3D/Inkjet-printed Millimeter Wave Components and Interconnects for Communication and Sensing

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***Abstract* — This paper presents the design and experimental results of 3D/inkjet printed circuits operating in millimeter wave frequencies. Millimeter wave technology is particularly suitable for 5G communication systems however it is also associated with a higher cost, and larger time-to-market. 3D/inkjet printing technology presents an exciting alternative to traditional fabrication techniques being cost-efficient, and allowing for rapid prototyping. This paper offers an overview of recent results associated with fully printed planar antennas, lens antennas, millimeter wave interconnects and sensors demonstrating the potential of the technology.**

***Index Terms* — Additive manufacturing, 3D printing, inkjet printing, mmWave, backscatter communication, lens antennas, System-on-package, interconnects.**

I. INTRODUCTION

Nowadays, 5G is leading a paradigm shift in communication and sensing with impact in every aspect of human life: smart homes/cities, wearables, structural heath monitoring, self-driven automobiles [1]. Millimeter wave operation offering an ultra-small circuit footprint, large bandwidth, and beamforming capability using large antenna arrays, is an ideal candidate to obtain the required performance and functionality. In addition, mechanical properties such as conformal structure and flexibility become important. However, mass adaptation of millimeter wave technology has yet to appear due to cost and challenges associated with circuit design and fabrication.

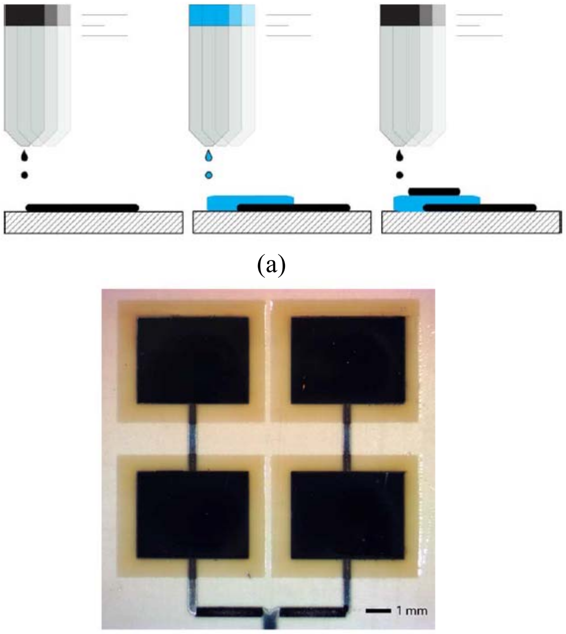
Millimeter wave systems are traditionally expensive to fabricate due to their inherent requirements for low loss, high performance materials, high resolution fabrication, and more expensive integrated circuit (IC) technologies. This translates to a low yield and a large time-to-market. For example, micro-machining technologies can deliver good performance at a high cost prohibiting mass production [2]. While IC fabrication cost is reducing due to advances in CMOS technologies, the challenge associated with packaging and system integration of the ICs with antennas, sensors and interconnects is often the bottleneck in terms of cost and performance, due to circuit parasitics, and fabrication tolerances. Additive (3D) manufacturing can provide an inexpensive and fast fabrication, however its use is typically demonstrated in low frequency electronics, requiring large features and low-end materials. Recently, 3D printed high frequency waveguide and antenna components have appeared in the literature [3][4], but 3D printing of complete millimeter wave subsystems has yet to appear due to a combination of lack of know-how associated with a joint optimization of the fabrication process, multiple and diverse material printing and post-processing, and circuit design.

Hybrid 3D/inkjet-printing is a promising technology to deliver the required system complexity in a single process. It directly connects rapid, on-demand prototyping to production, with reduced cost and design flexibility. This is due to a drastically lower cost of the fabrication equipment and the reduction/elimination of expenses associated with treatment of waste residues such as the lack of masks, photoresist, chemical etching. Additionally, there is cost reduction from the optimal use of materials due to the additive character of the technology where material is used only where needed, in contrast to conventional etching/milling methods. 3D/Inkjet fabrication technology enables printing on a variety of substrates from paper, textiles, glass, to standard printed circuit board materials, which makes it particularly suitable for IoT as well as communication and sensing applications. Furthermore, it is capable of synthesis and combination of a diverse set of materials with desired properties, which enables a larger design freedom. It provides a unique process for packaging and integration of heterogeneous components including ICs, sensors, passives, different materials, interconnects and even mechanical flexibility, stretch-ability and morphing.

In this paper, an overview of selected recent advances in 3D/inkjet printing of millimeter wave components is presented, including planar and lens antennas, backscatter communication tags, battery-less sensors and millimeter wave interconnects.

II. INKJET PRINTED MICROSTRIP ANTENNAS

An important challenge in inkjet printing towards fully printed systems is the ability for multilayer fabrication. In [5], a fully printed proximity fed 4 element microstrip patch array was demonstrated with measured 7 dBi gain at 24 GHz (Fig. 1b). The microstrip feed line was printed using a silver nanoparticle ink on commercial liquid crystal polymer (LCP) substrate. The substrate of the patch antenna was a 60-um thick SU-8 polymer layer printed on



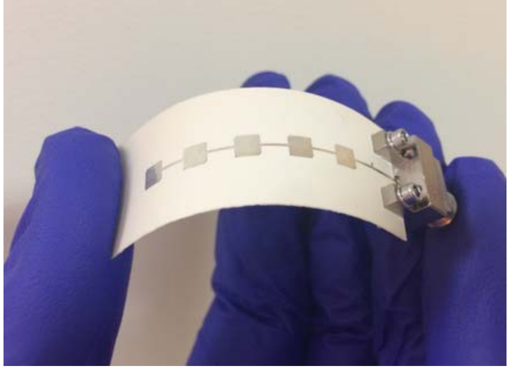
(a)

(b)

Fig. 1. 24 GHz inkjet-printed proximity fed patch antenna array [5], a) fabrication process, b) top view of the prototype.

top of the feed line, followed by the patch antennas printed using silver nanoparticle ink on top of the polymer (Fig. 1a). The fabrication process is presented in detail in [5].

Using LCP as a substrate further enables the implementation of flexible circuits. A 24 GHz series fed patch array fabricated by inkjet printing directly on LCP is shown in Fig. 2 [6]. 7 mil-thick LCP is used to achieve an array impedance bandwidth of more than 1 GHz. Silver nanoparticle ink is directly printed on the LCP substrate with excellent adhesion and immunity to cracks when bending the structure. The flexible properties of the LCP make such printed arrays suitable for conformal and wearable applications, e.g. for flexible sensors.



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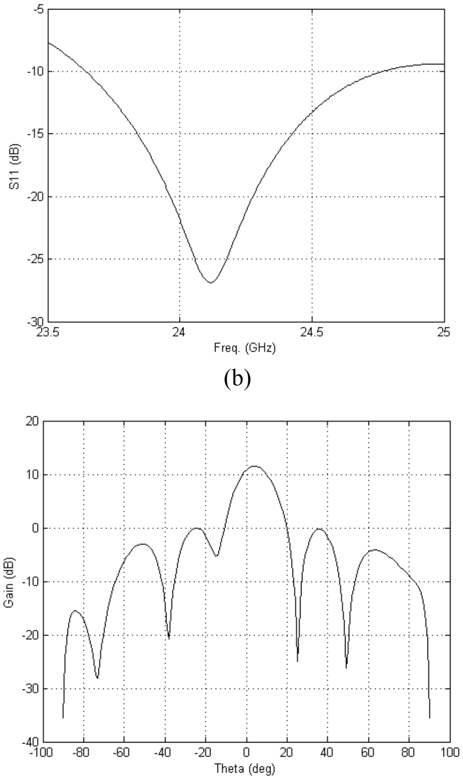


(b)

(c)

Fig. 2. 24 GHz series fed patch array on LCP substrate, a) array prototype and simulated s-parameters (b) and gain (c) [6].

III. 3D PRINTED LENS ANTENNAS

One of the first and natural applications of 3D printing technology in millimeter wave systems has been the fabrication of printed dielectric lens antennas, due to its ability to create complex shapes, in a fast manner and with low cost [3]. As an example, in Fig. 3, prototypes of a 24-GHz bifocal lens, printed using a stereolithography 3D printing process, are shown.

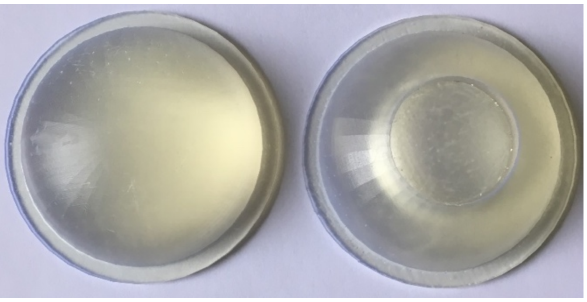


Fig. 3. 24 GHz 3D printed bifocal lens of 8 wavelengths diameter (left), zoned version of the design (right).

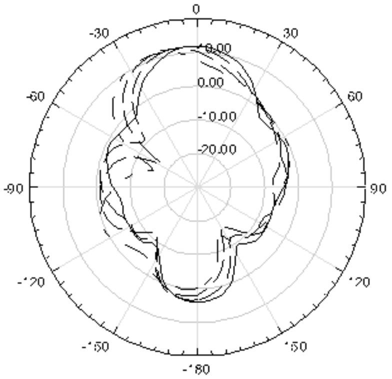


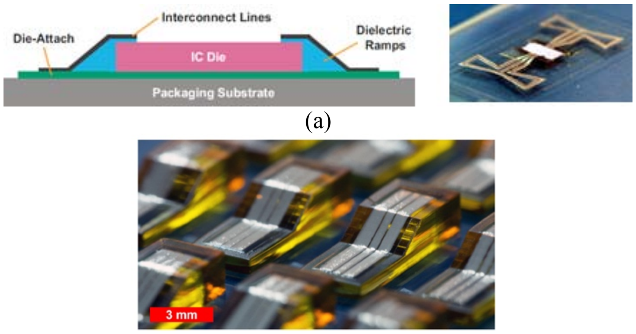
Fig. 4. Simulated radiation patterns of the directivity of a 24 GHz 3D printed bifocal lens of 2 wavelengths diameter.

A bifocal lens is particularly suitable for beam-scanning applications due to its ability to maintain minimum gain variation versus the scan angle [7]. Simulated radiation patterns of a small lens of 2 wavelengths diameter at 24 GHz excited by a patch antenna are shown in Fig. 4, obtained with a commercial finite element simulator. As the feed antenna moves towards the perimeter of the lens the beam is scanned. A maximum gain reduction of 0.5 dB is observed for a scanning angle of 21 deg. For comparison, the lens designed in [7] had a 1 dB reduction at 77 GHz.

Since lens design using 3D printing finds suitable application in millimeter wave systems, there is a strong interest in characterizing the permittivity and loss tangent of the various materials used in millimeter wave frequencies. Recent work in material characterization at E-band of commonly used photopolymer resins Vorex from MadeSolid and Porcelite from Tethon3D showed a permittivity of 2.6 and maximum loss tangent 0.019 for Vorex and a permittivity in the range of 3.4-3.7 and maximum loss tangent 0.026 for Porcelite [8]. A further exciting possibility towards lens design is the ability to control the density of the deposited material which allows the design of gradient index dielectric substrates [9].

IV. 3D/INKJET PRINTED INTERCONNECTS

The integration of active MMICs and passive structures such as antennas and the use of multilayer substrates presents a challenge in terms of developing high performance packaging and interconnect design. The combination of 3D stereolithography and inkjet materials printing enable novel interconnect structures such as ramp type interconnects (Fig. 5) [10]. Preliminary results of ramp structures showed a measured insertion loss of approximately 1 dB at X-band [10], while more recent results achieved 1.5 dB at 24 GHz [8]. The latter translated to and effective insertion loss of 0.2 dB/mm, while typical wire bonds feature insertion losses of 0.6-2 dB/mm [12], [13] for the same frequency band.



(a)

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Fig. 5. 3D/Inkjet printed millimeter wave ramp interconnects (a) [10]. b) [8].

IV. APPLICATIONS

There are many applications of the technology in millimeter waves due to its advantages of low cost and fast prototyping. One application related to communication is the implementation of a millimeter wave backscatter tag, a prototype of which is shown in Fig. 2a [6]. Backscatter communication has its roots in radar technology and it is based on changing the load of a receive antenna according to a desired information signal. An interrogating reader device is used to transmit a continuous wave signal towards the tag, part of which is scattered back to the reader containing the desired information due to the load modulation of the tag antenna. Passive UHF RFID systems operate based on this principle, however operation in millimeter wave frequencies permits a much larger bandwidth and enables high bit rate communication using a very low power tag front-end. The prototype shown in Fig. 2 used an off-the-shelf discrete p-HEMT as a switching element to modulate the load of the inkjet-printed series-fed patch array and achieved switching rates above 1 Gbps with an energy per bit of 0.15 pJ/bit [6].

A battery-less sensor based on an inkjet-printed retro-directive array operating at 28 GHz was demonstrated in [11]. The Van Atta retro-directive array can re-transmit a received signal towards its direction of arrival due to the proper interconnection between its elements, which implements the desired phase reversal necessary for the reflected wave to be directed towards its sender. A low frequency (MHz) oscillator based on a commercial Texas Instruments LM555 chip powered by a solar cell was used to modulate the backscattered signal from the array. The solar cell acts both as a power source and a proximity sensor by changing the bias voltage provided to the LM555 and consequently its oscillation frequency. In addition, an inkjet-printed carbon nanotube resistive sensor sensitive to the presence of ammonia gas was used as a frequency tuning element to the low frequency oscillator enabling a dual sensing functionality. Sensing experiments using the fabricated prototype demonstrated an operating range of up to 80 m [11].

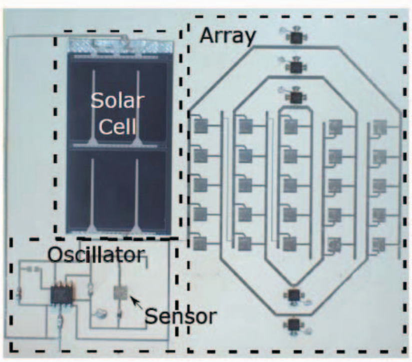

Fig. 6. 28 GHz battery-less sensor based on an inkjet-printed Van Atta retro-directive array [11].

VII. CONCLUSION

3D/Inkjet printing fabrication enables the low cost and fast prototyping of millimeter wave systems, and provides an exciting alternative to traditional fabrication techniques towards the commercialization of the technology. Several circuit examples were presented including antennas and arrays, lens structures and interconnects, and a selected set of sensing and communication applications based on modulated backscattering enabling an ultra-low power millimeter wave circuit implementation.

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