3D Printed Wearable Flexible SIW and Microfluidics Sensors for Internet of Things and Smart Health Applications

Wenjing Su, Zihan Wu, Yunnan Fang, Ryan Bahr, Pulugurtha Markondeya Raj, Rao Tummala, and Manos M. Tentzeris
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332
Email: wenjing.su@gatech.edu

***Abstract*—In this paper, a flexible SIW wearable sensing platform is proposed with a novel 3D printing process which enables fast-prototyping customized wearable devices. The fabrication utilizes state-of-the-art SLA 3D printing that features fast prototyping of easy-to-reconfigure flexible 3D objects. Two different flexible metallization approaches are explored in this paper, which are complementary to each other and provide an excellent 3D metallization solution together. Two 3D shape SIW transmission lines are shown with a great flexibility and great potential for wearable devices. Moreover, based on a SIW slot waveguide antenna, this paper presents a proof-of-concept microfluidics sensor with sensitivity of 1.7 MHz/Er, which can be used as a wearable sensing device for real-time monitoring of body fluids. The proposed SIW-based flexible wearable devices along with the microfluidics sensors can be used in various Internet-of-Things applications, such as smart health and food quality monitoring.**

***Index Terms*—Internet-of-Things, Smart health, 3D printing, microfluidics, SIW, wearable sensors, flexible waveguides**

I. INTRODUCTION

Recently, wearable sensors and “smart skins” have drawn a lot of attention from academia and industry, as they enable real-time health monitoring and distributed “smart health”. For instance, the real-time monitoring of bodily fluids, such as tears, sweat, urine and blood through wireless wearable fluidic sensors, can effectively track the patient’s health status and alert him/her in time to prevent any life-threatening situations. Thus, microfluidics-based microwave sensors have been an important element in realizing the desired “smart health” Internet-of-Things (IoT) implementations and systems[1], [2]. On one hand, a wearable sensor should be imperceptible so that it won’t affect the normal activities of human. Thus the wearable sensor is preferred to be miniaturized, customized and flexible. On the other hand, the sensor operation should be virtually unaffected from the ambient conditions and unrelated human activity, thus sufficient electromagnetic isolation is significant.

Additive manufacturing techniques, including 3D printing, have been increasingly applied to microwave sensor prototyping[3]. With Stereolithography (SLA) 3D printing, high-resolution customized sensors can be easily designed and quickly prototyped. Moreover, 3D printing enables low-cost production, leading to affordable and disposable sensors. By printing flexible materials in optimized 3D configurations, the resulting sensing devices can achieve excellent stretchability and twist-ability. Furthermore, as metallization is a significant challenge for 3D printed electronics, a combination of massive (large-area) metallization and selective metallization approaches that are presented in this paper could play a critical role in wearable electronics.

Moreover, SIW or dielectric-filled waveguide strcutures are known for high performance in higher frequencies as they can eliminate the radiation loss, provide perfect electromagnetic isolation from the environment and feature a relatively stable performance during bending, thus becoming a great candidate to construct wearable microwave devices. This paper utilizes SIW structures and slot waveguide structures for flexible and high performance wearable designs.

In this paper, we introduce a novel approach for design and fabrication of low-cost flexible customized wearable sensors, which can be used in “smart health” Internet-of-Things (IoT) applications.

II. FABRICATION

A. *SLA 3D printing*

stereolithography (SLA) printing technology utilizes a rapidly scanning ultraviolet (UV) laser beam to selectively cure/solidify photopolymer patterns layer by layer to prototype 3D objects. The substrate of SIW is printed by a SLA 3D printer, FormLabs Form2, with 50 μm spacial resolution. The 3D model of the SIW is defined by a 3D CAD STereoLithography file (.stl). The SLA printer would cross-link the photopolymer resin with a 140-μm-beam-width (FWHM) and 250-mW-intensity laser. After printing, the printed prototype will be raised in the isopropyl alcohol (IPA) for several minutes to remove any uncured resin, followed by a UV exposure with bath in water to fully cure the structure. FormLabs flexible resin (FLGR02), featuring 80% elongation, was used and have a permittivity around 2.8 with tangent loss around 0.06.

B. *Metallization*

The metallization of 3D printed dielectric objects has many challenges, especially in flexible structures. A high conductivity thin layer of conductor is needed to guarantee the absence of breakage/cracks under bending conditions.

1) Massive metallization: For massive metallization without a strong need for a specific pattern, metallization can be achieved by simply rinsing the 3D prototypes into a silver nanoparticle ink bath followed by a bake. As 3D printed prototypes generally have a high surface roughness, the ink attaches to the prototypes due to the surface energy. After the bath, the prototypes are baked in the oven at 120°C to sinter

978-1-5090-6360-4/17/$31.00 ©2017 IEEE

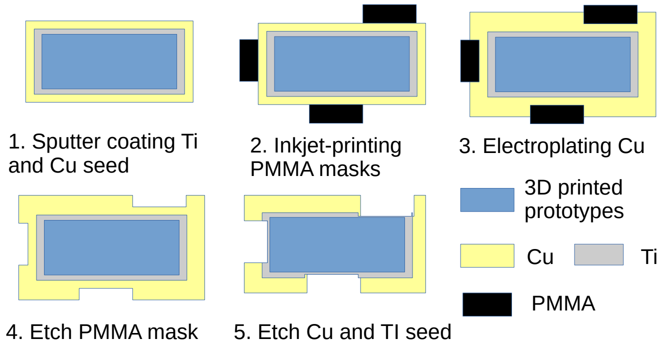


Fig. 1. Selective 2.5D metallization process with a cut in the middle of the SIW to show a cross-section view.

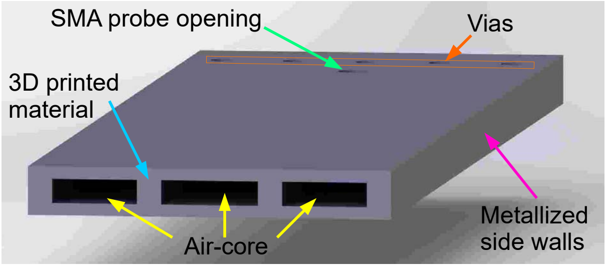
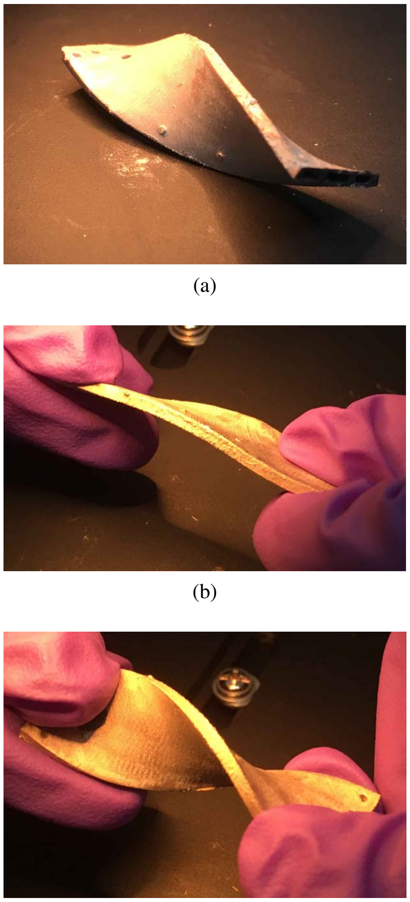


Fig. 2. Diagonal view of 3D printed air core SIW which is cut in half to show the cross-section of the SIW.


(a)

(b)

(c)

Fig. 3. Photo of the twisted SIW in various states: (a) original (120° twisted); (b) flat (0° twisted); (c) 180° twisted.

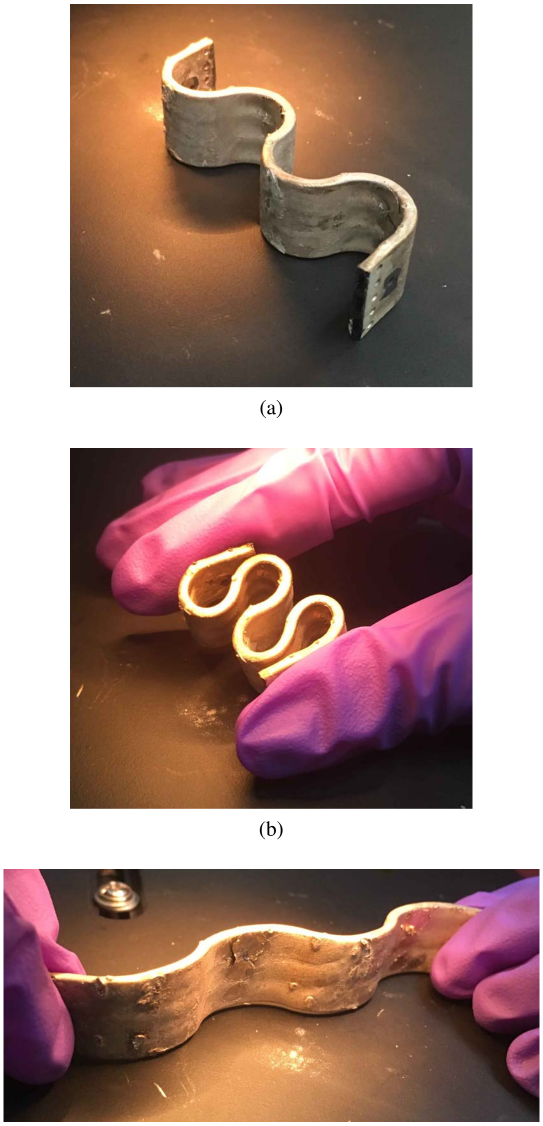
the silver nanoparticles. A sheet resistance of less than 0.05 Ohm/square can be easily achieved with repeating the bath-and-bake process twice. This process is simple, fast, straightforward and cost-effective, so the two proof-of-concept flexible 3D SIW transmission lines are metallized using this method.

2) Selective metallization: In the case of selective metallization or patterning, a much better controlled process is required. Bath-and-bake processes usually have limited bonding strength between 3D printed prototype and the conductor, and the uniformity of the conductivity depends on the shape of the prototypes. A semi-additive process (SAP), which is widely used in packaging and Print Circuit Boards (PCB) was adjusted for additive manufacturing to selectively metallize the 3D printed prototypes, as shown in Fig. 1. Firstly, the prototypes were sputter coated using a thin layer of Titanium as the bonding layer and then a 400 nm copper layer as the electroplating seed. Then, instead of photolithography in traditional SAP process, inkjet-printing, an additive manufacturing process, was used to deposit a 20 μm Poly(methyl methacrylate) (PMMA) mask to prevent the contact of the electrolyte and the seed layer at the specific areas where copper should be prevented from forming during electroplating. The shape of the mask is designed to be the projection of the negative of the pattern in the printing direction. Multiple prints at different angle can effectively pattern any outer surface of any 3D prototype. After the mask is deposited on the different faces of the 3D printed object, the prototype is soaked in a copper salt solution with negative charge which results in copper growth only on areas that are conductive. Around 5 μm thick copper is deposited in 40 minutes. After that, the PMMA mask is removed via a acetone bath and then the copper and titanium seed below is etched with etchant in a carefully controlled time to prevent over-etching of the electroplated copper.

III. FLEXIBLE 3D SIW TRANSMISSION LINE

In general, photopolymers feature a high dielectric loss, which would affect significantly the performance, thus the SIW was designed to have an air core inside, which also decreases the stress of the material when bent and facilitates a better flexibility. To reduce the radiation loss, the presented SIW transmission line uses side walls on both sides. However, due to the 3D printing constraints, resin that has been trapped inside the substrate needs to have an opening so that it can flow out, thus vias are applied to the two ends of SIW to replace the side walls. The SIW cross-section shown in Fig. 2 is 2 mm thick in total with 1 mm thick air core, and has 15 mm width for 50 Ohms impedance matching. Two 1 mm width supportive walls are designed to be located at the 1/3 and 2/3 width positions effectively preventing the deformation of the structure during bending.

A twisted SIW transmission line prototype is shown in


(a)

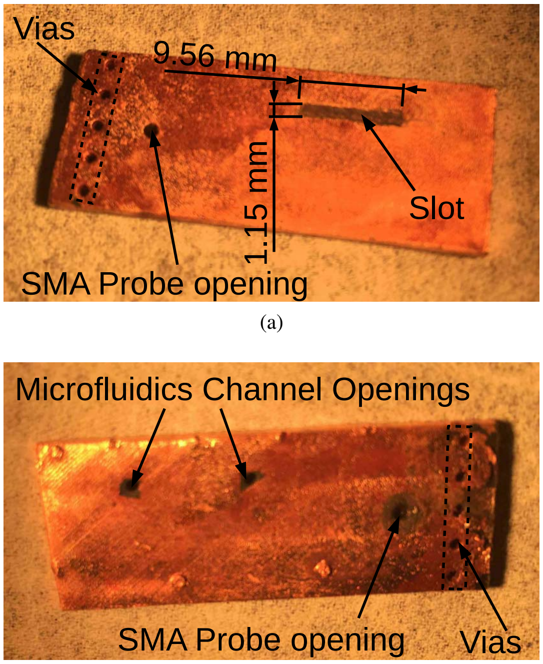
(b)

(c)

Fig. 4. Photo of the wavy SIW in various states: (a) original (6.71 cm length); (b) compress (4 cm length); (c) stretched (9 cm length).

TABLE I
PERMITTIVITY AND TANGENT LOSS OF THE FLUIDS[4], [5] AT 12 GHZ

Fluids	Relative Permittivity	Tangent Loss
Air	1	0
Ethanol	5	0.5
Water	53.6	0.662



(a)

(b)

Fig. 5. Photo of 3D printed microfluidics sensors.

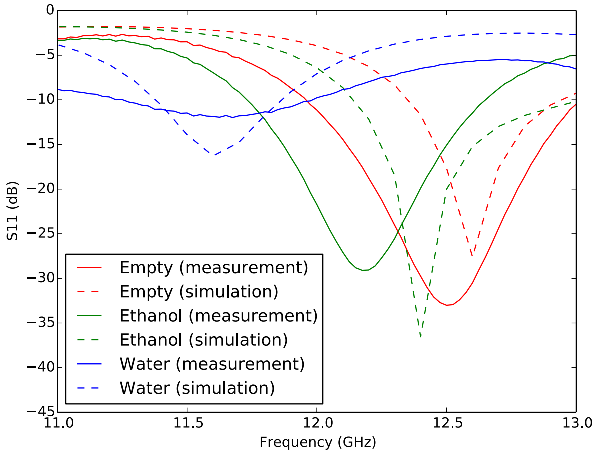


Fig. 6. S11 of the antenna sensor when different fluids or air filled in channel.

Fig. 3 enabling 0° to 180° twisting without any damage, demonstrating the great flexibility of the design. In Fig. 4, a wave-like SIW can be compressed to less than 4 cm and be stretched to more than 9 cm without cracks, featuring excellent stretchability/compressibility.

IV. MICROFLUIDICS SLOT WAVEGUIDE ANTENNA SENSORS

A microfluidics sensor based on the proposed flexible SIW structure was designed, optimized and simulated with Ansoft HFSS. A slot waveguide structure was used with a microfluidics channel right underneath the slot. The permittivity value of the fluids is varying for different solution contents inside the microfluidics channel, which would potentially provide useful information about the user's health status. Thus, for different fluids inside the channel, the electrical length of the slot is changing. The sensor was measured with an Anritsu VNA for air, ethanol and water inside the channel. The permittivity values of the tested fluids are shown in the Table. I. Observing S11 in Fig. 6, it's easy to notice the resonant frequency is shifted with permittivity while the loss of fluids affects the bandwidth/Q-factor of the antenna. A good linearity can be

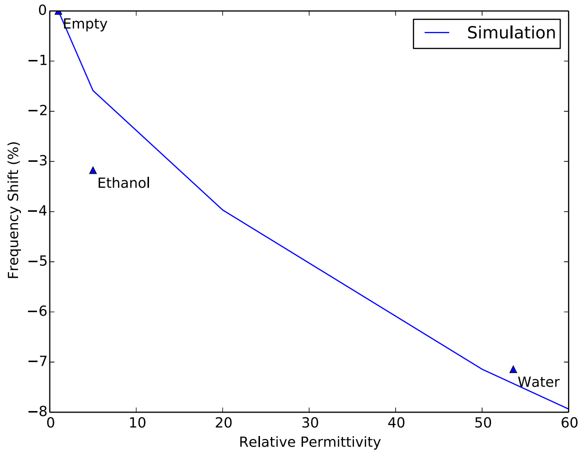


Fig. 7. The relation between the resonant frequency shift of the sensor and the permittivity value of the material filled in channel. The line shows the simulation result and the triangles are the measurement results for empty, ethanol-filled, and water-filled channels.

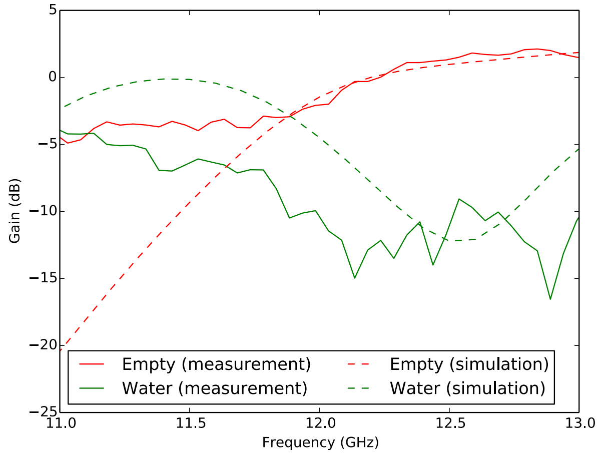


Fig. 8. Maximum gain of the slot waveguide antenna for empty channel and water-filled channel. Due to the dielectric loss of water and impedance mismatching, the maximum gain for a water-filled microfluidics channel is lower than that for an empty channel.

seen for the sensor as shown in Fig. 7, and the ethanol variance from simulation and measurement may be due to impurities in the ethanol solution used. In Fig. 8, the frequency with the maximum slot waveguide gain is also shifted to a lower frequency when filling the underlying microfluidic channel with water, showing that the operation frequency of the antenna was shifted accordingly for different contents of the channel.

V. CONCLUSION

This paper introduces novel flexible 3D sensing platforms based on 3D printed SIW structures that enable on-demand customized wearable devices along with a novel additive manufacturing process to prototype them with 3D printing and a 2.5D low-cost metallization process. A microfluidics sensor based on this platform is presented, with a sensitivity of 1.7 MHz/Er. The proposed SIW-based flexible/stretchable wearable platforms along with the microfluidics sensors can be used in various internet-of-things applications including smart health.

ACKNOWLEDGMENT

Authors would like thanks National Science Foundation (NSF), Defense Threat Reduction Agency (DTRA), and Semiconductor Research Corporation (SRC) for supporting this work.

REFERENCES

[1] F. Benito-Lopez, S. Coyle, R. Byrne, and D. Diamond, “Sensing sweat in real-time using wearable microfluidics,” in *Proceedings of the 7th International Workshop on Wearable and Implantable Body Sensor Networks, Singapore*, 2010.

[2] W. Su, B. S. Cook, and M. M. Tentzeris, “Additively manufactured microfluidics-based “peel-and-replace” RF sensors for wearable applications,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 6, pp. 1928–1936, 2016.

[3] W. Su, B. S. Cook, Y. Fang, and M. M. Tentzeris, “Fully inkjet-printed microfluidics: a solution to low-cost rapid three-dimensional microfluidics fabrication with numerous electrical and sensing applications,” *Scientific reports*, 2016.

[4] U. Kaatze, “Complex permittivity of water as a function of frequency and temperature,” *Journal of Chemical and Engineering Data*, vol. 34, no. 4, pp. 371–374, 1989.

[5] P. Petong, R. Pottel, and U. Kaatze, “Dielectric relaxation of h-bonded liquids. mixtures of ethanol and n-hexanol at different compositions and temperatures,” *The Journal of Physical Chemistry A*, vol. 103, no. 31, pp. 6114–6121, 1999.