Fully Inkjet-Printed Multilayer Microstrip and T-Resonator Structures for the RF Characterization of Printable Materials and Interconnects

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Abstract**—A vertically-integrated, fully inkjet-printed microwave structure is demonstrated for the first time, where both the metallic elements and the platform substrate are completely fabricated with the additive inkjet printing process. The surface uniformity of SU-8 polymer ink is outlined as a function of layer deposition to provide a desirable profile for a thick RF substrate application. Inkjet-printed vias are demonstrated and realized as microwave substrate interconnects within SU-8. Microstrip and T-resonator structures are developed to demonstrate the application of these inkjet-printed platforms for the RF characterization of a printable material, where the relative permittivity of the substrate is extracted as a function of frequency from 1–30 GHz.**

Index Terms**—Dielectric Substrates, Inkjet Printing, Interconnects, Low-Cost Electronics, Printed Circuits, T-Resonator.**

I. INTRODUCTION

The fabrication technology of inkjet printing has been rapidly growing in popularity within the past decade in the realm of electronic device fabrication. Utilizing a purely additive process, specialized inks are used to deposit micron-scale droplets onto a wide variety of substrates to create complex electronic designs, providing a rapid, low-cost, and environmentally preferable alternative to typical cleanroom fabrication methods. The combination of conductive silver nanoparticle-based and dielectric polymer-based ink formulas have recently allowed for the advancement of inkjet printing with the realization of multilayer passive RF components, microfluidic platforms, and high-gain millimeter-wave antenna arrays [1]–[3].

Though there are many demonstrations of inkjet printing technology on such substrates as glass, LCP, and paper, there still exists the need to distance electronic fabrication from a select catalog of RF substrate materials. In such applications as on-chip wireless communication and system-on-package (SoP) devices, circuit isolation and substrate deposition is limited to existing fabrication techniques, which rely on the constraints of the surrounding topology. It is desired to have the ability to fabricate and integrate electronic platforms that are independent and versatile in both material and electrical aspects. The acquisition of this capability leads us to achieving ultra-miniaturized electronics which require extremely high integration of RF and other device components.

This work demonstrates the first fully additive, vertically-integrated deposition of a complete microwave structure on an electrically isolated glass substrate. The fully printed structure consists of a printed ground plane, thick dielectric substrate, and electronic topology. Inkjet-printed vias are constructed and characterized in relation to the effects of printed substrate uniformity. As an application of this platform, a microstrip line and T-resonator structure are utilized to demonstrate a typical microwave material characterization. From this fabrication, the relative permittivity is extracted from the printed dielectric substrate in relation to frequency from 1–30 GHz. The results demonstrate the feasibility of fully inkjet-printed platforms and systems that have the potential to be deposited on virtually any material. This work suggests the possibility of further application of printed electronic technology for on-chip electronic fabrication.

II. FABRICATION PROCESS CHARACTERIZATION

The vertically-integrated inkjet fabrication process utilizes the Dimatix-2831 (www.dimatix.com) printing platform, a piezoelectric drop-on-demand inkjet system. The conductive ink used to pattern metallic layers is ANP Silverjet DGP-40LT-15C (ANP Corporation, Sejong-si, South Korea), which contains 30-35 $w\%$ silver nanoparticles dispersed in a TGME (triethylene glycol monoethyl ether) solvent. This ink is used as received with a viscosity of 10 cP and a surface tension of 35 mN/m. Once printed, the metallic ink is sintered in an oven at 180 °C for one hour, yielding 800 nm thick layers with a resistivity of 11 $\mu\Omega$-cm.

The dielectric ink used to pattern insulating layers is a long-chain polymer ink formulated to produce dielectric layers with thicknesses up to and beyond 100 μm, while also maintaining desirable surface properties that allow silver ink deposition [3]. The polymer ink is a formulation of 35 $w\%$ SU-8 polymer (MicroChem, Newton, MA, USA) in cyclopentane with a UV-cross-linking agent, yielding an ink with a viscosity of 13.4 cP and a surface tension of 30 mN/m. Once printed, the dielectric ink is heated to 120 °C for 10 min before being exposed to a thickness-dependent amount of 365 nm UV light, followed by a post exposure bake at 120 °C for 5 min, yielding layer thicknesses from 4 to 6 μm.

The profile uniformity of a printed structure of SU-8 dielectric is dependent on the number of printed layers deposited in a defined area. For the profile scans in Fig. 1, SU-8 polymer ink is printed on a glass slide in a single printing session of 8 and 15 layers. The 8 layer print yields a uniform profile with a coffee-ring effect present at structure edges. As the layer count increases from 8 to 15 in the 15 layer print, the profile of the structure becomes that of a convex dome. After baking the printed polymers, a second printing session adds 6 more layers to the 8 layer structure, yielding a 14 layer structure without a convex shape. In order to produce thick

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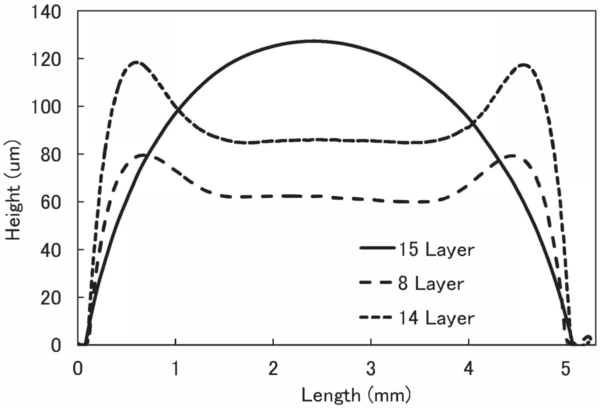

Fig. 1. Profile scans of SU-8 dielectric substrates with single and multiple printing and curing sessions.

dielectric films with uniform profiles, multiple printing and curing sessions are used in this fabrication.

In order to truly realize multilayer inkjet-printed RF devices and modules, inkjet-printed vias have to be realized in this fabrication. From an additive approach, vias are constructed through a lack of material deposition in a small area. One issue with this additive approach of via fabrication is the presence of slanted walls on the edges of printed dielectric structures. Multi-session printing of dielectric layers increases the slope of the walls of dielectric structures, shown in Fig. 2, helping to conform the shape of inkjet-printed vias to traditional vertical-wall vias. The ramp-up distance of the SU-8 sidewalls from zero thickness

A test structure is fabricated in order to determine the DC resistance of the inkjet-printed vias. A four layer (25 μm) dielectric structure with via holes is printed on top of ten traces of four layer (3 μm) silver nanoparticle ink. On top of the dielectric, four-layer silver traces are printed with and without the via connection to the bottom traces in order to determine the DC resistance of the ramp-up vias, shown in Fig. 2. Comparing the DC resistances of the complete and incomplete traces, the printed samples yield an average DC resistance of 0.073 Ω with a standard deviation of 0.041 Ω for the 1 mm length ramp-up vias, which is an improvement on the efficiency [4],[5] and variance [6] of inkjet-printed vias presented in previous works. Table 1 provides a summary of the measured via components.

III. MICROSTRIP LINE

To demonstrate the concept of this purely additive high-frequency fabrication platform, a microstrip line is fabricated on a printed SU-8 substrate with silver nanoparticle ink. In order to achieve the transition from CPW for GSG probe to a microstrip line with a feasible microstrip line width and CPW gap, the thickness of SU-8 is chosen to be 80 μm. The cross section of 8 layers and 14 layers of SU8 substrate are depicted on Fig 1. The edge of the SU-8 substrate has 20 μm and 30 μm peaks respectively because of the coffee-ring effect of the printed film. The CPW to microstrip line transition is printed on top of the peaks, extending the CPW ground lines to the ground plane of circuit. The physical dimensions of the microstrip line with CPW to microstrip line transition are shown in Fig 3. The gap between CPW ground and signal pads is 100 μm.

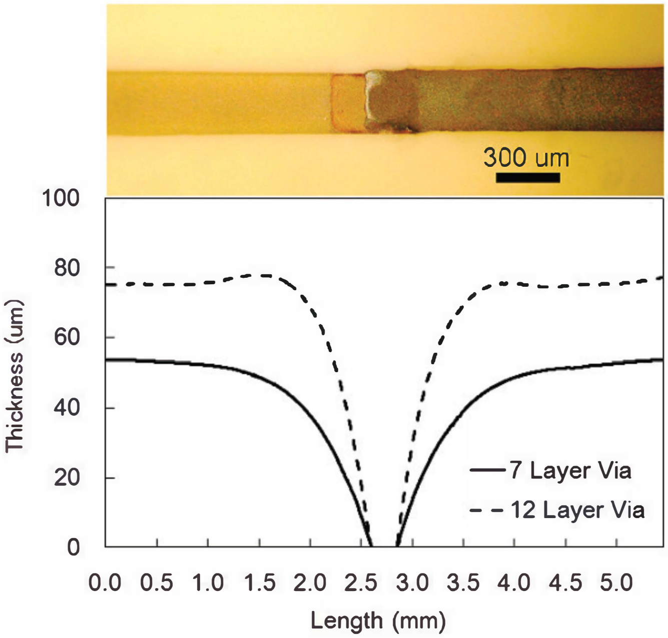

Fig. 2. Profile scans of inkjet-printed vias realized in 7 and 12 layer SU-8 dielectric substrates via transition test structure fabricated to measure DC resistance of ramp-up vias.

TABLE 1

Summary of Measured DC Via Resistances

	Incomplete Lines (Ω) Top	**Incomplete Lines (Ω)** Bottom	**Completed Lines (Ω)**
	0.345	0.251	0.692
	0.328	0.267	0.617
	0.345	0.238	0.623
	0.310	0.241	0.693
	0.298	0.250	0.631
	0.361	0.251	0.685
	0.354	0.235	0.654
	0.364	0.252	0.606
	0.342	0.247	0.676
	0.286	0.238	0.660
Average	0.333	0.247	0.654
Std. Dev.	0.026	0.009	0.031
Via Average	0.073		
Via Std. Dev.	0.041		

In order to characterize the line loss and group delay of the microstrip line, a 37369A vector network analyzer provided by Anritsu is utilized. The effects of probe and open length are de-embedded with the use of a printed TRL calibration. The line loss and group delay of the 6 mm microstrip line with respect to frequency are shown in Fig. 4a and 4b, respectively, from 1–30 GHz. The line loss increases as

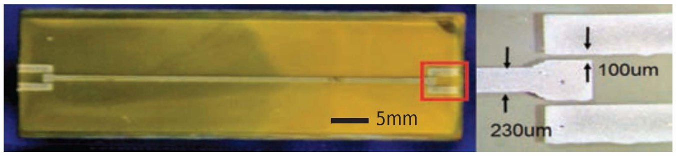

Fig. 3. Physical dimension of microstrip line with CPW to microstrip line transition.

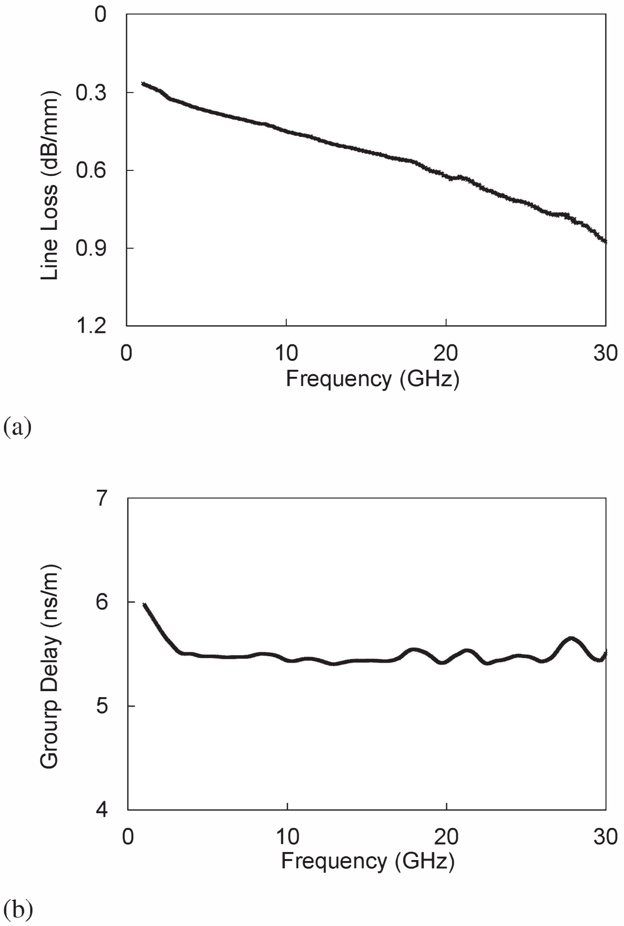

Fig. 4. Microstrip line loss (a) and group delay (b) as a function of frequency.

frequency increases because of an increase in dielectric loss and surface resistance. Additionally, radiation from the line also increases with frequency. The group velocity decreases slightly at lower frequency but remains almost constant above 5 GHz up to 30 GHz which is the measurement limit of the equipments.

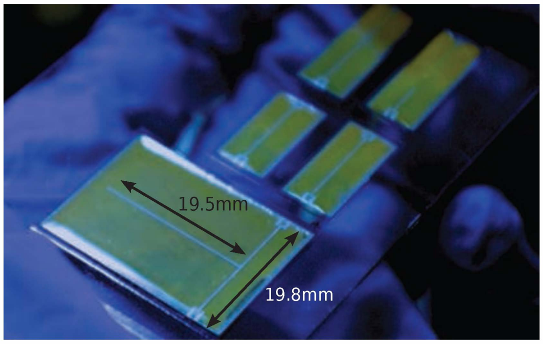

Fig. 5. Physical dimensions of printed T-resonator.

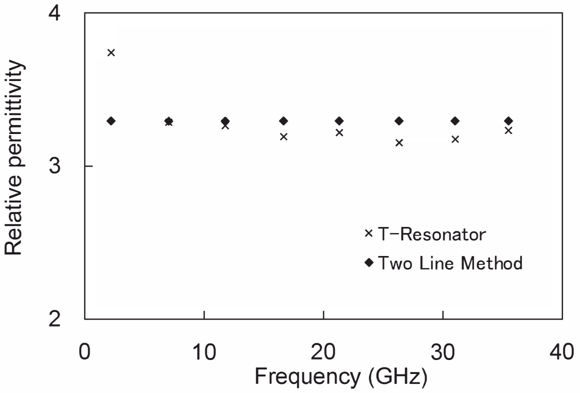

Fig. 6. Relative permittivity of printed SU-8 substrate.

IV. T-RESONATOR

Another structure commonly utilized for RF material characterization is the T-resonator, which can be easily fabricated using multi-layer inkjet printing technologies. As a proof-of-concept demonstration, a purely additive microstrip T-resonator with a fundamental resonant frequency at 2.21 GHz was utilized for the RF characterization of a completely inkjet-printed topology, consisting of a microstrip line on top of a printed SU-8 substrate. Using the harmonics of the resonant frequency at 2.21 GHz, the T-resonator is used to characterize the relative permittivity of the SU-8 substrate up to 30 GHz. Fig. 5 shows the fabricated T-resonator, including a microstrip transmission line with length 19.8 mm and a microstrip resonating line with length 19.5 mm.

To validate the accuracy of the characterization, both T-Resonator and two line method are adopted [7]–[9]. The relative permittivity obtained by utilizing these two methods are shown in Fig. 6. Both of the results are well matched and comparable to results shown in previous work [10]. Measurements also agree with the expected trend in the material characteristics, where the relative permittivity gradually decreases as the frequency increases.

V. CONCLUSION

This work demonstrates the first fully inkjet-printed, vertically-integrated microwave structure, where each element of the platform, including the ground plane and substrate, are deposited through the additive process of inkjet printing. Using this platform, microstrip and T-resonator structures are fabricated in order to extract the relative permittivity of the printed SU-8 substrate. Improvements to material characterization are reserved future work.

Further applications of this technology extend to fabricating microwave structures, such as antennas and RF passive components, on virtually any base material, helping realize a low-cost, environmentally friendly, versatile application platform for SoP and on-chip device topologies.

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