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A Fully Inkjet Printed 3D Honeycomb Inspired Patch Antenna

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Abstract — The ability to inkjet print three-dimensional objects with integrated conductive metal provides many opportunities for fabrication of radio frequency electronics and electronics in general. Both a plastic material and silver conductor are deposited by inkjet printing in this work. This is the first demonstration of a fully 3D Multijet printing process with integrated polymer and metal. A 2.4 GHz patch antenna is successfully fabricated with good performance proving the viability of the process. The inkjet printed plastic surface is very smooth, with less than 100 nm root mean square roughness. The printed silver nanoparticles are laser sintered to achieve adequate conductivity of 1e^6 S/m while keeping the process below 80ºC and avoiding damage to the polymer. The antenna is designed with a honeycomb substrate which minimizes material consumption. This reduces the weight, dielectric constant and dielectric loss which are all around beneficial. The antenna is entirely inkjet printed including the ground plane conductor and achieves an impressive 81% efficiency. The honeycomb substrate weighs twenty times less than a solid substrate. For comparison the honeycomb antenna provides an efficiency nearly 15% greater than a similarly fabricated antenna with a solid substrate.

Index Terms — 3D printing, Antenna, Inkjet, Multijet, UV-curable Polymer, Silver Nanoparticle.

I. Introduction

Inkjet printing which is common in offices and homes for graphics printing, is now being applied to fabricate 3D objects. Materials are deposited drop by drop in a digitally defined location to build a 3D object layer by layer. A major benefit is that no masks or tooling are required. It is possible to stack or array inkjet print-heads in order to print several materials within the same process or to increase the build speed. Industrial print-heads can deposit kilograms of material per hour making it an attractive process. There are several example of physical objects fabricated by inkjet in [1].

In academic research there are many groups working on inkjet printing of conductors, dielectrics and semiconductors. In the future, these materials could be used to fabricate transistors [2], [3] lighting [4], and solar cells [5]. Although these complex active devices are exciting, a more near term application of inkjet printed electronics will likely be in passive circuits, interconnects, and antennas. Several antennas have been realized by inkjet printing of silver nanoparticle ink in 2D on plastics and paper [6], [7]. There have also been papers utilizing high precision 3D printed dielectrics to demonstrate THz, high frequency antennas and lenses [8] [9]. Only a few 3D printed antennas at radio frequency have been reported [10], [11] [12]. These previous reports utilize common 3D printing techniques such as fused deposition modeling and stereolithography. 3D inkjet printed reflectors and lenses are demonstrated in [13] and [14]. These inkjet printed dielectric antennas either do not incorporate metal or use metal sputtered in high vacuum.

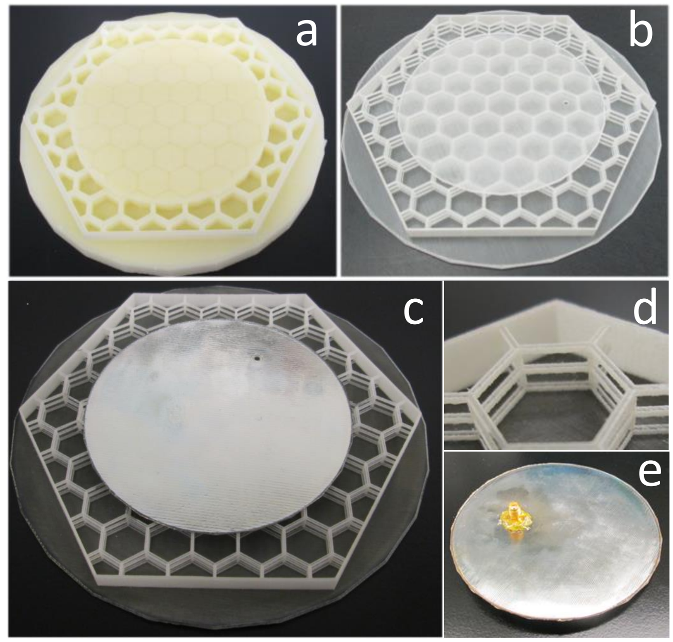

Fig. 1. 3D Multijet printed structure with wax support material (a), remaining polymer shell after melting the wax (b), final antenna with inkjet printed silver ink (c), zoomed in view of honeycomb (d), back of antenna with probe feed (e).

The major challenges of 3D printing radio frequency antennas are; poor surface roughness, integration of the conductor and dielectric, low conductivity of printed metals and poor dielectric losses. Poor surface roughness is pointed out in [11] and is inherent to many 3D printing processes. While 3D printing of conductors and metals is feasible, combining them together in the same process is challenging mainly due to temperature compatibility. Metal nanoparticles provide potential to overcome this challenge since the nanoparticles allow much lower processing temperatures than a bulk metal. Silver nanoparticle ink can be additively patterned, but in order to get the best conductivity sintering temperatures above 180ºC are required [15] [16]. These temperatures are still incompatible with many printed dielectrics. Pastes, aerosols and plating solutions are demonstrated on 3D plastic structures but this limits the flexibility of the process [10] [17]. It would be ideal to have a conductor that can be printed with the dielectric layer by layer. Another concern for 3D printing is the high dielectric loss of the materials. Some printed polymer materials have dissipation factors around 0.02 which is an order of magnitude worse compared to common microwave materials [18] [19].

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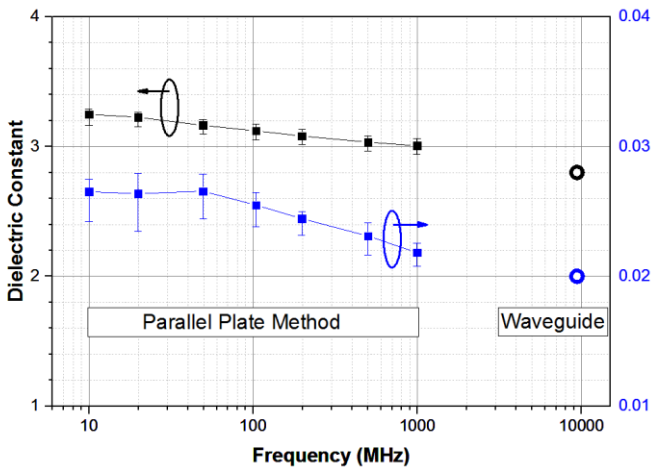

Fig. 2. Dielectric properties of 3DSystems UV-Cure Polymer Material (Hard Acrylic based). Bars represent the maximum and minimum measurement values of five test samples with the parallel plate method while filled squares are the average value. Circular data point at 9.375 GHz is from a waveguide measurement.

In this paper, a 3D inkjet printing process is introduced which integrates both dielectric and conductor and solves the issues mentioned above. The inkjet printed polymer is smoothed and leveled by a planarizer as it is deposited providing surface roughness better than 100 nm root mean square. Both the dielectric polymer and silver conductor are additively deposited by inkjet printing which makes the process versatile. The silver nanoparticle ink is sintered with a carbon dioxide engraving laser providing a conductive layer without damaging the dielectric. Finally, the use of a printed honeycomb structure allows tailoring of the dielectric constant and significantly improves the dielectric loss. It is well known that air filled dielectrics improve performance as demonstrated by micromachining polymers [20] or using air filled polymer foam like substrates [21]. By utilizing additive inkjet printing to realize a honeycomb structure the material consumption is reduced while providing this performance benefit. Two patch antennas have been fabricated for comparison. One with a solid printed substrate and another with a honeycomb substrate. The honeycomb substrate antenna has a peak gain of 8 dBi and efficiency of 81%. For comparison the solid substrate patch has a gain of 5.8 dBi and measured efficiency of 67%. Electromagnetic simulations are also presented which match well with the measurements.

II. Materials And Fabrication

Three inks are used to fabricate the antenna; a wax material, a UV-cured polymer, and a silver nanoparticle ink. The wax and polymer are used to form the 3D structure. They are printed with a 3DSystems 5500 Multijet printer that has 1236 inkjet nozzles and can eject ~2.5 Kg of material per hour. The printer has a spatial resolution of 33 × 33 × 29 µm in x, y and z directions. The polymer material is printed and cured layer by layer with UV lights. The wax is a support material deposited

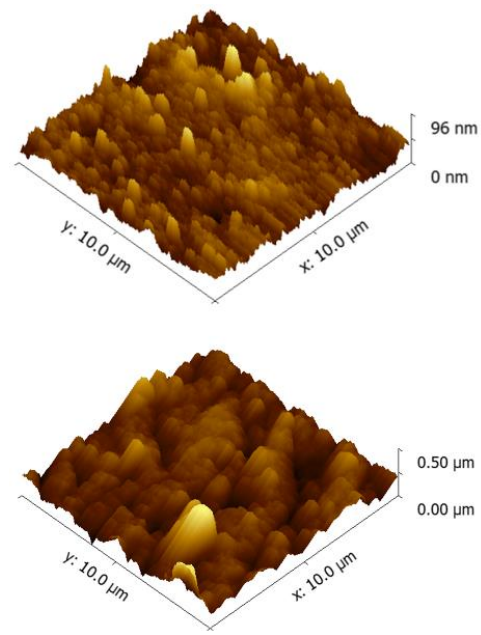

Fig. 3. Atomic force microscopy of inkjet printed Silver nanoparticle surface 11 nm root mean square roughness (top) Inkjet printed polymer material surface 95 nm root mean square roughness (bottom)

in unison, it encases the UV-cured polymer and supports any overhangs. In Fig. 1(a) and (b) the wax material can be seen encasing the polymer which is subsequently melted and washed off. The final antenna with printed silver is also shown in Fig. 1(c). A Dimatix 2831 inkjet printer is used to print the silver nanoparticle ink (Sigma Aldrich Silver Ink 719048) with a disposable 10 Pico-liter 16 nozzle head. While it is best to print all materials within the same printer, the nanoparticle ink is not stable enough to use with non-disposable inkjet-heads. Producing a stable conductive ink is currently being investigated.

After UV-curing, the polymer material is rigid, with good mechanical properties similar to polycarbonate. It is not an ideal radio frequency dielectric though, with a dissipation factor of around 0.02. The material has been characterized from 10 MHz to 1 GHz with an Agilent E4991 impedance analyzer and dielectric test fixture 16453A, results are shown in Fig. 2. Measurement of five different samples shows there is a range especially in the dissipation factor at low frequency. A single waveguide test done at Delsen Labs in California USA characterized the material at 9.375 GHz and is also plotted in Fig. 2 and shown as a circle. The dielectric shows some dispersion with increasing frequency, ranging from 3.2 in the low MHz to 2.8 at 9.375 GHz. Although the precise value of dissipation factor is difficult to measure, it is around 0.03 - 0.02 over this frequency range.

A major benefit of 3D printing is that complex internal features can easily be fabricated, which would be difficult to realize with traditional tooling. The honeycomb substrate used in this work provides a reduced dielectric constant and improved dissipation factor which are both desirable for

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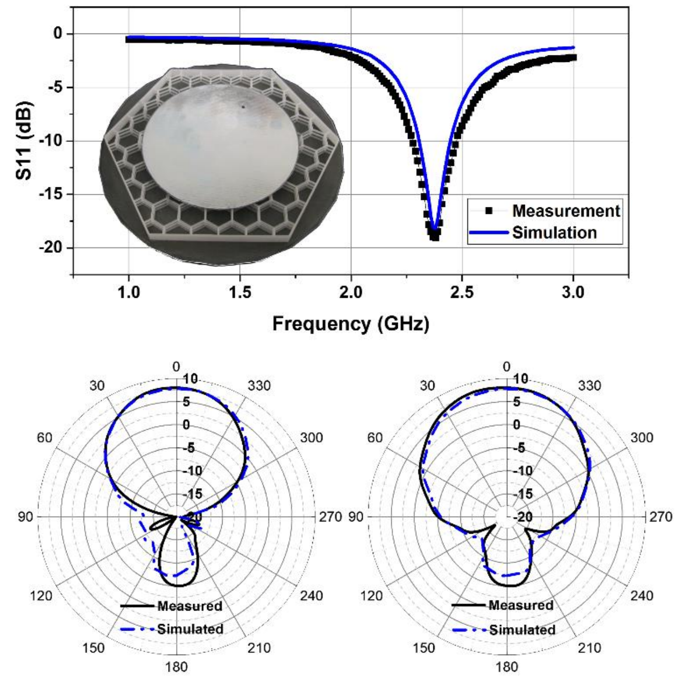

Fig. 4. Measurements and simulations of the honeycomb patch antenna, magnitude of S11 versus frequency (top), E-plane radiation pattern cut (bottom left), H-plane cut (bottom right)

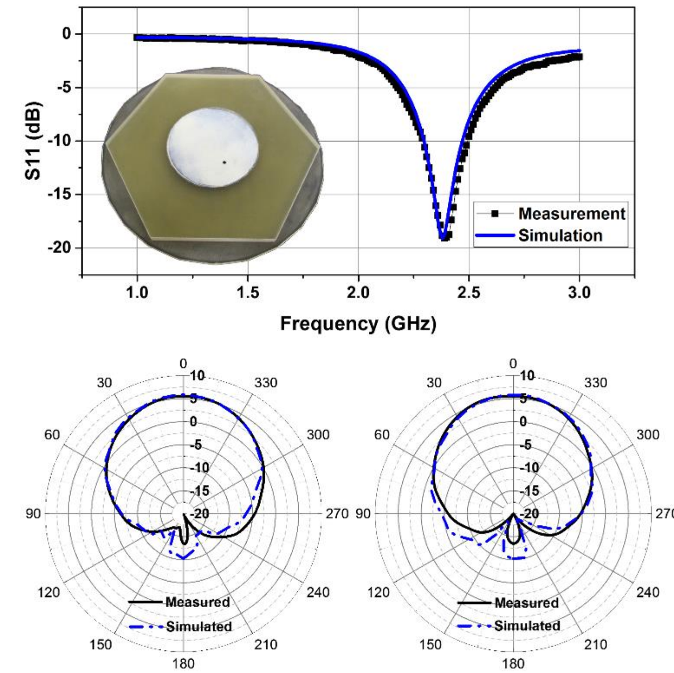

Fig. 5. Measurements and simulations of the solid substrate patch antenna, magnitude of S11 versus frequency (top), E-plane radiation pattern cut (bottom left), H-plane cut (bottom right)

antenna performance. The use of a planarizer which levels the material as it is being printed provides smooth finished surfaces. Atomic force microscopy scans of the printed surfaces show roughness better than 100 nm root mean square for the UV-polymer seen in Fig. 3. This is a major improvement over 3D printed surfaces in [11] [22] with 10-30 µm of roughness.

The silver nanoparticle ink in this work is printed at 30°C and is fluid after being deposited. This allows the ink to be very smooth with root mean square roughness of 11 nm as shown in Fig. 3. Although nanoparticle sintering occurs at reduced temperature relative to bulk metal, temperatures above 180°C are best. However, these temperatures are above the glass transition point for the UV-cured polymer. In order to achieve conductivity at much lower temperature a laser sintering process is used [23]. A total of six silver layers are printed, three layers at a time and partial dried at 80°C to avoid excessive ink spreading. After the six layers are printed and dried, laser sintering is performed which takes about 15 minutes. A CO_2 engraving laser (Universal Laser system PLS6.75) operated at 60W and a speed of 30 cm/s defocused 20 mm above the silver ink and giving 1000 pulses per inch is utilized. The final thickness of the printed silver is approximately 3.5 um measured by a Dektak profilometer. It should be noted that both the patch and the ground plane are printed in this fashion. The antenna is probe-fed using a coaxial connector shown in Fig. 1(e). Since soldering the thin nanoparticle silver is not possible, a silver epoxy (Duralco 120) is used. A non-conductive epoxy (Loctite Quickset) is used on top for additional strength. The conductivity of the inkjet printed silver has been measured by four-point probe method to be $1e^6$ S/m which is lower than bulk silver at $6.3e^7$ S/m. However, adequate antenna performance is achieved and the process does not exceed 80°C.

III. Antenna Design and Results

The patch antenna is one of the simplest and most well studied antennas. They are popular because they are planar, low profile, and can provide different polarizations. The linearly polarized patches in this work, are designed to operate at 2.4 GHz, a popular industrial scientific and medical band. High Frequency Structure Simulator (HFSS) software is used in this work. Two patches are compared, the first antenna has a solid 3D printed substrate. Both honeycomb and solid substrate patches are fabricated using the same process and materials. The second antenna is a honeycomb structure which is meant to emulate air while maintaining structural support. The honeycomb structure is chosen because it minimizes material. Each hexagon has 4.5 mm length sides and the beams are 500um thick shown in Fig. 1(d). For the honeycomb structure, the dielectric constant and dissipation factor were estimated to be 1.1 and $2e^{-3}$ respectively. This estimate was made by calculating the volume filling factor of the honeycomb and using a weighted average. The effective dielectric properties were used to simplify the simulation of the honeycomb structure and save computing time. Although this method is not the most accurate it provides a sufficient estimate for this work, as shown in [13]. A near field Satimo Star lab system is used to measure the antennas. The antenna radiation efficiency is

TABLE II
ANTENNA PARAMETERS

Antenna	Patch Radius (mm)	Substrate Thickness (mm)	Center Freq. (GHz)	Total Weight (gram)	Peak Gain (dBi)	Radiation Efficiency (%)
Solid Substrate	20	5.0	2.4	35.0	5.7	67
Honeycomb Substrate	32	5.0	2.4	5.8	8.0	81

measured to be 81% and 67% respectively. The simulated efficiency for comparison is 84% and 71%. Simulations show that by doubling the printed silver layers to 12 the efficiency of the honeycomb substrate could be pushed to 91%. The Table below highlights key measured parameters of the two. Both patches are matched well at 2.4 GHz as shown in Fig. 4 and Fig. 5. The air like dielectric substrate provides a larger patch with 32 mm radius however the weight is reduced to only 5.8 grams including the connector.

From Table 1 it is clear that the gain has increased and efficiency is improved in the case of the honeycomb structure. An interesting observation is seen when comparing the E and H plane cuts at low elevation angles (50^o to 90^o) for the solid substrate antenna Fig. 5. The patterns are equalized, which is not the case for the honeycomb antenna at low elevation. This is true for both the simulations and measurements. The phenomenon of equalizing the E and H plane patterns at low elevation angles is shown in [24] and occurs at a specific combination of dielectric constant and ground plane size for the circular patch.

IV. CONCLUSION

Inkjet printing is transitioning from solely a graphic arts medium into a useful fabrication tool. The ability to deposit multiple materials and the scalability of inkjet systems with thousands of nozzles makes it possible to realize large and complex parts. A process is presented where inkjet printed UV-cured polymer, and silver nanoparticle ink are integrated together. Silver nanoparticle ink is selectively laser sintered to provide conductivity without damaging the surrounding UV-polymer. The printed surfaces are smooth, better than 100 nm root mean square. The dielectric constant has been lowered and dissipation factor improved by using a mostly air filled honeycomb structure. Although the conductivity of the printed metal is still inferior to bulk metal. An antenna that is light weight with improved efficiency and reasonable gain is demonstrated. With future advances in printed metals, performance could one day overcome conventional fabrication methods.

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