Novel 3D printed Liquid-metal-alloy microfluidics-based Zigzag and Helical Antennas for Origami Reconfigurable Antenna “Trees”

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***Abstract*—The first-of-its-kind origami antenna “tree” model is introduced in this paper, enabling the integration of multiple 3D antennas with a minimal interference and an on-demand reconfigurability of frequency, polarization and radiation pattern to optimize performance in dynamically changing environments. EGaIn, a liquid metal alloy(LMA) is used to switch between antennas and to enable flexible implementations. An origami structure, the zipper tube, coupled with Voronoi topology implementations is utilized as the scaffolding structure facilitating the mechanical tuning of the radiation pattern while minimizing storage requirements. The “tree” was fabricated by 3D printing, enabling on-demand fast-prototyping and low-cost manufacturing. A proof-of-concept two-antennas “tree” (zigzag/helical antenna) was presented, featuring a dual-band (3GHz/5GHz) operability and different polarizations (linear/circular) along with varying radiation patterns with “tree” compression. The “tree” can be applied to various dynamically changing scenaria such as wireless communications, collapsible/portable radars, satellite communications, while it can also realize numerous other reconfigurable RF components, such as filters, reflectors and shielding structures.**

***Index Terms*—antenna, 3D printing, origami, Liquid-metal-alloy, reconfigurable, microfluidics, static antenna topologies**

I. INTRODUCTION

Antennas are critical components of communication and radar systems, so their common inability to adjust to new operating scenarios can impose significant limitations to system performance. Reconfigurable antennas, on the other side, can adapt to changing system requirements or environmental conditions; they can ameliorate or eliminate these restrictions and provide additional levels of functionality for any system while adding substantial degrees of freedom and functionality to the communication systems [1]. The need of such reconfigurability can be fulfilled by a single reconfigurable antenna or a platform that integrates multiple antennas. However, the single-platform integration of numerous antennas can be challenging due to high interference. In order to achieve superior reconfigurability than virtually any single reconfigurable antenna while prevent most interference, this paper demonstrates, for the first time, a novel antennas “tree” configuration: a integration of antennas that feature reconfigurable capability in all aspects, such as frequency, radiation pattern, and/or polarization.

Liquid metal alloy (LMA), especially Eutectic Gallium-Indium (EGaIn), features a great potential in reconfigurable electronics due to its non-poisonous, high-conductivity, flowable and stretchable properties [2]. With the help of microfluidics, a tool that allows the manipulation of small amounts of liquids, LMA can be transferred within structures of various shapes [3]. Furthermore, unlike all solid materials, liquid metal is stretchable with literally no failure point and is only limited by the channel’s stretchability. This excellent flexibility facilitates bending as much as needed, although it could complicate the accurate control of the mechanical deformations of the antenna structure. Therefore, an origami (“zipper”) structure is utilized here to effectively control the mechanical movement of the antenna.

As a effective solution for mechanical reconfiguration, origami-based radio frequency (RF) structures have been reported both without and with 3D printing [4], [5], in which the breakage along the foldlines is one of the biggest challenges. As the above mentioned, the breakage of metal during bending can be effectively resolved through the use of LMA. Moreover, in order to reduce the stress of substrates along the foldlines while maintaining the correct structure, a Voronoi topology is introduced to the microwave sturctures for the first time. Voronoized the shape is a equivalent “skeleton” (frame) of original continuous solid structures using the Voronoi graph of boundary points, which provides a synthetic and lightweight representation of objects with much less material [6].

The “tree” structure combines LMA microfluidics channels, 3D antenna sturctures, and origami voronoized supports, which lead to a rather sophisticate 3D topology, which is hard to fabricate with conventional fabrication methods. However, with 3D printing, the structure can be easily fabricated in a cost efficient and fast prototyping fashion which allows various on-demand antennas to be integrated on the same antennas “tree” within hours.

This paper presents a first-of-its-kind 3D printed antennas “tree” that can integrate virtually any antenna and is capable to reconfigure in frequency, radiation pattern and polarization by filling/unfilling the LMA or folding/unfolding the origami scaffolding structure, enabling numerous potential applications including wireless communications, flying and space platforms, collapsible/portable radars, satellite communications.

II. PRINCIPLE OF OPERATION

Fig. 1 shows the proof-of-concept structure, which can be seen as a tree, while each antenna along with its impedance transformer represents a “branch”. All antennas share the same feed, which can be seen as the “root” of the tree, as shown in Fig. 2b. This antenna tree can be reconfigured in three ways: switching between antennas through the use of microfluidics, tuning the filling volume of LMA, and compressing the origami structure. First, through the use of microfluidics

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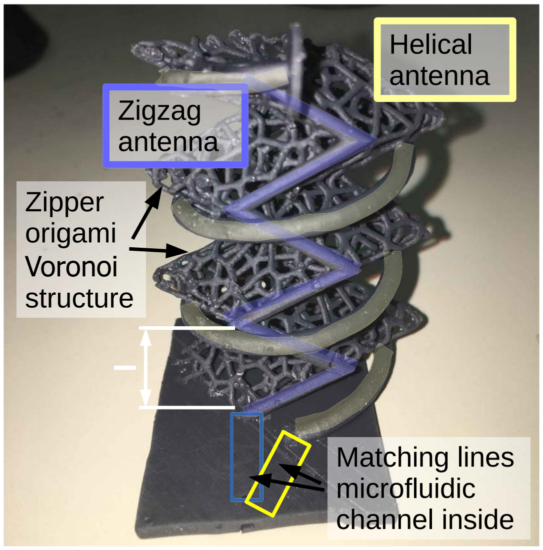
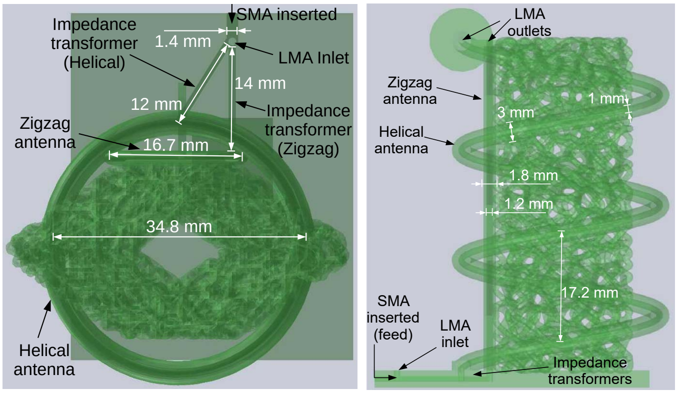


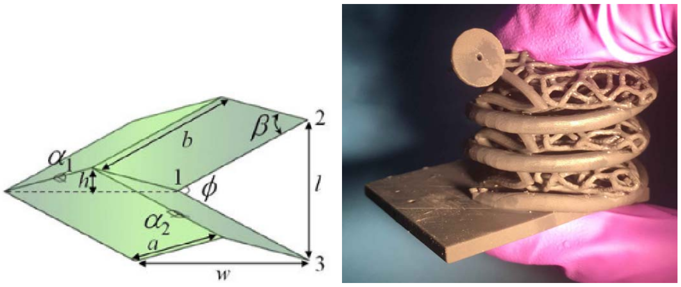
Fig. 1. A photo of the 3D Printed origami antenna tree. The zigzag antenna and its matching circuit are marked in blue while helical antenna and its matching circuit in yellow.



(a) (b)

Fig. 2. Top view (a) and side view (b) of the 3D model of the proposed “tree” with dimensions. Certain transparency was added to assist understanding of the structure.

switches, LMA can be easily directed to a specific impedance transformer and antenna while other “branches” are left empty thus preventing any significant interference to the working “branch”. In this way, the antennas “tree” can integrate any antenna that can be realized with LMA, while all these antennas can operate independently of each other. As a proof of concept, two “branches”, a zigzag antenna and a helical antenna, are presented in this paper, as shown in Fig. 1. Beside switching between the “branches”, the proposed configuration can also be used to accurately control the volume of filling LMA (e.g. number of turns). For example, for zigzag and helical antenna, the number of turns of the antenna depends on the volume of LMA, which changing the maximum gain of the antenna. As a result, the gain of the antennas can be tuned [3], by filling different volume. The filling and unfilling of the “branch” can be realized by microfluidics pumps and controlled by microcontrollers.



(a) (b)

Fig. 3. (a) Pattern and parameters of a Miura-ori cell, which is the base for the zipper tube. Reprint from [7]. (b) A photo of a 3D printed zipper-tube in compression.

TABLE I
CRITICAL ANGLE α AND HEIGHT OF EACH SEGMENT

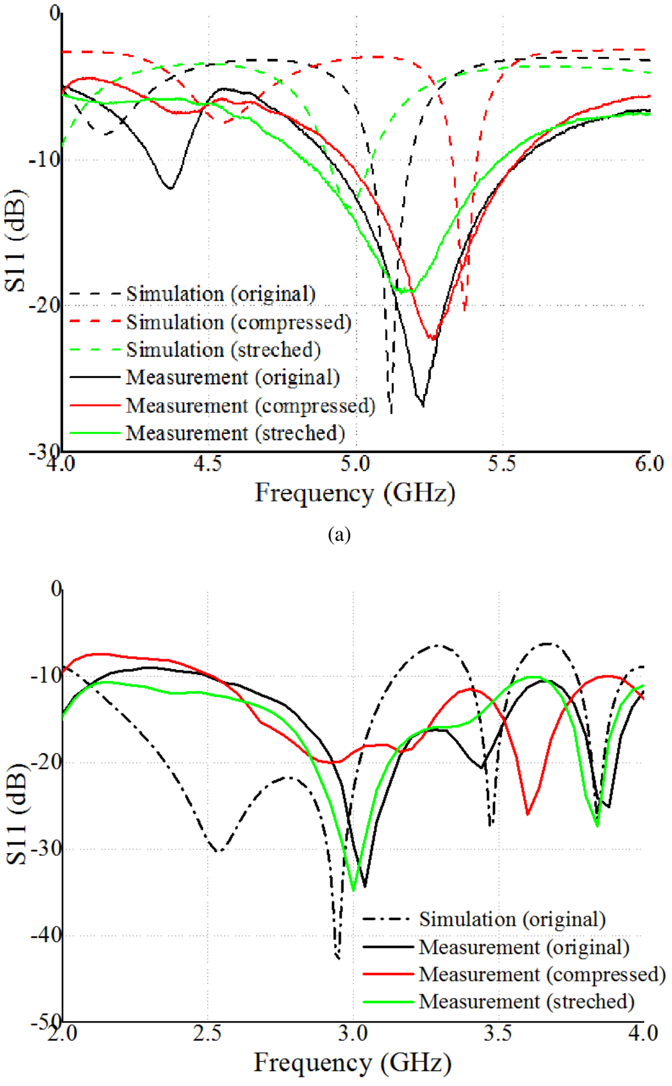
Status	$\alpha 1$	l (mm)
Compressed (maximum)	35	7.3
Original	90	17.2
Streched (maximum)	150	23.5

Moreover, a zipper-tube based scaffolding origami structure is utilized that allows the mechanical reconfigurability of all antennas through mechanical folding and compression. A typical symmetrical unit cell for a zipper-tube, is realized by overlapping two symmetry Miura-ori unit cells (Fig. 3a) along their edges, and for antennas like zigzag antennas and helical antennas, each zipper segment can be attached to one turn/repeatable element, thus allowing multiple structures to get actuated simultaneously. The height of each segment (l) and the shape of the zipper tube depends on a single critical angle, $\alpha 1$ controlling the compression/stretching status of the “tree” as shown in Table. I [7]. , which significantly facilitates the easy tuning of the attached structures. A proof-of-concept three-segments zipper tube origami strcture is fabricated to mechanically tune the two “tree” antennas as shown in Fig. 1.

III. 3D PRINTING FABRICATION OF THE “TREE”

A. 3D printing and Voronoi

The dielectric origami and microfluidic structures, as shown in Fig. 1, are additively manufactured using a stereolithography (SLA) 3D printer, FormLabs form 2, featuring 50 um spacial resolution. SLA printing technology is using a moving ultraviolet (UV) laser beam to selectively cure/solidify photo-polymer patterns layer by layer. FormLabs flexible resin (FLGR02), featuring 80% elongation, demonstrated a great flexibility. However, origami structures usually feature hinges with extremely small bending radius and the endurance of this material is limited, so the structure may break at hinges after 15-20 times of compression. This issue could not be resolved by simply decreasing the thickness as thinner wall would largely affect printing performance. Therefore, Voronoi, a topology to reconstruct the model into a skeleton-like structure without changing the macro shape was used to reduce the stress of the material [6] while drastically saving material and production time. After Voronoized the origami structure, more than 200 times of compression have been performed



(a)

(b)

Fig. 4. Measured and simulated S11 of the zigzag antenna (a) and the helical antenna (b) under different folding states. The fabricated wall of microfluidics channel is thinner than that in the 3D model which causes the simulated resonant frequencies to be lower than the measured ones.

and no breakage was found. Fig. 3b shows compressing the Voronoized origami zipper tube with two fingers.

B. Liquid metal alloy

The LMA used is EGaIn (Sigma-Aldrich, 495425), an alloy with 75%wt Gallium and 25%wt Indium, which features a 15.5 °C melting point and a $29.4 \times 10^{-6}\Omega$*cm resistivity that enables high-performance electronic designs [2]. Due to its liquid nature, LMA ensures a "never-fail" bending and a continuous self-healing even if cracks occur under extreme folding conditions, which facilitates the realization of rugged flexible/compressible LMA antennas. The bulk viscosity of EGaIn is 1.9910 mPa*s (twice of water, one 4000th of ketchup), which enabling trouble-less flowing in the channels. Gallium oxidizes easily when exposed to air, an effect that could prevent the proper flow of LMA. To dissolve/avoid the oxidation skin of the EGaIn, sodium hydroxide (NaOH) solution was circulated inside the microfluidic channel before the filling with EGaIn. In order to accurately control the flow of LMA, microfluidics pumps are needed to inject and withdraw LMA to/from the channels. As a proof-of-concept, a syringe pump was used in this paper.

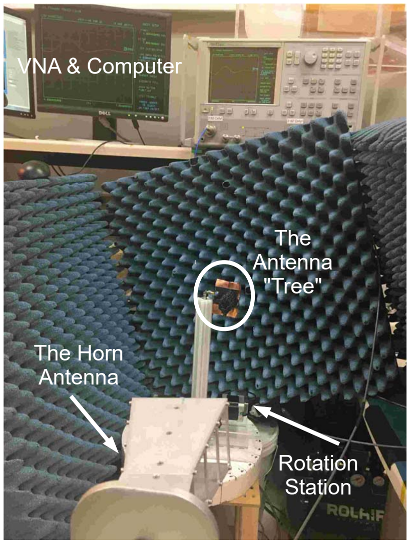


Fig. 5. Measurement setup for the radiation pattern of the zigzag antenna. A horn antenna and roatation station were used to measure the zigzag antenna.

IV. ANTENNAS ON THE "TREE"

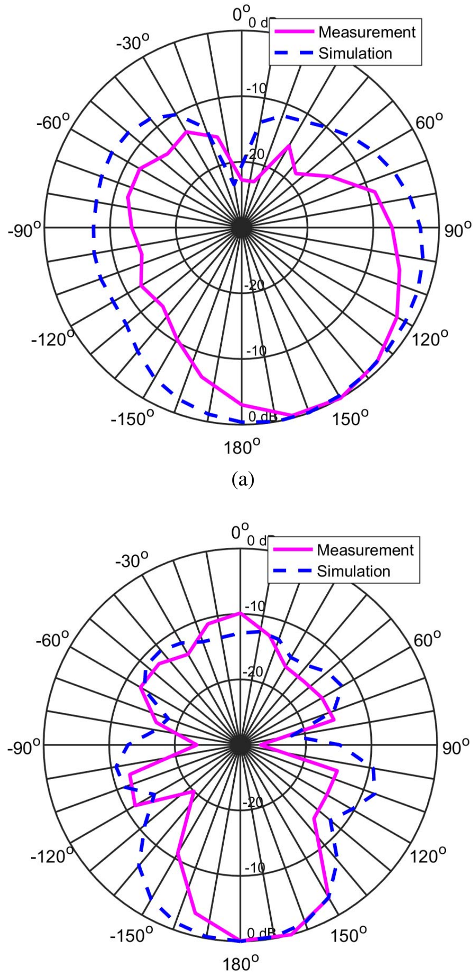
Without loss of generality and for proof of concept demonstration purposes, a regular helical antenna (circularly polarized) and a zigzag antenna (linearly polarized) were fabricated on the "tree". In order to obtain different polarization, a regular helical antenna and a zigzag antenna which is a special case of helical antenna with linear polarization, are fabricated in the tree. Two antennas were simulated and optimized with Ansoft HFSS with their dimension in Fig. 2. After the fabrication, the prototype were measured with an vector network analyzer (VNA) for the original (uncompressed), maximum compressed and maximum stretched states. And the radiation patterns were measured with setup shown in Fig. 5.

A. Branch No. 1: Zigzag antenna

A zigzag antenna was designed to work at 5 GHz. Fig. 4a shows a good matching for various folding states, which ensures the effective radiation performance for different mechanical reconfiguration states. The respective simulated and measured radiation patterns are shown in Fig. 6. As the zipper got compressed, the zigzag antenna featured a trend to shift from directional to omnidirectional radiation patterns and the 3dB beam width (HPBW) increased from 28° (original) to 60° (compressed).

B. Branch No. 2: Helical antenna

The second antenna is a helical antenna, which features a good impedance matching and a radiation pattern variance for different states of mechanical deformation as shown in Fig. 4b and Fig. 7. Similar to the zigzag antenna, when fully



(a)

(b)

Fig. 6. Measured and simulated normalized radiation pattern of the compressed (a) and of the original (b) zigzag antenna at 3 GHz.

compressed, the HPBW of the helical antenna increased from 60° to 90°.

V. CONCLUSION

This paper presents the reconfigurable antenna "tree", a novel approach to realize integrated reconfigurable antennas by combining LMA microfluidics and Voronoi origami structures. This approach can be realized only through the recent developments in flexible 3D printing technologies that enable the quick prototyping of on-demand 3D foldable/compressible antennas. A proof-of-concept antenna "tree" prototype that features dual-band radiation and different polarizations was presented for the first time. This "tree" can effectively adapt to various dynamically changing scenaria and can be potentially applied in wireless communications, flying platforms, collapsible/portable radars, satellite communications.

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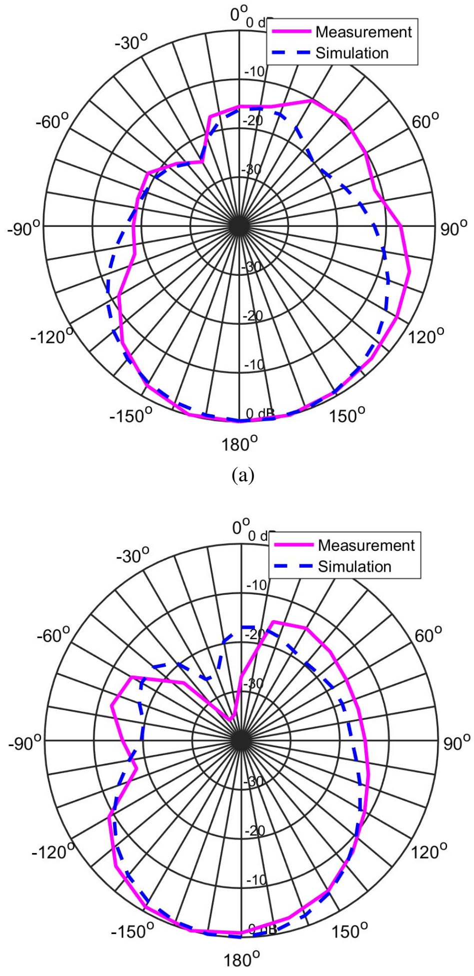

(a)

(b)

Fig. 7. Measured and simulated normalized radiation pattern of the compressed (a) and of the original (b) helical antenna at 5 GHz.

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