Additive Manufacturing for Next Generation Microwave Electronics and Antennas

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Abstract

The paper will discuss the integration of 3D printing and inkjet printing fabrication technologies for microwave and millimeter-wave applications. With the recent advancements in 3D and inkjet printing technology, achieving resolution down to 50 um, it is feasible to fabricate electronic components and antennas operating in the millimeter-wave regime. The nature of additive manufacturing allows designers to create custom components and devices for specialized applications and provides an excellent and inexpensive way of prototyping electronic designs. The combination of multiple printable materials enables the vertical integration of conductive, dielectric, and semi-conductive materials which are the fundamental components of passive and active circuit elements such as inductors, capacitors, diodes, and transistors. Also, the on-demand manner of printing can eliminate the use of subtractive fabrication processes, which are necessary for conventional micro-fabrication processes such as photolithography, and drastically reduce the cost and material waste of fabrication.

The utilization of 3D and inkjet printing to fabricate integrated circuits interconnects and antennas is an interesting avenue for research due to the customized nature of certain applications such as automotive radar and 5G wireless solutions. This paper will explore different ways of interfacing with monolithic microwave integrated circuits (MMICs) using additive manufacturing methods including printed vias, ramp interconnects, and wire bonds. With these structures, microwave properties such as matching and losses can be improved due to the ease of printing tailored interfaces that match with each individual device. It will also include demonstration of fully additively-manufactured antennas exhibiting excellent bandwidth and circular polarization, something that is expensive and difficult to achieve with traditional manufacturing methods. Finally, the paper will also introduce future directions for additively-manufactured electronics, including the packaging of high-power devices, cooling functionality, and using exotic materials for electromagnetic interference shielding and flexibility.

INTRODUCTION

Additive manufacturing has been gaining a lot of traction in the past decade as it promises very fast prototyping and low-cost manufacturing. Components that typically have month long lead times can be fabricated in mere days or even hours. Every year, additional 3D printable materials are being introduced to the market, and with that 3D printing can be utilized for new applications. One area of additive manufacturing is inkjet printing, which is a drop on demand method of printing large areas of devices with high accuracy, where metal, dielectric and semiconducting inks can be deposited quickly on almost all surfaces. Inkjet printing is extremely fast and low cost and can be utilized for applications at mm-wave frequencies allowing for fast prototyping and roll to roll manufacturing [1]. Additionally, the drop on demand nature of inkjet printing facilitates a low temperature (<200ºC) process as the metal is directly deposited on top of the substrate instead of using high temperature PVD systems. With this, flexible substrates are easily metallized without any bending or warping. Another area of additive manufacturing is 3D printing. 3D printers utilize a 3D model and a slicer to slice the model into very thin layers and recreates the model using these layers. Traditionally 3D prints were fabricated using fused deposition model (FDM) where a polymer filament, usually PLA or ABS plastics, was melted and extruded to make the model layer by layer. However new stereolithography (SLA) systems, where the model is built onto a platform in a photoactive resin bath, are generally able to achieve very high (10um) resolution print layers. Another big benefit of SLA printing is its surface roughness, which is on the order of hundreds of nanometers [2]. These two factors allow for 3D SLA printed parts to be utilized in high frequency mm-wave applications.

This paper will delve into several topics in high frequency designs using both 3D and inkjet printing. Designs for fully inkjet printed RF passive components such as capacitors and inductors will be presented. These devices are critical to RF systems and are used in various ways including impedance matching and DC/RF chokes. These devices can be easily manufactured in the same process, in the same inkjet printer, saving time and cost. Other passive devices such as die interconnects will be discussed. These fully additive manufactured interconnects, which replaces wire bonding, are a revolutionary way of designing smart packaging, the inclusion of many different functionality in one smart package. Next advanced 3D printed antennas are presented. These specific antennas demonstrate complex structures that are difficult or impossible to fabricate using traditional manufacturing techniques and drastically reduce the time of prototype to production. These antennas introduce advantageous features, such as high bandwidth or ease of integration with other components. Finally, the paper will explore future topics for research.

INKJET PRINTED PASSIVE COMPONENTS

Typically, in an RF system, baluns, capacitors and inductors are utilized as in signal conditioning, impedance matching, coupling/choking applications. These devices are critical to RF applications and should have low loss and high quality (Q) factor. Typically, lumped components in standard surface mount packages, such as 0603, are placed and soldered onto circuit boards. However, these packages are tall and bulky and can snap off when bent on flexible substrates. Inkjet printed capacitors and inductors are planar structures, conformal, and low loss which can withstand bending when printed on flexible substrates such as LCP. Additionally, components which generally take many fabrication steps, such as metallization and dielectric deposition can be completed in one inkjet printing process. The additive, drop-on-demand aspect of fabrication is also low waste, which can save drastic costs when printing in massive quantities.

Metal Insulator Metal Capacitors

Metal insulator metal (MIM) capacitors are the most basic single layer capacitors. These capacitors are two metal electrodes separated by a dielectric, both of which can be inkjet printable. For metal conductive layers, silver nano particle (SNP) was printed and for dielectric insulator layers, polyvinylpyrrolidone(PVP) was printed for thin films (>0.5μm), or production epoxy based negative photo resist for thick films(>3μm). These allow for various controls of capacitance values, as printing thicker or thinner dielectrics or changing the electrode area, granting full control of design specifications based on the end application. Flexible MIM capacitors fabricated on polyimide substrates show self-resonance frequency(SRF) of >1GHz[3], while MIM capacitors with 1.6μm – 1.8μm thick PVP dielectric and SNP metal electrodes were fabricated on silicon substrate as shown in Fig.1 has SRF of 1.2GHz, a maximum Q factor of 25, with a capacitance per area of 33pF/mm^2 [4].

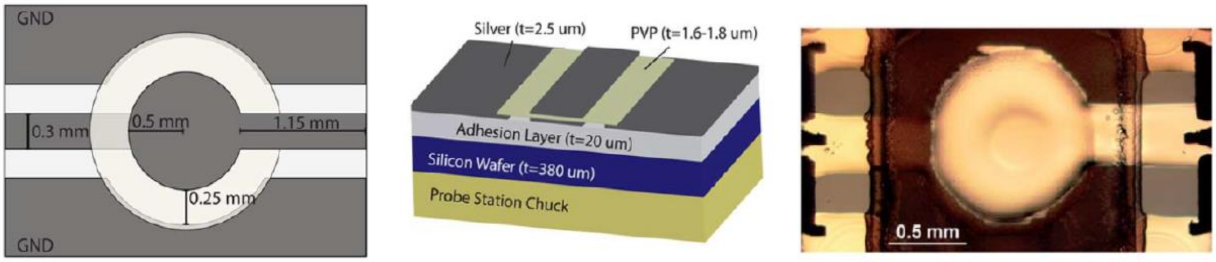
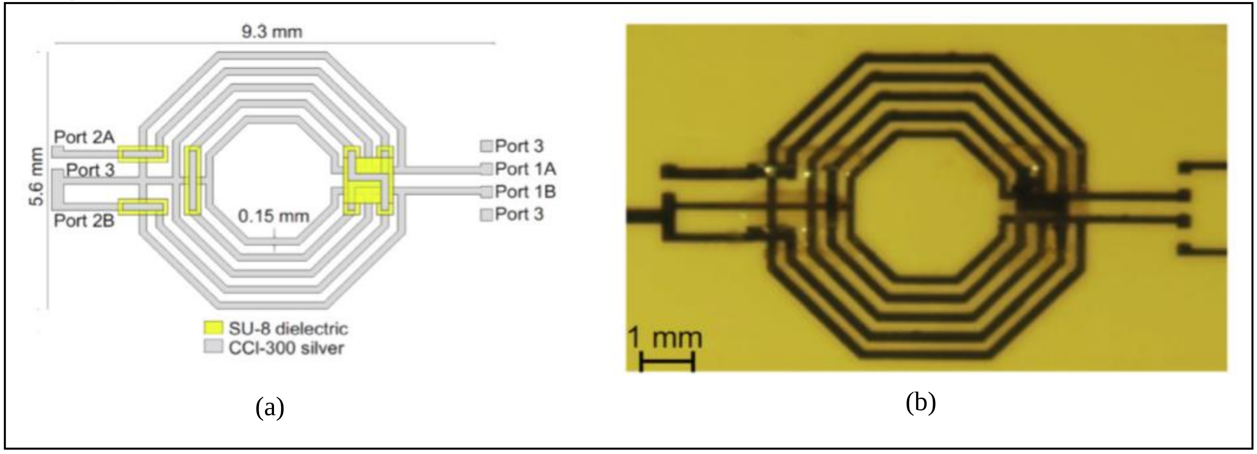


Fig. 1. Inkjet printed MIM capacitors on silicon wafers

Baluns and Inductors

Inductors and baluns are similar spiral structures. Baluns are usually used in signal conditioning applications to change balanced signals into unbalanced and vice versa. Transformer based baluns incorporate three windings in 5-layer structures as shown in Fig. 2a and b respectively [5]. The transformer balun demonstrates the complex structures that can be fabricated using additive inkjet printing. Inductors have a similar winding structure since they require long conductive traces to get appreciable inductance values. 1.5 turn inductors were fabricated with SNP ink as the conductive metal and epoxy based negative photo resist ink as the dielectric layer separators and shows a Q factor of 21 at 1 GHz [6]. Both applications are inherently multilayer structures, but these demonstrations show the ease of inkjet printing multilayer RF components which can operate at high frequencies and the level of integration that can be achieved by utilizing inkjet printing to reduce processing steps.



(a)

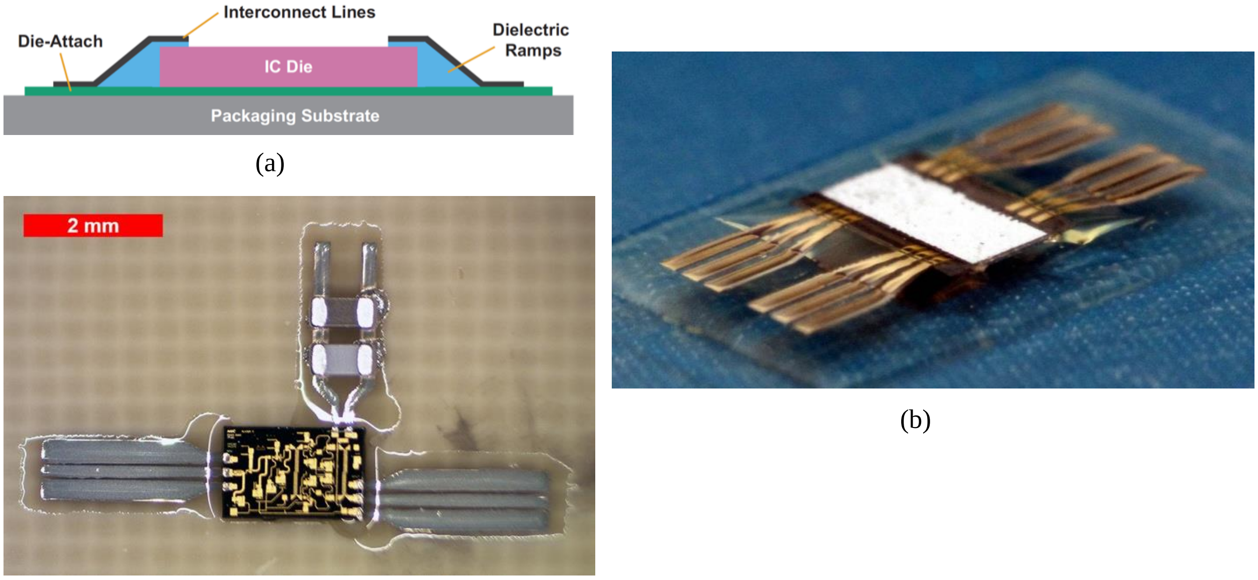
(b)

Fig 2. Inkjet printed 5-layer RF balun schematic (a) and fabricated sample on LCP (b).

INTERCONNECTS

Interconnects are essential packaging components for the practical implementation of any microelectronic device in a functional electronic system. Specifically, first-level interconnects are responsible for interconnecting a microelectronic chip, or die, with its packaging substrate. In a modern wireless system, this packaging substrate can take the form of a metallic leadframe for traditionally packaged off-the-shelf components, a laminate-based interposer for signal fanout and redistribution, or a printed circuit board (PCB) where a chip is integrated directly with other packaged components on the primary host substrate. These packaging methods typically achieve first-level interconnection through bond wire or flip-chip technologies depending on several design factors, including signal pad location, thermal path management, and the routing of signals below an interconnected device. Wire and ribbon bonding are rapid, low-cost, and mature methods for realizing these chip-to-board interconnects, however increased parasitics and mechanical stability are highlighted concerns that must be considered in a practical setting [7]. With the recent growth of additive manufacturing technologies for the development of wireless components, packages, and systems, the first-level interconnect is a prime candidate for investigating the integration of inkjet and 3D printing fabrication methods to realize fully-printed 3D RF interconnect transitions.

The use of additive manufacturing technologies for the interconnection process has the potential to offer several improvements from traditional wire bonding solutions, including lower parasitic inductance, higher mechanical reliability, and increased system-level reconfigurability. Lower parasitic inductance is achieved through the reduction of the bondwire *loop length*, where printed interconnects are realized in a conformal low-profile fashion. Mechanical reliability has the potential to be improved through the elimination of the thermosonic bonding process and again the conformal nature of printing technology. Finally, the printing technologies targeted for interconnection are the same that are currently used for fabricating other system-level components such as antennas and passives, enabling a single-tool solution for packaging, rapid system prototyping, and product development. Fig. 3(a) shows a 2D-model of a fully-printed ramp interconnection method utilizing inkjet printing with polymer- and metal-based inks [8]. First, a die is attached to a substrate using a polymer ink as a pattern-defined die attach. Next, a polymer ink is printed to pattern 3D ramp transitions from the host substrate to the top surface of the die. Finally, a silver nanoparticle-based ink is printed to pattern RF interconnects up to the pads of a die. Fig. 3(b) shows an image of coplanar waveguide (CPW) first-level interconnects fabricated through inkjet printing, highlighting the ability to pattern 50 Ohm transmission lines directly to the top surface of a die. The interconnects presented in the reference work exhibit a per-length loss of 0.6–0.8 dB/mm and an inductance that is approximately half a standard bond wire. These ramps can be directly integrated with active wireless components, such as a Ka-band monolithic microwave integrated circuit (MMIC) low noise amplifier (LNA) device, as shown in Fig. 3(c) [9].



(a)

(b)

(c)

Fig. 3. (a) 2D model of inkjet-printed 3D ramp interconnects with die [8]. (b) Perspective image of inkjet-printed CPW transmission line interconnects with die. (c) Fully-printed ramp interconnects with Ka-band LNA MMIC device [9].

Though inkjet printing processes offer a variety of solutions for first-level interconnection, the integration of 3D printing technologies introduce an additional plane of design for the development of 3D system-in-package (SiP) microelectronic packaging schemes, where the functional diversity of the package is broadened to include such components as in-package antennas, passive components, sensors, and microfluidic architecture for thermal management. These reconfigurable application-specific system packages, or “smart” packages, are realized through the integration of inkjet and 3D printing technologies, as outlined in the process flow presented in Fig. 4 [10]. The highlight of this process is the manipulation of the IC encapsulant, typically the final step in the traditional microelectronic packaging procedure where an epoxy mold compound (EMC) is transfer molded onto an attached and interconnected die in order to protect the device from environmental elements. Functionality is added to the encapsulant component using additive printing technologies to realize through-mold vias (TMVs), which enable the interconnection of an IC die with multiple planes embedded within an encapsulant. These TMVs are fabricated through the integration of inkjet and 3D printing methods. Fig. 5(a) shows a perspective image of 3D/inkjet-printed arbitrarily sloped CPW TMV interconnects for mm-wave device packaging [11]. A study of different ramp slopes was able to achieve CPW TMVs with a maximum slope of 65° and a per-length loss of less than 0.6 dB/mm. Fig. 5(b) shows a proof-of-concept demonstration of a CPW TMV-integrated partial IC encapsulant realized through a combination of inkjet and 3D printing, corresponding to the schematic shown previously in Fig. 2 [10]. The fully-printed TMV is a fundamental component in the development of highly-reconfigurable “smart” packages with application-specific functionality for a variety of emerging wireless applications.

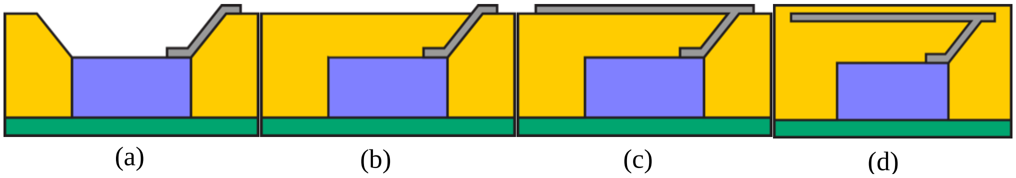


Fig. 4. “Smart” wireless encapsulant process flow: (a) 3D print partial encapsulant with die and inkjet print sloped TMV. (b) Cap partial encapsulant with photopolymer resin leaving exposed TMV interconnecting to embedded die. (c) Inkjet print antenna, passive, or another SiP component. (d) 3D print final encapsulant. [10]

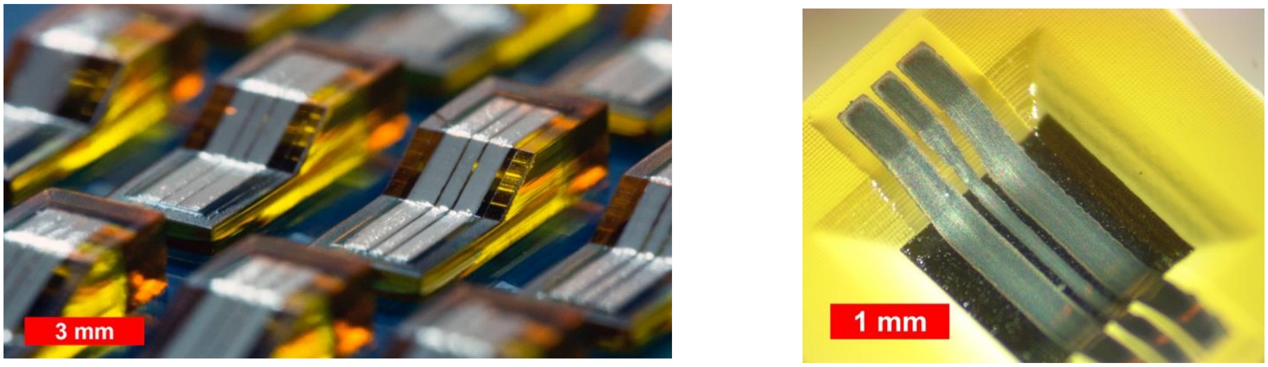


Fig. 5. Fully-printed sloped TMV interconnects realized through the combination of inkjet and 3D printing: (a) TMV test vehicle with arbitrarily-sloped interconnects [11], (b) fully-printed TMV-integrated partial IC encapsulant [10].

ADDITIVE MANUFACTURED ANTENNAS

3D printing offers the ability to create truly 3D free form structures, as opposed to 2D planar structures fabricated in a 3D compatible material. The advantage of 3D printing to make antennas is to generate complex shapes and structures that cannot be fabricated utilizing traditional subtractive techniques. The advanced and complex shapes that can be easily generated using 3D printing can allow the antenna to have high performance features such as high bandwidth or ease of system integration. Two antennas will be discussed. One is a 3D printed Voronoi discone tessellation antenna which is based on Voronoi tessellation mathematical models, demonstrating >100% of center frequency bandwidth. Another is a fully additively manufactured log spiral antenna operating at mm-wave frequencies with integrated balun. Both antennas were printed using a commercially available 3D printer using proprietary resin.

Voronoi antenna patterns are an excellent demonstrator of the capabilities of 3D printed structures. The Voronoi tessellation occurs by subdividing a plane into polygons where the size and numbers of borders of each polygon is determined by finding the half way distance between user-generated seed points and finding the midpoint between its neighbors [12]. This tessellation structure is then projected onto a discone surface and fed from the bottom as shown in Fig. 6a

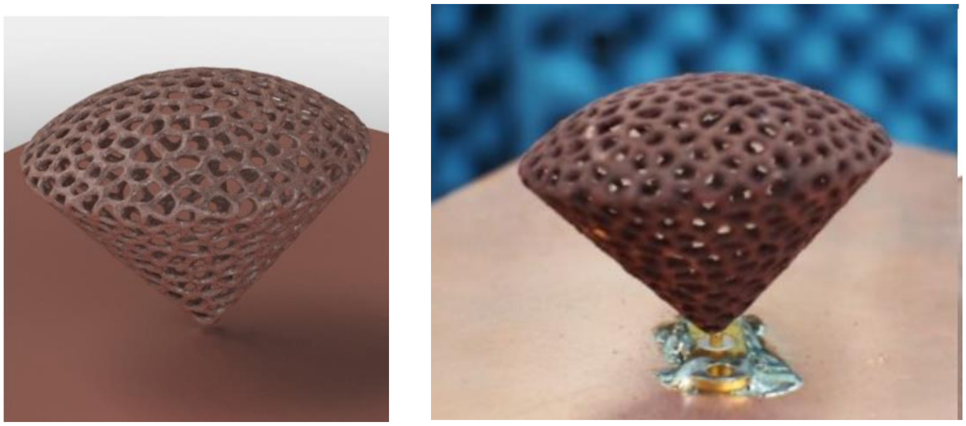
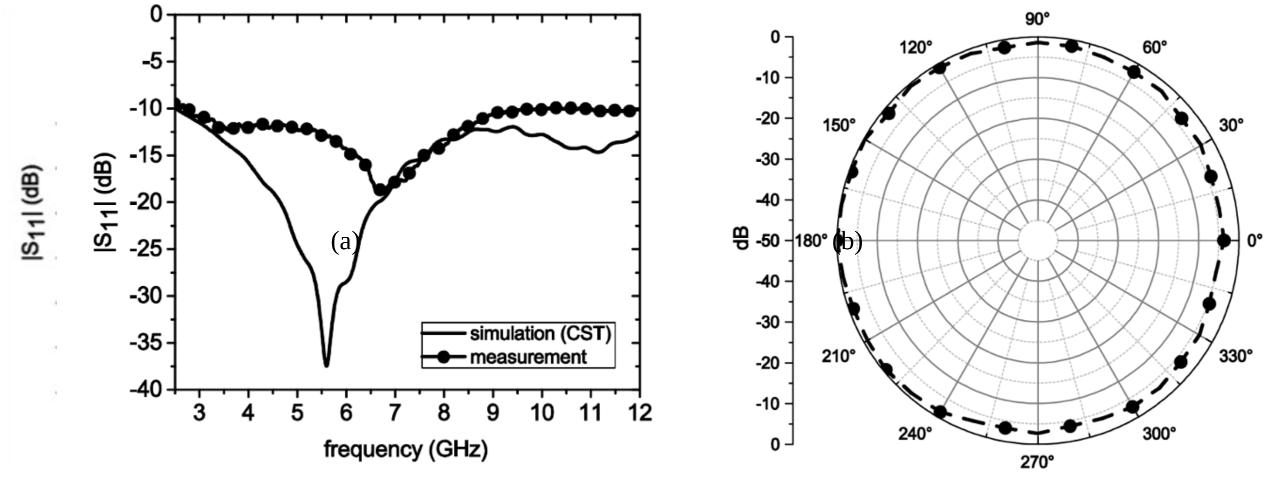


Fig. 6. Voronoi CAD model (a) and the fabricated antenna on the measurement setup for the Voronoi antenna with SMA feeding

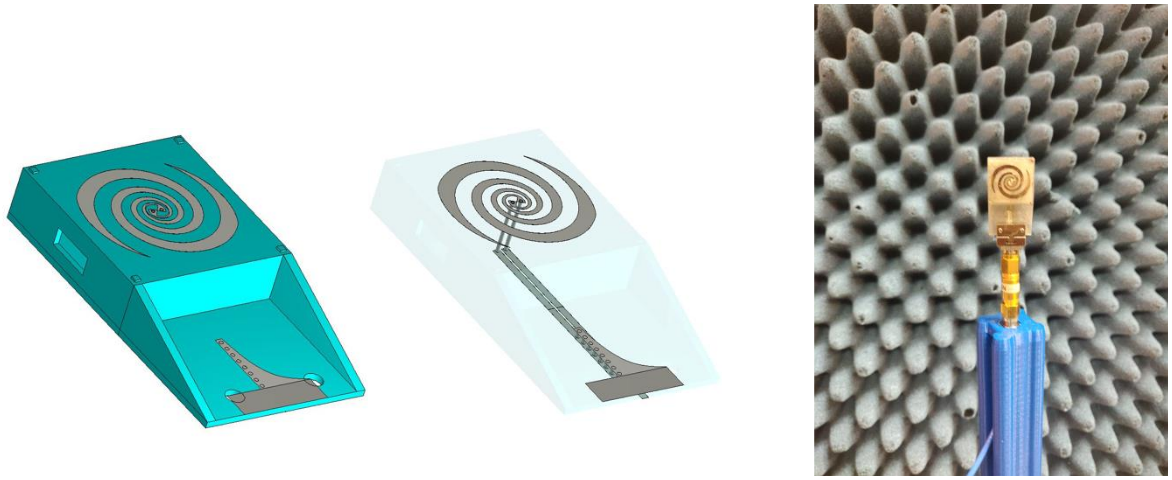
After printing the 3D structure, the conductive copper was electrolessly plated onto the surface of the antenna. This was done utilizing surface treatment of the acrylate surface with PdCl$_2$ solution and then submerged into a homemade copper electroless plating bath made of cupric sulfate and sodium potassium tartrate tetrahydrate. The surface is then completely covered with copper. Radiation patterns and S11 measurements can be seen in Fig. 7 showing omnidirectional gain and broadband matching, respectively.



(a). (b).

Fig. 7. Voronoi antenna S11 measurements (a) and gain pattern (b).

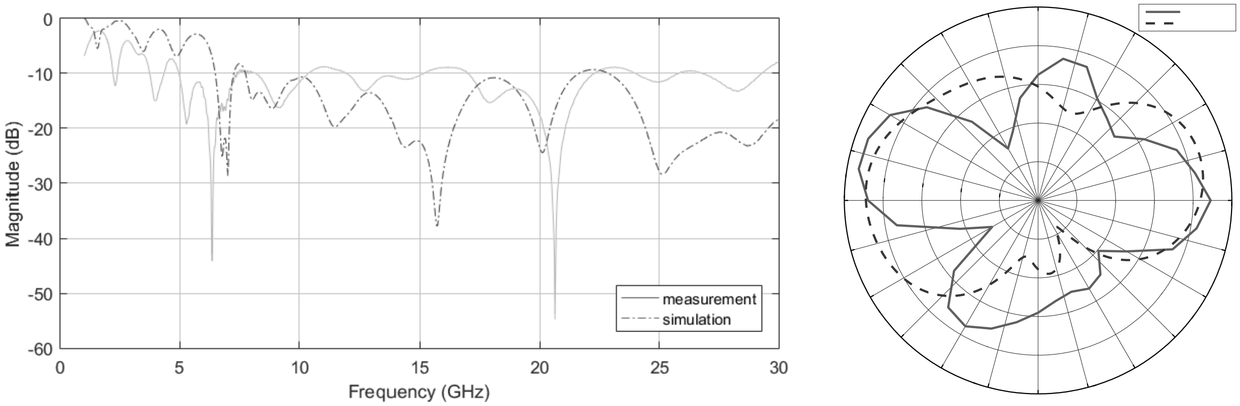
Spiral antennas are primarily as high bandwidth antennas with circular polarization. The two balanced arms of the spiral antenna gives good circular polarization, meaning the antenna can be interrogated from all orientations, eliminating the problems of misalignment. One drawback of spiral antennas is its balanced structure which requires a balun to transform the signal to a unbalanced signal so that it can be interfaced with board level circuits or measuring equipment. Typically baluns are soldered onto the ends in the center of the spiral, but this is a challenge as in high frequencies, soldering can cause undesirable effects since the tolerances are very small.



(a) (b)

Fig. 8 (a) CAD model of the log spiral antenna with integrated balun visible on the backside (b) Fabricated antenna mounted on measuring station.

An additively manufactured antenna was designed and fabricated for this work as shown in Fig 8. The base of the antenna structure was 3D printed using a commercially available photo sensitive resin and the antenna was metallized using a production silver nanoparticle ink. A key feature of this antenna is its inclusion of an integrated balun using a microstrip to coplanar stripline transition as described in [13]. The inclusion of these structures allows for integration with other circuit components such as ICs as the balun allows for a seamless transition to microstrip lines. The CAD model can be seen in Fig. 8 as well as the fabricated devices on top of the measuring equipment. Note that the structure the spiral was printed on is hollow, making this particularly difficult to manufacture in a standard process of milling, but trivial with a 3D printer. The measured S11 parameters are plotted in Fig. 9a and the gain measurements in Fig 9b.



(a)

Fig. 9 (a) S11 measurement results (b)Normalized gain pattern showing expected behavior of a logspiral antenna.

CONCLUSIONS

This paper reviewed some of the state-of-the art designs in high frequency additive manufactured passive devices, IC interconnects, and introduced some new antenna designs that are possible only with additive manufacturing. Future topics of research includes utilizing higher integration with active devices to create smart packaging, improving quality factor and SRF resonance of RF and system integration with 3D printed antennas. Additionally, additive manufacturing tolerance and minimum feature sizes are still behind traditional fabrication methods, however many other areas are being explored, such as two-photon polymerization printing, which can meet or exceed traditional methods of fabrication. These topics will greatly benefit 5G applications in creating the next generation of smart electronics.

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