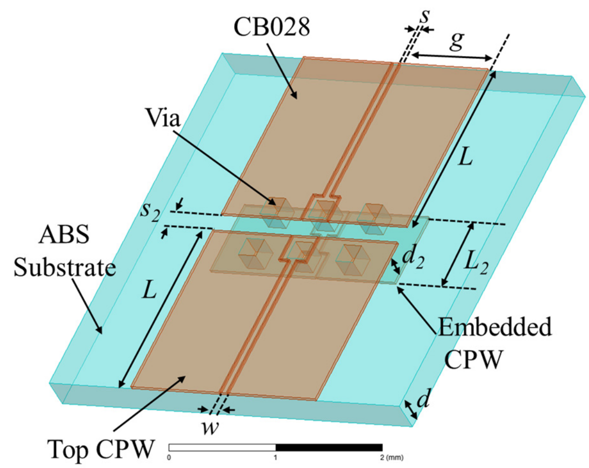


Fig. 1. CPW via test structure. This structure has a total of 40 mm of transmission line length and two vertical transitions.

II. Design and Fabrication

With the purpose of testing the performance of the via, a multilayer CPW line with two vertical transitions is designed (Fig. 1). Such a structure allows the use of GSG RF probes for testing and characterization. The substrate material is chosen to be acrylonitrile butadiene styrene (ABS) due to its excellent mm-wave electrical properties [9], which are a relative electric permittivity ε_r= 2.39 and a loss tangent $tan\delta$= 0.0066 at 30 GHz. For the conductive layers, DuPont CB028 silver paste is used, which has a DC conductivity around 4 MS/m. The geometries are laser machined, which has been shown to improve the effective electric conductivity of the paste to around 10 MS/m [6].

Fig. 1 indicates the overall dimensions of the test structure, which are w = 85 µm, s = 12 µm, and g = 1 mm, for the CPW. These dimensions result in a characteristic impedance of 41 Ω, and a single mode operational bandwidth (based on keeping the CPW line width below λ_g/10) above 63 GHz. The line geometry, and thus the impedance, were chosen to ensure that the structure could be tested with the available probes in consideration of the probe pitch and also having a sufficiently large center conductor to ensure its physical integrity. All the simulations are done in Ansys Electronics Desktop 2016.2. On the top layer, two transmission line segments of length L= 1.9 mm, are connected to a bottom CPW layer of length L_2= 0.8 mm, that is embedded into the ABS substrate at a depth d_2= 200 µm. The total substrate thickness is d= 300 µm.

The fabrication is performed on a single system, a nScrypt 3Dn tabletop, that combines the capabilities of FDM and micro-dispensing, and that is integrated with a Lumera Super-Rapid-HE picosecond pulsed laser. Fabrication starts by 3D printing a 100 µm thick layer of ABS, using 50 µm thick individual layers, with a bed temperature of 90°C and an extruder nozzle at 235°C. The extruder tip diameter is 200 µm (Fig. 2(a)). This is followed by micro-dispensing of DuPont CB028 silver paste, using a nozzle of 125 µm inner diameter, 25 mm/s speed, printing height of 100 µm, and air pressure of 12 psi, as shown in Fig. 2(a). Laser machining is then used (Fig. 2(b)) in the same system, to create the required CPW slots as shown in Fig. 1. The laser wavelength is 1064 nm, the spot size is 12 µm, the average power is set to 1 W, the repetition rate to 100 KHz, and the speed to 25 mm/s. A total of two passes are used to achieve the slots.

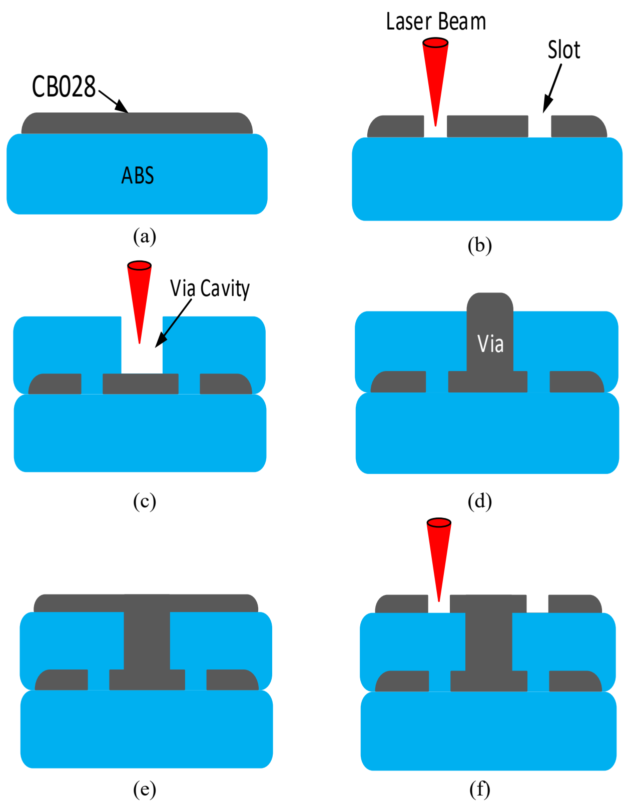


Fig. 2. Fabrication steps using FDM of ABS, micro-dispensing of CB028, and picosecond laser machining.

A second layer of ABS is deposited using FDM, which is then laser machined to create the via cavity in the substrate. This cavity is fabricated by sweeping the described beam setting on squared patterns of sweeps that are separated by 20 µm. These sweeps are repeated an average of 20 times, until the laser reaches the bottom CB028 layer, as shown in Fig. 2(c). Note that because of the undulated nature of the 3D printed ABS, the cavity depth was monitored every five passes, by using an IR camera and a laser scanner. The via cavity is then filled with CB028 using the micro-dispensing capability of the nScrypt printer. The tip of the pump is placed right on top of the via opening, and the valve is opened by 0.7 mm, and closed when the cavity is filled (Fig. 2(d)). The top conductive layer is micro-dispensed (Fig. 2(e)) and laser machined as depicted in Fig. 2(f), using the settings previously described. Note that the laser is also used to electrically separate the two top CPW lines, by s_2= 200 µm, as showing in Fig. 1.

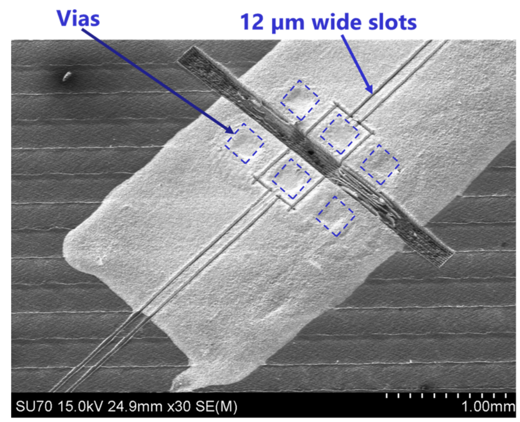


Fig. 3. SEM micrograph of the fabricated Via test structure.

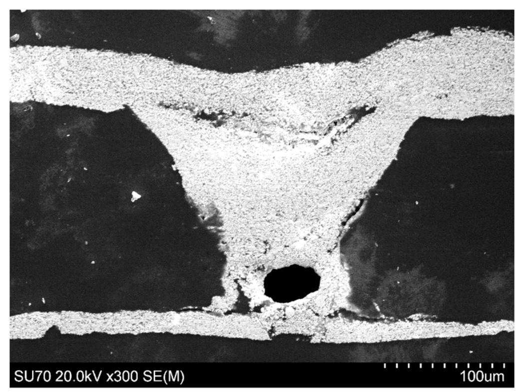


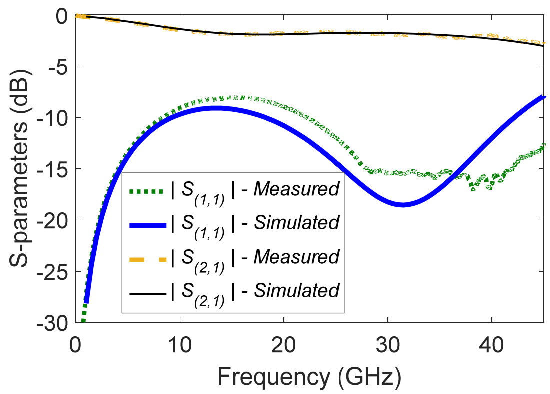
Fig. 4. Vertical cross-section of a single via structure.

III. Results

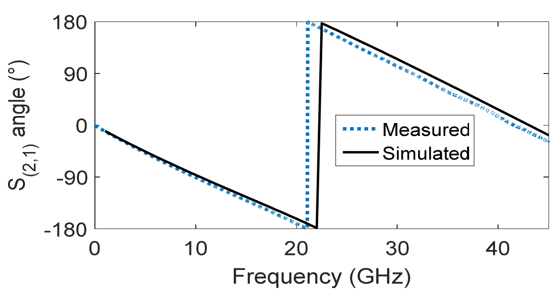
Fig. 3 shows a scanning electron microscope (SEM) image of the fabricated test structure. The position of the six vias is marked. Among the features that can be seen are the CPW slots, which are 12 µm wide, and the machined gap between the two top CPW lines. It is also possible to observe the FDM extrusion paths on the ABS substrate, which have a 45° angle with respect to the CPW. The part shown in Fig. 3 was placed on a two-part epoxy matrix, sliced, and polished to observe the structure of the via (Fig. 4). Note that the walls of the cavity are not vertical. This is an undesired effect of the laser machining that can be improved by changing the sweep orientation in between passes of the laser. Also, note the presence of an air cavity in the bottom middle of the structured. Such a cavity could be generated by air trapped inside the paste during the via filling process. The presence of those defects are reduced for larger via structures.

The minimum via size is primarily dictated by the ability to fill the cavity with the micro-dispensing system. With the current settings, a practical limit of 100 µm x 100 µm was found.

The S-parameters of the test structure are measured using a Keysight PNA N5227A, and GGB 40A 650 µm pitch probes. The PNA is calibrated using a CS-10 GGB Picoprobe substrate. The measured and simulated results are shown in Fig. 5. Note that the measured response, in particular, the transmission magnitude and phase, closely match the expected response from the simulation. This indicates that no major defects are present in the vias.



(a)



(b)

Fig. 5. Measured S parameters. (a) Magnitude of $S_{(1,1)}$ and $S_{(2,1)}$. (b) Phase of $S_{(2,1)}$.

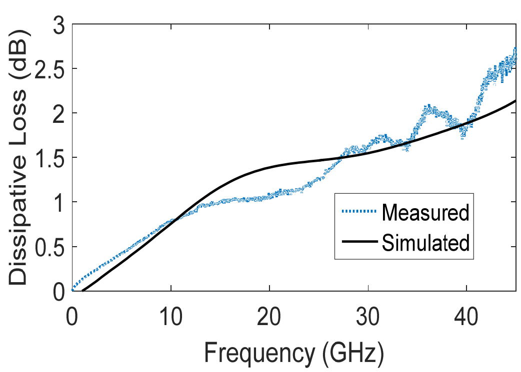


Fig. 6. Calculated dissipative losses of the test structure, including two vertical interconnects.

Fig. 6. shows the computed dissipative losses (*DL*) of the test structure, by using the well-known equation:

$$DL = |S_{(2,1)}|^2 / (1 - |S_{(1,1)}|^2) \quad (1)$$

where the S-parameters are in linear form. Note that the total loss at 40 and 45 GHz is 2 and 2.5 dB, respectively. To estimate the losses of a single vertical transition, a set of single layer CPW lines with the dimensions *w, s, g*, and length *L,* shown in Fig. 1, are fabricated and measured. These data extend to 40 GHz, and at this frequency the dissipative loss of the CPW lines is 0.7 dB for the 4 mm long lines. Therefore, the dissipative loss on each vertical transition is computed to be 0.65 dB at 40 GHz.

IV. Conclusion

The study presented in this work shows that the combination of FDM, micro-dispensing, and laser processing enables the fabrication of mm-wave low-loss vertical interconnects. Such capability makes possible the implementation mm-wave structural electronics, where the high-frequency circuits are embedded into functional structures.

Acknowledgment

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