A Novel 3-D Printed Loop Antenna Using Flexible NinjaFlex Material for Wearable and IoT applications

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***Abstract*— A stretchable, flexible loop antenna working at 2.4GHz ISM band was fabricated by the additive manufacturing (AM) 3-D printing technology. NinjaFlex, a flexible 3-D printable material was utilized for the first time as a 3-D hemi-sphere substrate for the loop antenna. A 3-D printer based on the Fused Diffusion Modelling (FDM) technology was employed to 3-D print the substrate material. The resonance frequency of the antenna shifts in response to the applied force which makes the configuration suitable for the wireless strain sensing application. The proposed antenna was designed for wearable electronics application such as health monitoring earrings. Hence it was designed in such a way that it maintains the Specific Absorption Rate (SAR) of the human head tissues within the assigned standard limits when placed near human replicating head. The proposed antenna system could be useful in the additively manufactured wearable packaging and IoT applications.**

Keywords—Flexible, Wearable, Additive Manufacturing, 3-D Printer, Strain Sensor, 2.4 GHz ISM, Wireless Sensor.

I. Introduction

For more than four decades, the semiconductor industry has rigorously followed Moore's Law in scaling down the CMOS technologies. A typical horizontal or 2-D System-On-Chip (SoC) is a system integration approach that integrates number of transistors as well as mixed-signal active and passive components. This entire assembly makes system bulky. Hence there exists fundamental limitation in compacting system further with SoC approach. This realization shifted research focus towards 3-D stacked System-in-Package (SiP) to make system compact as well as cost effective by shortening the wire interconnects. However, SiP systems are still limited by CMOS manufacturing process just like the SoC system. Designers can take SiP a step further by embedding both active and passive components, but passive component embedding is bulky and requires thick film. Thick-film component embedding distinguishes SiP from System-on-Package (SoP), a 3-D solution that incorporates vertical stacking of packages, embedding active and passive components. This makes system compact and cost effective than ever [1].

Electronic products continue to find new applications in personal, wearable, portable, healthcare, entertainment, automotive, environmental and security systems as well as IoTs. Industry demands compact, light-weight and low cost packaging solutions. Our vision is to integrate 3-D stacked packages of digital, analog, sensors, RF, optical systems together with 3-D printed packaging. Ever increasing 3-D printing technology has some inherent advantages over traditional ways of fabrication and they are as follows: 1) This rapid-prototyping topology has ability to realize same day prototypes which reduces prototyping time. 2) Low end-product cost due to availability of cheap 3-D printable material for packaging as well as 3-D stacked compact design reduces the length of the interconnects. Also it leaves less or no waste material. 3) 3-D printing allows designer to design complicated structure with higher degrees of freedom than conventional methods. Also it offers unit-level customization with local manufacturing [2]. 4) Low initial installation cost of manufacturing equipment assembly compared to traditional CMOS manufacturing processes. Hence in near future, enhanced 3-D printing may eventually be employed to manufacture end-use electronic packages. 5) Rapid increase in availability of different 3-D printable materials, with each exhibiting unique properties. This makes a rich material library for designer and manufacturer to fabricate electronic products for numerous applications like high strength 3-D printable carbon fiber and nylon for extreme condition electronic packaging and skin safe Bio Range for wearable applications.

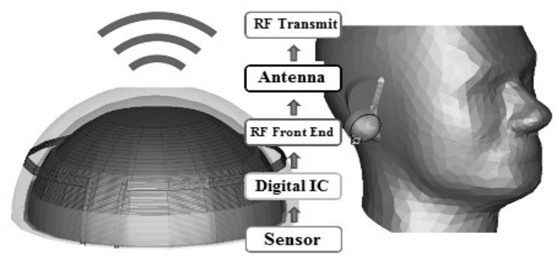

Fig. 1 3-D packaging for health monitoring and IoT applications

However there are fundamental issues with plastic packaging which are still a subject to research and cannot be ignored. Following are the issues that were observed with plastic packaging. 1) Plastics are prone to the moisture penetration and it affects long term reliability of the packaging. 2) Surface roughness could be a dominant issue at the higher frequencies. The plastic packaging durability and reliability test information can be found in [3].

This paper introduces a novel 3-D loop antenna on hemi-sphere utilizing the flexible NinjaFlex material for the first time. The proposed antenna can be useful for flexible, wearable and 3-D electronic packaging applications, such as health monitoring earrings and Internet-of-Things (IoT). Also the proposed configuration was tested for wireless strain detection application. It could be useful in tactile sensing for the "smart" skin and the flexible electronics [4] applications.

II. Design and Modelling

The electrically large circular loop antenna topology was chosen because of its large front and back lobes effectively synthesize a near omni-directional radiation pattern. This could be very useful in the "health monitoring earrings" applications enabling an almost non-intermittent connection to nearby wireless networks. The detailed loop antenna design procedure can be found in [5]. Without loss of generality, the optimized parameters of the 3D fabricated prototype were chosen to be equal to $k\rho = C/\lambda = 0.896$ at 2.4 GHz and $\Omega = 2 \ln (2\pi\rho/b) = 5.3675$, where k = wavenumber, ρ = radius of loop, C = Circumference of the loop, λ = wavelength, b = metal trace thickness. Thickness of the substrate was chosen to be 1.5mm for SMA connector to get a firm grip while feeding the loop.

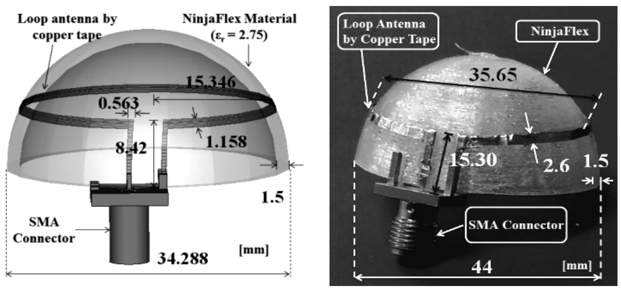

Fig. 2 a) Optimized simulation model of the loop antenna in CST Microwave Studio, b) Fabricated 3-D loop prototype antenna with dimensions after tuning

The relation between the loop radius ρ, hemi-sphere radius r and height of the loop from ground z was found by the spherical to cylindrical coordinate system conversion formula. It gave the value of r when ρ was chosen from the designing method mentioned in [5] and the z was optimized in such a way that feeding line would make least potential radiation loss.

III. 3-D Printing and NinjaFlex Material

Among several different methods of 3-D printing, the Fused Deposition Modeling (FDM) technology is the most widely used technique. This 3-D printing technology was utilized to 3-D print the NinjaFlex substrate. Typical FDM 3-D printers use a thermoplastic filament as a cartridge material in the form of plastic threads or filaments which are unwounded from a coil and fed to the extrusion head. This material is heated to its melting point at the extrusion head and then extruded out of the extrusion nozzle, layer by layer, to create a three dimensional object.

NinjaFlex filament was introduced by Fenner Drives Inc. in 2014. It is a type of thermoplastic elastomers, made up of combinations of the thermoplastic and the rubber, which provides the flexible properties to the material. It is very important for the effective 3-D printing of this material to fully investigate and optimize the melting temperature, the extrusion width, the layer height and the print speed to ensure smooth and the near-hermetic designs. These parameters were optimized in the Slicer software. The extrusion temperature was set to the melting temperature of the NinjaFlex at 230^0C. The extrusion width was optimized to 0.5mm to realize the hermetic 3-D model. Also, the layer height was optimized to 200μm to have smooth flow of the extruding material; this specification typically decides the thickness of each layer as well printing time. The Ninjaflex substrate was 3-D printed by Hyrel 3-D printer and then the copper tape of the optimized loop antenna size was glued on the top of the 3-D hemispherical support. The connection between the 50 Ω-coaxial SMA connector and the loop antenna terminals was realized utilizing a silver epoxy.

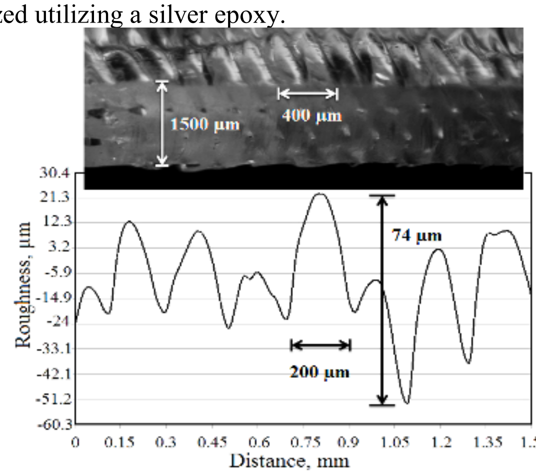

Fig. 3 Profilometer measurement compared with microscopic cross section photo of the NinjaFlex ring

The surface roughness of the NinjaFlex material was measured by KLA Tencor Alpha-Step D-500 Stylus profilometer in order to have some preliminary estimates of the losses at high frequencies. The surface roughness information is useful to estimate losses at higher frequencies due to the surface roughness. The microscopic cross section image was taken through AmScope Microscope. The 3D printed substrate has periodic as well as random elevations and depressions on its surface with maximum difference of 74μm between the tallest elevation and the deepest depression measured. 200μm width of the elevation indicates the layer height.

IV. Results

A. Return Loss S_{11}

The antenna characteristics were measured using a Rhode & Schwarz ZVA8 vector network analyzer in the frequency range of 2–3 GHz.

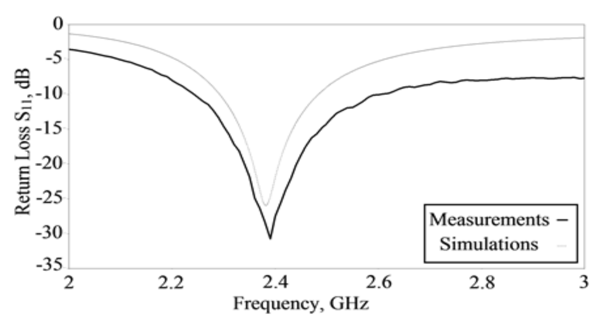

Fig. 5 Return loss S_{11} of the loop antenna prototype

Fig. 5 shows good agreement between the measured and the simulated return loss S_{11} results of the 3-D loop antenna, which was tuned to operate in the bandwidth of 2.32-2.5 GHz 2.4-2.5 GHz ISM band. However losses can be seen at the higher frequencies due to the surface roughness of 3-D printed NinjaFlex. These losses could be reduced by inkjet printing SU-8 photoresist layers to smoothen the surface.

B. Specific Absorption Rate (SAR) Measurement

As the proposed 3-D antenna/packaging was intended to be used in wearable bio-monitoring devices, such as the health monitoring earrings, it was essential to guarantee it will radiate within the standard safely limitations when placed on the user's body [6]. Hence the proposed antenna parameters were optimized to get a null towards head when placed on the ear of the human head replicating model. In the CST MW studio, the SMA connector and the discrete port were used to excite the loop antenna and then the SAR measurements were taken to fully understand the effect of power and excitation method variation on the SAR values. FCC and CENELEC assign a limit on the SAR in the US and Europe respectively.

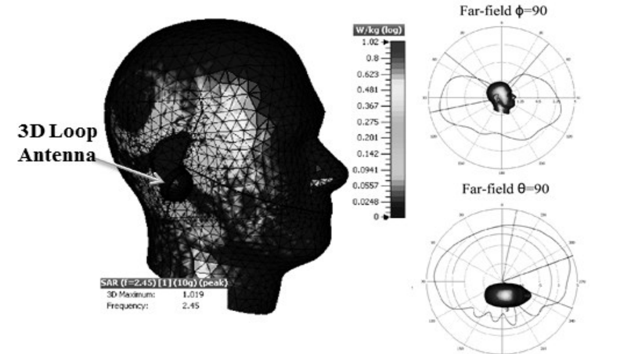

Fig. 6 Simulated SAR values and the radiation pattern for an ear-mounted 3-D loop antenna configuration

In the simulations, the specific anthropomorphic mannequin (SAM) phantom head model, provided by CST Microwave Studio, was utilized. The outer shell of the head had a fixed relative permittivity of $\varepsilon_r = 5$ with an electrical conductivity of 0.01252 S/m [6] and the head simulating liquid had a relative permittivity of $\varepsilon_r = 42$ with an electrical conductivity of 0.99 S/m. The following table indicates the effect of different excitation methods on SAR values.

TABLE I. SAR values for different types of excitation methods

Type of Excitation	Avg. mass 1gm FCC Std., W/kg	Avg. mass 10gm CENELEC Std., W/kg
Limitations	1.6	2
SMA	1.45	1.02
Discrete	1.58	1.09

C. Strain Sensor

The flexible properties of NinjaFlex make it a very appropriate material for wireless strain sensing applications. Hence, the variations of the antenna's return loss S_{11} with respect to numerous values of deformation were thoroughly investigated. The resulting change in the antenna shape affects the capacitance across the loop configuration to change, eventually changing the tuning frequency of the configuration, effectively. It was crucial to make an assembly to obtain persistent values of the deformation over same applied force without using the standard metallic mechanical tester. Various 3-D printed slots prototypes with the different dimensions corresponding to applied strain of 0, 3, 6..15% on the sensor were fabricated. The same recovering position of the sensor was maintained while taking 4 cycles of the measurements to ensure repeatability and reliability of the sensor.

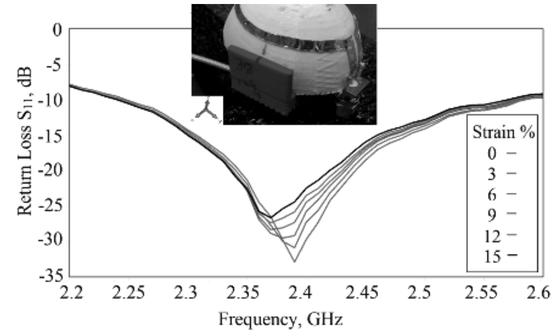

Fig. 7 Measured return loss of the loop antenna under different strain percentages

There were no signs of any physical damage after stretching, twisting and folding the 3D topology multiple times.

V. Conclusions

A novel 3-D printable and flexible packing material- Ninjaflex was introduced to manufacture fully 3-D RF configuration in the GHz operation frequency ranges, demonstrating the excellent capabilities of additive manufacturing technologies for applications such as wireless strain sensing and wearable bio-monitoring. The obtained resonance frequency band in the 2.4GHz ISM band shows its importance in additively manufactured packaging. Repeatable flexible property of the NinjaFlex makes it useful in the wireless strain sensing application. The proposed antenna is the first step to the realization of the fully printed arbitrary-shaped 3-D stacked multilayer packaging based on the SOP concept utilizing exclusively 3-D printing. Hence, the proposed topology could be a breakthrough in the first real world scalable implementations of low cost, compact, lightweight wearable and the IoT applications.

Acknowledgment

The authors gratefully acknowledge the financial support from NSF and DTRA.

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