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Inkjet-/3D-/4D-Printed ”Zero-Power” Flexible Wearable Wireless Modules for Smart Biomonitoring and Pathogen Sensing

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***Abstract*— With the development of Additive Manufacturing Technologies, the realization of inkjet-3D/-4D printing of complex structures for flexible wearable wireless modules has become a reality. This paper provides a review of the current state-of-the-art in semi-passive/fully-passive conformal, sensors, and the wireless powering of wearable wireless devices. This paper presents the advantages of mm-Wave additively manufactured modules for both high-speed wireless communications and wireless sensing with mmID as well as pathogen detection through inkjet-printing of multi-material electrochemical sensors enabling highly scalable low-cost 5G powered IoT devices for biomonitoring and pathogen sensing.**

***Keywords*— additive manufacturing, inkjet printing, 3D printing, energy harvester, backscatter, 5G, IoT, RFID, biomonitoring, pathogen sensing**

I. INTRODUCTION

With the recent proliferation of 5G and Internet-of-Things (IoT) technologies, there is great a potential paradigm shift in wireless, wearable biomonitoring systems. However, traditional subtractive manufacturing techniques used to realize these next-generation systems suffer from high costs due to material waste and a limited in dimensionality inherently limiting the potential form-factors for these wearable systems. Therefore, there has been an ever growing interest for the utilization of Additive Manufacturing Technologies (AMT) due the ability to selectively deposit a variety of materials on flexible substrates to realize 2.5D designs. With the addition of 3D printing technology, a layer-by-layer additive manufacturing process can be utilized for the realization of complex 3D/4D geometries with high resolution enabling mm-Wave wireless, wearable, sensors, System-on-Package (SoP), zero-power devices for ubiquitous biomonitoring [1], [2]. This paper presents an overview of the use of Additive Manufacturing Techniques for the development of wireless modules the next generation wireless systems for biomonitoring applications. Section II details the use of Additive Manufacturing Techniques to develop wearable tracking and wireless sensing system in IoT. Section III presents the advantages of Additive Manufacturing for pathogen sensing, in particular for the detection of COVID-19 through electrochemical sensing techniques. Section IV describes the utilization of Additive Manufacturing to enable the powering of wearable devices for ubiquitous biomonitoring.

II. FLEXIBLE, LOW-POWER MM-WAVE WIRELESS SENSORS FOR WEARABLE APPLICATIONS

In recent years, there has been an growing interest in Radio Frequency Identification (RFID) and Millimeter-wave Identification (mmID) systems for biomonitoring applications. This technology provides a low-cost and ultra-low power solution for ubiquitous wireless biomonitoring. Traditionally, RFID systems have operated at Ultra-High Frequency (UHF), however, these systems struggle inherently with limitations on the available bandwidth and require large bulky reader and tag systems, thereby, limiting the feasible data-rate and the ability to utilize UHF systems in wearable applications. Thus, through increasing the frequency of operation these mmID systems inherently benefit from compact designs and potential for high data-rate communication given the ultra-wide bandwidth at mm-Wave. The authors in [3] presented a mmID operating at 24 GHz with a demonstrated a data-rate on the order of gigabit per second. Additionally, this mmID was manufactured utilizing AMT on 7 mil flexible ligquid crystal polymer (LCP) substrate ($\epsilon = 3.14, tan(\delta) = 0.002$), with inkjet-printed silver nanoparticle (SNP) and can be viewed in Figure 1. Thus, enabling high data-rate communication for wearable biomonitoring applications for low-latency ubiquitous health monitoring. In addition wearable, low-latency wireless communication/sensing, smart skins (SS) for ubiquitous wireless sensing, being enabled through the use of AMT and smart materials, have recently been explored to provide data driven solutions in Internet-of-Things (IoT) systems. In [4], the authors present a chip-less, long range humidity sensor, additively manufactured with inkjet printing SNP on 5 mil Kapton HN ($\epsilon = 3.1, tan(\delta) = 0.003$), a flexible, low-loss substrate. The fabricated sensor is displayed in Figure 2. This passive sensor relies on a high-gain reflect array enabling long-range wireless sensing and presents a road map for future batteryless, wearable, wireless biomonitoring sensors. Furthermore, the authors in [5], a semi-passive, miniaturized RFID tag utilized for spatial localization is demonstrated. This ultra-low, RFID

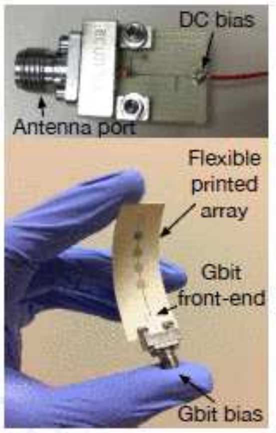


Fig. 1. Additively manufactured inkjet-printed, flexible front-end for high data-rate biomonitoring applications.

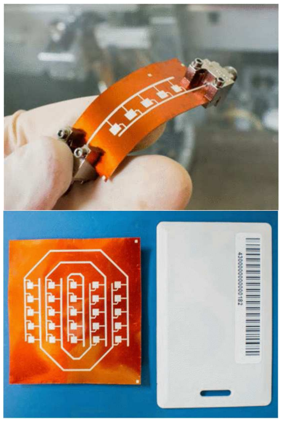


Fig. 2. Additively manufactured inkjet-printed, Smart-Skin humidity sensor.

tag fabricated with inkjet printed technologies on flexible 7 mils LCP $(= 3.14, tan = 0.0025)$. The presented system combines the low-cost AMT, mmID, and Frequency Modulated Continuous Wave (FMCW) enabling next-generation ultra-low power, wearable, wireless posture and gesture recognition systems. Thus, through the use of AMT, wearable, flexible realizations of mm-Wave devices provide tremendous potential in future biomonioring applications.

III. FLEXIBLE MODULES FOR PATHOGEN SENSING

A proof-of-concept Covid-19 electrochemical sensor, which was composed of a functionalized working electrode, a counter electrode, a reference electrode and some conducting lines, was fabricated via screen-printing or inkjet-printing followed by functionalization. The substrate on which such a sensor was printed was either rigid (such as alumina plates) or flexible (such as polyimide films). Figure 3a shows the basic topology of our flexible Covid-19 sensors, while Figure 3b shows a scanning electron microscopic image of the functionalized working electrode in a sensor. Depending on the detecting target (antibody IgG, IgM or SARS-Cov-2 virus etc.), the functionalization process with antibody/antigen biological molecules is slightly different. Chronoamperometry (CA) technique was employed to measure the steady-state current change during the sensing process. In our work, different potentiastats were used for the sensing measurements. Two commercial potentiastats, one traditional bulky potentiastat and one handheld portable potentiastat were used to do the measurements. Wired sensing (as opposed to wireless sensing) was realized on the traditional potentiastat, while both wired and Bluetooth-based wireless sensing were realized on the handheld portable potentiastat. Besides, a home-developed open source potentiastat was also used for the sensing measurements. Our Covid-19 sensors were able to not only detect recombinant Covid-19 IgG antibody of as low as 1 pg/ml but also clearly differentiate Covid-19 positive blood samples from their negative counterparts. Our sensors were also able to clearly differentiate Covid-19 IgM positive blood samples from their negative counterparts. Our Covid-19 sensors can be easily modified to detect viral or bacterial pathogens including SARS-Cov-2 virus.

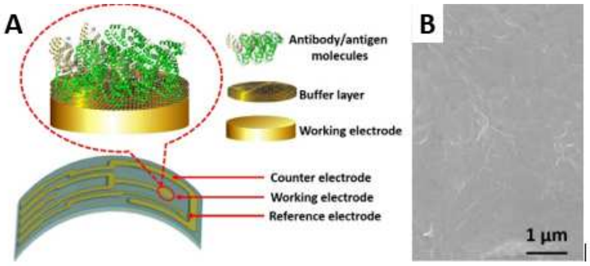


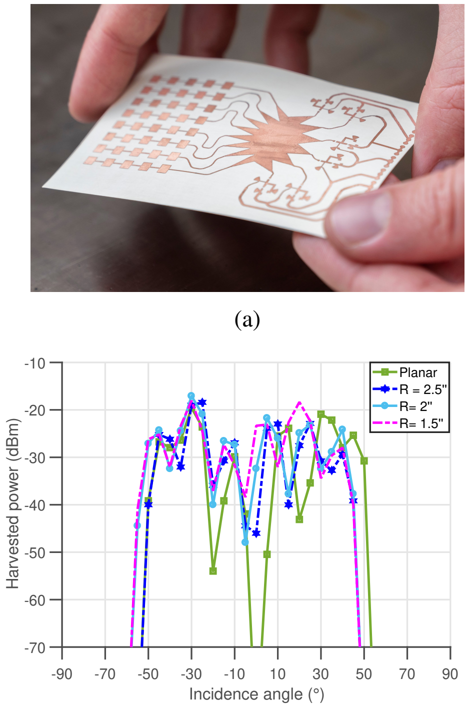
Fig. 3. (a) Topology of a Covid-19 sensor (Inset shows topology of the functionalized working electrode in the sensor). (b) Scanning electron microscopic image of a functionalized working electrode.

IV. POWERING WEARABLE AND IOT DEVICES WITH MM-WAVE ENERGY

The design of wearable, conformal, and lightweight health monitoring devices capable of communicating data in real-time can contribute, to a large extent, to disease early diagnosis. However, at the core of wearables hardware design, is the power source that remains a major limitation to the implementation of these valuable devices in critical scenarios. The most common power sources used in consumer hardware devices are batteries. However, they are usually bulky, require maintenance and produce harmful chemical waste. Solar, piezoelectric and electromagnetic energy harvesting have been gaining a lot of attention for their ability to provide clean energy with minimal complexity. In particular, mm-wave power transfer has demonstrated the ability to power IoT devices at ranges exceeding $100\,\mathrm{m}$ from 5G/mm-wave base stations [6]. The implementation of mm-wave energy harvesters has been executed in a variety of ways ranging from printed on flexible thin substrates to fully-embedded in a package using hybrid, inkjet and 3D, printing [7], [8]. Fig. 4a shows the printed prototype of a proof-of-concept planar 5G-powered Rotman lens-based harvester. The lens was carefully designed based on a scalability study to choose the optimal number of antenna and beam ports. Rectifiers were connected on the beam ports to transform the combined and focused mm-wave energy, captured by the antenna arrays, to DC power. The addition of the Rotman lens as an intermediate element between the antennas and the rectifiers enabled the succesful combination of a high gain of $17\,\mathrm{dBi}$ and wide angular coverage of 120°. Tested on both planar and curved surfaces, the mm-wave harvester demonstrated an efficient power conversion and robust performance with respect to angles of incidence, as shown in Fig. 4b. Such an implementation combining flexibility, orientation-agnostic energy harvesting, and long-range capabilities could have a disruptive effect in the emergence of 5G-powered wearable and biomonitoring devices.

V. CONCLUSION

This paper has reviewed the recent advances in additive manufacturing processes including inkjet printing and hybrid printing techniques to enable wearable wireless modules for



(a)

(b)

Fig. 4. (a) Photo of the fully-printed planar Rotman lens-based harvester and (b) Measured harvested powers versus incidence angles for different curvatures [6].

biomonitoring and pathogen detection. These advancements include flexible, compact, wearable, semi-passive and fully-passive wireless sensing modules featuring high-speed data rates for wireless communication for wearables as well as ultra-sensitive electrochemical detection of COVID-19 while been implemented as 5G-powered wearable IoT devices.

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