Additive Manufacturing Techniques for Origami Inspired 4D Printed RF Components and Modules

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Abstract — Additive manufacturing (AM) is a growing method due to the ability to produce with little to no waste, construction of previously impossible designs, and less tooling needed for fabrication. While every manufacturing method has advantages and drawbacks, this paper covers AM techniques for 2D, 3D, and 4D printing, demonstrating RF devices which utilize each dimension and discussing the challenges related to using each technology towards microwave designs. Complex, previously impossible, modules can be fabricated rapidly setting the foundation for the way new designs are prototyped and manufactured.

Index Terms — Additive Manufacturing, Inkjet Printing, 3D Printing, FDM, PolyJet Shape Memory Polymers, 4D Printing, Antenna, Origami.

I. Introduction

As additive manufacturing becomes increasingly used in industry practices, new techniques and designs will be explored that allow the creation of systems that were previously strenuous to manufacture. Engineers have been focusing on origami structures to allow designs that can be actuated while retaining high strength properties. For RF devices, origami inspired designs presents itself as opportunity to drastically reduce the footprint of RF devices and antennas while allowing for a real-time tenability and shape reconfigurability.

A variety of AM methods is discussed here in order of the evolution of dimensions and its application towards 4D printing and incorporating origami inspired designs. Each dimension is identified discussing the potential and feasibility of sub-manufacturing method investigated, based on the accuracy, resolution, or materials accessible to each process.

Section II will introduce inkjet printing abilities and its application to 3D printing. Section III will discuss the 3D printing technologies and their respective properties. Section IV contains how 4D printing is achieved of RF devices.

II. 2D/Inkjet Printing

A. *Technology and Ink Materials*

The foundation of 2D electronic inkjet printing technology is based on the drop-on-demand deposition of ink materials onto a host substrate. The integrity of an inkjet-printed electronic device is reliant on the properties of the printing platform, the host substrate, and the ink materials. The printing platform controls the dispensing of ink material droplets, where such factors of voltage, jetting waveform, and cartridge temperature help control the formulation and ejection of droplets. The Dimatix DMP-2831, a common industrial material inkjet printer, offers variable control of all necessary parameters of printing as well as the dimensional spacing of droplets down to 5 um [1].

The variety of ink materials used with inkjet printing can be functionally categorized as conducting, dielectric, and sensing. Conducting inks are typically composed of suspensions of noble metal nanoparticles, such as gold and silver. The utilization of nanoparticles allows for room temperature jetting and low temperature processing conditions, yielding resistivity in the range of 5x that of bulk metal. Diammine silver acetate (DSA) is an alternative to nanoparticle based inks that removes the process of sintering at the cost of a reduction in conductivity. Dielectric inks are typically polymer based with medium relative permittivity (e_r=3-4) and vary most significantly in their printed thickness, which can vary from several hundreds of nanometers for metal-insulator-metal (MIM) capacitors to several hundreds of micrometers for fully-printed dielectric substrates and spacers. Sensing inks are typically comprised of carbonic nanomaterial dispersions, such as carbon nanotubes (CNTs) and graphene oxide flakes. These inks are capable of depositing nanoscale films for applications such as gas sensing, humidity sensing, and flexible organic active devices.

The host substrate is as equally important as the ink materials and the printing platform. When an ink droplet is ejected and interacts with a substrate, the surface tension of the ink must be within the same range of the total free surface energy of the substrate in order to achieve good wetting and avoid material bleeding or balling up. Additionally, the surface roughness of the substrate must be suitable for layer-by-layer film deposition of the ink material, which relies on the surface energy of the substrate as well as the thickness of the deposited layers.

B. *RF Applications and Modules*

Due to their low complexity, requirement for flexibility and low, and pervasiveness, printing technologies effectively made their entry into the RF world for the fabrication of UHF RFID antennas. This innovation had been triggered largely by the introduction of silver nanoparticle inks for high quality conductor printing. Since then, a wide range of new material inks have enabled this technology with a wide RF component, modules and systems manufacturing versatility. Inkjet-printing, as the most versatile printing method, has demonstrated the fabrication of a wide range of high performance antennas, even into the mm-range and sub-terahertz frequency realm (Fig. 1), high frequency operable multilayer discrete components (capacitors, inductors, vias), chemical films and microfluidic channels for wireless sensing, as well as hybrid electronics flexible systems, such as a rollable ground penetrating radar

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(GPR), a solar powered RF beacon and far and short range RF energy harvesting modules.

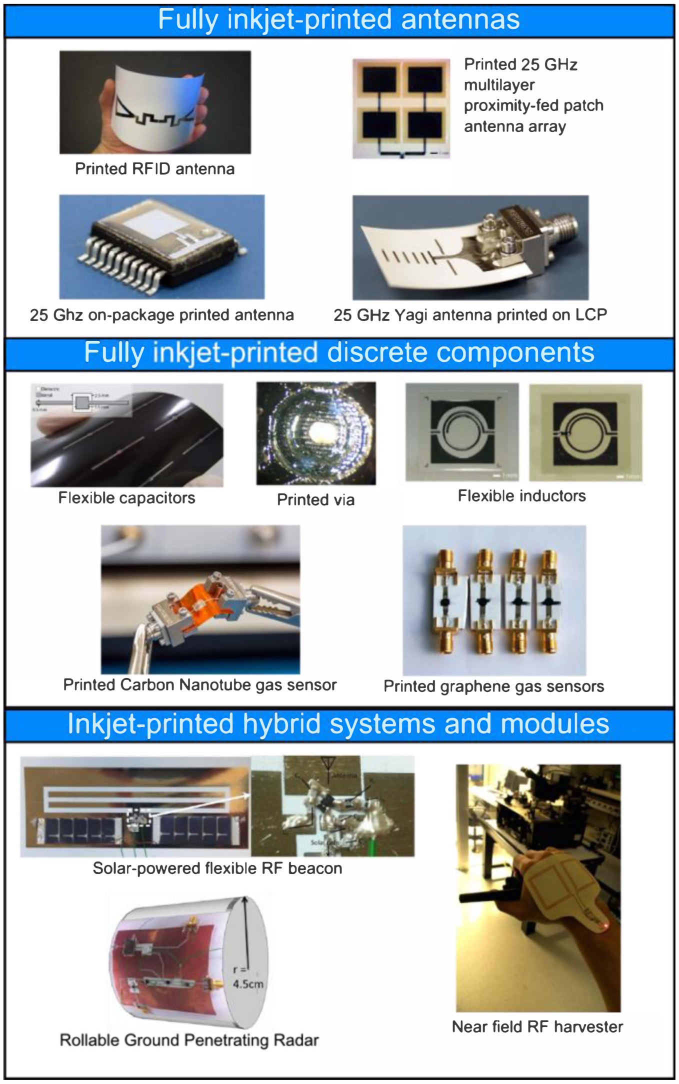

Figure 1. Inkjet Printed RF modules

As shown, 2D printing methods have demonstrated a very good performance for the fabrication of 2D, flexible electronics. However, they are generally limited in their material deposition rate in fully 3D/curved configurations, which prevents them from being applied to the fabrication of truly 3D structures. Fortunately, 2D printing methods are only a subset of a larger class of fully additive manufacturing tools that includes techniques which have been increasingly investigated for the low-cost additive fabrication of full-dimension 3D RF components and modules.

III. 3D PRINTING

A. *Common Design*

There are a variety of 3D printing techniques. Historically, many were created for prototyping purposes to allow small scale manufacturing of new designs. All of them generally involve a technique called 'slicing,' which converts a 3D solid model into a machine readable file that is composed of layers. The most common cited resolution is the height of each layer, often in the range of 20-300 microns depending on the manufacturing method, with the most advanced techniques reaching resolutions below .1 um [2]. Different removable support materials or structures may be required depending on the process. A quick review of different 3D printing techniques are discussed with their criteria related to manufacturing devices for microwave purposes.

B. *Fused Deposition Modeling (FDM)*

Fused Fused Deposition Modeling is the most common 3D printing technique, exponentially gaining popularity after the expiration of key patents. The resolution of the layer height varies between 20-100 um for most printers, often limited by the stepper motors and threading on the Z-axis.

FDM printing functions by feeding filaments of polymer into a heated extruder that is on a XYZ moving platform. After the polymer exceeds the glass transition or melting temperature, the material is deposited. The minimum repeatable feature size is determined by the nozzle diameter. Most printers come with a diameter of .4-.5mm, though in order to improve resolution and surface roughness, diameters of .2 mm can be obtained for select model printers. Tests have shown that with this nozzle a surface variation below 6 um currently can be obtained.

While the resolution and surface roughness may not be as precise as with other 3D printing techniques, the simplicity in the FDM process enables the capability to use multiple nozzles simultaneously, allowing multiple materials and different technologies such as Drop-On-Demand (DOD), Direct Printing Additive Manufacturing (DPAM), or laser sintering tools to coexist on a single platform allowing complex conductive, multimaterial structures.

A large selection of filaments are available, such as ABS, PLA, HIPS, polyurethane, composites are available consisting of PLA or ABS combined with copper, bronze, wood, iron, steel, carbon fiber, and ceramics. Custom materials can be fabricated with the appropriate tools, and mixed during printing. While the material library is large, only a minority have been characterized up the RF frequency range [3][4].

C. *Stereolithography (SLA)*

Stereolithography involves a tank of resin in which layers are cured using either a laser or DLP-based projector UV source. As the material is essentially grown rather than deposited, the process is smoother and of higher resolution with layers of .1 – 25 um and minimum features of .1 – 300 um available, with the larger values being typical of SLA printers. Due the need of a

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photopolymer resin, the materials are much more limited and multiple material printers on a single platform are unavailable.

D. PolyJet Printing

PolyJet printing is a process by Objet owned by Stratasys that works similarly to SLA, though depositing 16 um layers of photopolymer resin through inkjet nozzles [5]. Materials can be mixed while printing creating gradients. Proprietary materials are used, with no current method of incorporating conductive inks or materials. A mixture of TangoBlack (a rubber-like highly flexible polymer) and VeroWhite (a stiff polymer) can be combined to get shape memory gradients that react to heat.

E. Selective Laser Sintering/Melting (SLS/SLM)~~For the preliminary test of the chipless tag measurement, the tests are held in an anechoic chamber with a (MODEL) VNA to validate the successful transmission of hand position. The experiment setup block diagram is shown in the Fig.6. The reader's antennas are oriented in correspondence with the hand gestures sensor's cross-polarized antennas, in order to minimize crosstalk and maximize isolation between interrogation signal and encoded tag sign~~

Selective Laser Sintering/Melting involves fusing polymer or metallic powders below 50 um in diameter. Similarly to SLA, only a single material can be used at once. With the use of smaller particles, printing resolution can be increased. Using 5 um particles and 30 um laser diameter (also the smallest feature size) results in layers of 2 um thick.

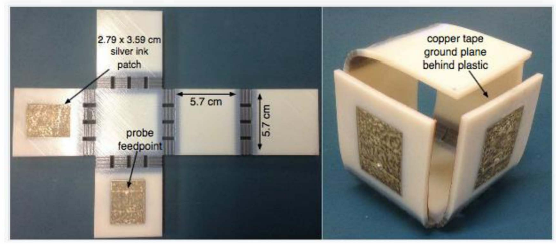
IV. 4D PRINTING

A. Intro to 4D Printing

Certain polymers have a feature characteristic shape memory effects (SME), adequately called shape memory polymers (SMP). Specifically, shape memory materials are "smart" materials which recover from a temporary deformed shape to their original permanent shape. This allows printing in another dimension, time, that can be exploited with 3D printing to allow a controllable angle of actuation, providing microwave devices with an easy-to-control reconfigurability up to an unprecedented degree, thus allowing for real-time frequency and direction tuning, extreme miniaturization and portability as well as real time control of radiation patterns and directivity to dramatically improve energy harvesting and wireless communication protocols. While many SMP are thermo-responsive, technologies for shape memory include shape memory alloys (SMA) which allow electrical stimuli, though they tend to be quite lossy due to their commonly resistive nature of the material. With 3D printing, fully 3D hinging and origami shapes can easily be fabricated at room temperatures and the SMA designs are rigid for various intermediate shapes. After heating near the glass transition temperature the material is pliable into a new temporary design which will be retained at normal conditions (room temperature). If heat is introduced to the system again, the design will transition to its original permanent state.

B. 4D Prototypes

An Objet260 PolyJet 3D printer can be used to print a mixture of TangoBlack and VeroWhite, creating an SMP. Hinges of the SMP mixture, called Grey60, are printed on in conjunction with solid panels of VeroWhite to create actuatable platforms for microwave devices [6]. On top of the VeroWhite, silver nanoparticle ink is first deposited followed by a silver acetate ink to fill any voids between particles.



The 4D printed origami cube allows antenna diversity in order to improve communications and energy harvesting with other modules that would be unavailable to orientation stationary designs, while taking in the advantageous origami properties of strength, low volume, and large surface areas reducing the amount of raw materials and fabrication time necessary.

Figure 2. 4D Printed structure with inkjet printed patch antenna operating at 2.38 GHz from fully extended (left) to folded (right).

V. CONCLUSION

Additive manufacturing techniques have been discussed and innovative designs demonstrated. Inkjet printed sensors, components, antennas, and systems have been pioneered for RF functionality. With the rapid advancement of state-of-the-art 3D/4D printing technologies, new microwave devices are developed for applications that enable new dimensions actuating, compact, wireless designs improving operability of the devices. With a wide range of freedom in design, a growing library of materials, and constantly improving resolution and accuracy, AM will remain a prime method in the manufacturing of novel microwave devices.

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